Heuristic Path Finding Method for Online Game Environment

By

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Abstract

A Heuristic Path Finding Method is developed that resolves the bottleneck for system performance in the online game industry. In order to obtain a satisfactory performance, the background processing system for pathfinding has to sacrifice either efficiency or accuracy.

Under this method, designers analyze the game map structure and build area information first. The online game system will then generate path templates for in-game usage based on the map information. As the templates are being generated, the system’s pathfinding Artificial Intelligence (AI) will pick a path from the templates and adjust it accordingly to produce a real path. This method improves pathfinding approaches with higher accuracy, is less time consuming and requires fewer resources from the game system. We have created a testing system for testing and evaluating pathfinding related work. With this testing system, extensive experiments have demonstrated the advantages of our method over a few known algorithms.
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Chapter 1 Introduction

Pathfinding Used in The Modern World

Pathfinding is a topic that has been discussed over and over for generations. At the same time, there have been many algorithms developed to solve various types of pathfinding issues. In this chapter, we are first going to have a glance at how pathfinding utilities are used in the modern world, and then gradually narrow the scope to focus on the problems we want to resolve.

1.1 Pathfindings under Different Applications

When developing a pathfinding method, there are different types of requests and accessible information one needs to consider. In terms of requests, some methods dedicate to finding the target despite of potential detour, some methods seek the shortest path regardless of the time required, while other methods pursue the shortest time by lowering the importance of path length requirement. In terms of accessible information, some methods provide world coordinates, others provide only a response time. Simply put, there is no ultimate way to satisfy all kinds of pathfinding requests. All methods are limited by the accessible information provided by the environment. Here we will list the background information that researchers developing pathfinding techniques would based on.

1.1.1 Pathfinding without Geographical Information

Cyberspace is the most known example in this category. Browsing the internet requires the use of computers, cables and virtual messages. With a group of computers connected by cables, every computer generates messages to establish its
relative position within the group. What this achieves is that the computer group can build its own virtual map specifying the physical relationships of all group members.

There is no geographical information such as direction or distance required for this map. The metric used to estimate the relation between computers is substituted by the time needed for sending and receiving information. The most known algorithm in this category is Dijkstra's algorithm (Tim and Mark 2000).

1.1.2 Pathfinding without An Overview of Geographical Information

The typical type is robot pathfinding. There are annual robot competitions hosted by organizations such as FIRST Robotics Competition (FIRST Robotics Competition, FIRST). Though there have been no breakthrough for a long time, robot pathfinding is still among competition options. Without knowing at first its starting location, a robot needs a pathfinding Artificial Intelligence (AI) to explore its environment and find a path to the destination. It tries to build a map according to the information gathered from the environment. This method does not guarantee the shortest time or the shortest path to reach a target; the AI may reach the destination without completely exploring the entire map, or it may need to explore the entire map before reaching the target.

The main challenges of this pathfinding method are to correctly recognize its environment and to initialize a map scratch. Once these can be achieved, the AI can avoid repeating errors and reason out correct paths more efficiently.

1.1.3 Pathfinding with An Overview of Map Information

One example of this type of pathfinding is the Global Positioning System (GPS) (Global Positioning System, National Executive Committee). Nowadays wireless communication is everywhere as satellites are being sent into space and
orbiting our planet. Since now we can have a clear view of the earth, using the GPS is definitely a viable solution. Users send messages to the server to identify their location and request for a path to the target. The server processes the messages, builds the best solution according to the current map information, and then guides the users to their destination.

Electronic game is another example. The designer of the game sets up fantastic virtual environment for players to explore. To the game engine, the map is already in existence and fully-learned. The AI only reads the on and off signals, unlike players who can recognize 2D image in a much quicker and more meaningful way. In order to make Non-player Characters (NPC) move more smartly or humanly, the game system plans the path according to its processing maps.

These types of pathfinding methods have a clear view of the map, geographic orientation, and the condition of all parts of the map. All these attributes assist in reaching a better result.

1.2 Game Types and Pathfinding Requirement

Our method is focused on the online games, but it is important to explain our method further by breaking down the game category into different game types, including online game, and the reason for this will be apparent shortly. Here we are going to introduce our catalog of game types and how they affect pathfinding requests. In general, graphics are always the most resource-intensive functionality in game design. Visual effects are always the first priority, resulting in various other functions being pushed aside to be less important, and AI is an example. When the rules of a game are simple, designer can place more emphasis on the story telling while simplifying the AI design without affecting the overall experience for the players.
Here we will discuss five game types according to the way the AI moves. We will also describe the role AI movement plays in each game type and how it is implemented and simplified in consideration of performance. The five game types are

1) Pathfinding not required at all,
2) Pre-determined movements,
3) Pathfinding for few requests,
4) Pathfinding for numerous requests,
5) Pathfinding for numerous requests in an online game server

1.2.1 Pathfinding not Required At All

Games fall under this category include puzzle games, object-finding games and simple First Player Shooter games (FPS). Basing on common games, puzzle games such as Jigsaw365 (Figure 1-1) and Luxor (Figure 1-2) allow objects to move to destination directly without any hindrance. Object-finding games such as The Mirror Mysteries (Figure 1-3) and Big City Adventure have fixed objects that require no movement at all. Simple FPS games such as The Bank Of Jasker (Figure 1-4) permit objects to move up and down but in the same spots. These limitations restrict players' movements in the game and involve high repetition in user control. Some games of this type introduced attributes such as timing or story narration to enrich game content.
Figure 1-1 Snapshot of Jigsaw 365 (Jigsaw 365, Playtonium)

Figure 1-2 Snapshot of Luxor 3 (Luxor 3, Big Fish Games)
Figure 1-3 Snapshot of Mirror Mysteries (Mirror Mysteries, Big Fish Games)

Figure 1-4 Snapshot of The Bank of Jasper (The Bank of Jasper, Flashgames247.com)
1.2.2 Pre-determined Movements

In this game type, game objects automatically move around according to predetermined path. This movement does not interact with the environment. Some games of this type move objects according to the player's intention, but this does not involve pathfinding, the player simply chooses one of the pre-defined paths and follows it. Some examples of this game type are Cake Shop (Figure 1-5) and Go-Go Gourmet (Figure 1-6). Even though players do not control the movements and cannot change the paths, the movements of the objects provide some other attributes to the game design, such as time management. We categorize this as a separate game type as it does allow some degrees of variation in object movements, which adds to the richness of the game content. However, this variation in movement does not require pathfinding, it is only a variation in a list of selection.

Figure 1-5 Snapshot of Cake Shop 2 (Cake Shop 2, Big Fish Games)
1.2.3 Pathfinding for Few Requests

Movement in this game type is more intelligent than that of the previous two categories. Games of this type come with a complete concept of their own virtual world, such as direction, distance, static objects, interactive objects, friendly relationship, hostile relationship, etc. Based on these information, computer controlled objects interact with the players in a meaningful way, such as moving closer to actively attack, defending for the player, following player as a companion, or even just as an impartial third party. Even though interactive AI can also be achieved in simpler games requiring less or no movement in the objects, such as those we mentioned earlier, the AI in this particular game type chooses its response according to the object attributes and various selections while moving freely and intelligently in
the game world. This creates the illusion of time and space and promotes players to explore the game world by giving them more control flexibility in movement.

Most console games belong to this game type, such as The Sims (Figure 1-7) and Neverwinter Nights (Figure 1-8). Since a game's performance relies heavily upon the player's hardware, games only activate objects within player's viewport to increase its overall performance.

Figure 1-7 Snapshot of The Sims 2 (The Sims 2, Electronic Arts Inc)
1.2.4 Pathfinding for Numerous Requests

Strategy games are a type of games that have active AI objects running outside of a player's viewport. Efficiency is the first priority for game systems. AI plays an important role in the game content of this type. Both the computer and the player control a group of game objects. The computer directs the objects of its own team to compete with the player. Though the movement of the computer's team is not visible to the player, it does perform tasks almost the same way as the player does. The AI team gathers game resources, defeats enemies, constructs buildings and builds its troops. Even objects belonging to a player rely on AI control. The game provides functionality to allow a player to queue tasks on one object, then the object automatically moves around the world to complete a series of assignments.

This is a game type of heavy interactivity between AI and the players. Interactivity means higher capacity and resource requirement. Since the game AI is
not smart enough to actually set a strategy to beat the player, there are two ways to lighten the game’s workload: one is to allow the AI to cheat in game, the other is to simplify possible activities.

If AI cheats in the game by calculating in advance instead of making real movement according to player’s concurrent status in runtime, the game could end up being very unfair to the players or too easy to win, both cases would make the game not worth playing. Therefore, this game type generally limits the degree of controls in AI’s ability so it has expertise in a few specific tasks, which helps to level the abilities of AI and the players. Although currently in most games of this type, the AI generally cannot beat the players, it is a very challenging game type and the only one that emphasizes the role of AI.

The amount of pathfinding requests in this type is significantly more than the previous types, but the targeted system is still focused on the personal computer. To allow acceptable performance, there should be limitations on AI, so as on pathfinding techniques. A example of this game type is Age of Empire (Figure 1-9).
Online games are the main topic under this category. It is basically constituted by internet, hosting server and clients. Game content and interaction between players are mainly located on the server. How resource is used is different in online games and in console games. A console game has to handle the physics of the movements, virtual effect, AI calculation and game content on its own. Virtual presentation usually uses most of the system resources, game content and AI compete for the remaining. For online games, on the other hand, the client side is devoted to graphic and the physics of the movements, and the game server is dedicated to content management and AI. Theoretically, online game is more likely to have better AI, but, because of its multi-player attribute, management of client interaction adds another heavy load to the system. Pathfinding calculation is still at risk of being sacrificed.
In this environment, there are usually many players logging on to a host server concurrently, and the objects around each player are activated when any of the online players approach. There is nowhere to secretly save system resource. To keep performance within acceptable range, online game service providers can either upgrade hardware to increase its capability, or to optimize system structure to meet the large amount of requests. Examples of this game type are World of Warcraft (Figure 1-10) and Lineage (Figure 1-11).

*Figure 1-10 Snapshot of World of Warcraft (World of Warcraft, Blizzard Entertainment)*
1.3 Motivation and Contribution of This Thesis

1.3.1 Motivation

There are various pathfinding methods already in existence. They are devoted to make the AI smarter at every movement decision, and, in order to meet quality requirement, the AI takes time to “think” in order to process all the requests simultaneously. But there is no such time for online game. With a wide accessibility via the Internet, instant response and massive requests processing are the new demands for game performances.

In many well developed online games where players are tempted by fantastic effects and abundant contents, we can still observe problems caused by poor pathfinding approaches, such as detouring, being stuck and going through solid objects. In gaming industry, an excuse for adopting such poor pathfinding approaches
always rooted from the tradeoff between the good solutions and computing resources. There is an apparent dilemma between the good solutions and the computing time for finding the good solutions. This thesis attempts to find an approach such that good solution and acceptable online time cost can be achieved simultaneously.

1.3.2 Contribution

Our method is designed to resolve a massive amount of requests within a limited amount of time. Therefore, our theory focuses on a pathfinding method that is equipped with the map information. Time is in fact a challenge as computers only processes binary information, which is good for massive simple checking, but not for more advanced processing.

Instantaneous response is a very important attribute to game performance. With numerous requests, system resource will hardly afford to allow AI making the best decision at all times. The game system maintainer can choose to either expand hardware resource or to sacrifice AI accuracy. Game producers inevitably ponder between performance and accuracy when considering pushing a product from console to an online platform.

Heuristic Path Finding Approach is a solution to massive pathfinding requests that need instant response. It makes good use of the preparation phase by analyzing the map structure and creating optimized path templates before the service goes online. At runtime, the system knows the possible connection between the start and the ending location as soon as requests are sent in by referring back to the path template, AI can determine that there is no valid path in between immediately if there is no corresponding path template. Our method groups together the locations as areas and builds paths in advance, so that it saves a lot of time from re-performing the search for
each single request. It minimizes uncertainty of possible path, simplifies the work of runtime pathfinding and lowers the usage of system resource.

The remaining chapters of this thesis are organized as follows. In the next chapter, Overview of Current Pathfinding Approach, we introduce 3 pathfinding methods which are popular in game development. Chapter 3 describes how Heuristic Path Finding Method works and its design details. In Chapter 4, Implementation Details and Subjects of Measurement describes the design of the testing system we created to test the various pathfinding methods, and discusses the major indicators used in the experiment to compare the methods. Chapter 5 demonstrates our experiments and presents the results and the accompanying analysis. Finally, the conclusions and discussions of future work are provided in Chapter 6.
Chapter 2 Overview of current pathfinding approach

A game map design highly affects pathfinding performance. The reason is that generally, game designers create virtual world by decorating it with many objects such as plants, swamps, fields, buildings, etc., and would expect players to get immersed into this fantasy. Technical designers tend to unify all objects and set them into a certain kind of order. Similar to a driver who needs a trip plan to reach his destination, the AI of a game needs a game map in order to analyze its surroundings to build a path plan. A coordinate system is the most straightforward reference to AI movement in that it provides direction and measurement, and is implemented as the foundation of the game environment.

Various pathfinding methods and theories exist, and some of them are very comprehensive. Comprehensive method naturally demands more system resource. Taking this into consideration, one needs to realize that in a virtual game world, there are so many details to plan and manage, and pathfinding is only a minor one. Without a doubt, all game designers want to create a vivid game world by using good pathfinding technique, but there is only limited resource on hand. Therefore, instead of using the ultimate solution, game designers usually choose less complicated methods but are just sufficient enough to meet the requirement. The following discussion introduces three of the most popular methods: A* pathfinding algorithm, waypoint and navigation mesh.

A game map is generally designed in coordinate system with integer values. The coordinate system is straightforward to human and at the same time fits the computer’s functionality. The reasons to develop game maps with integer values are 1) floating-point arithmetic is much slower than integer computation, and 2) monitors used to present game content could not present the partial of one pixel. Under this
guild line, there are only eight directions in maximum for one object to move in a two-dimensional game world

2.1 A * Algorithm

A* algorithm was proposed in 1968 (Hart, Nilsson, 2003), as a type of heuristic pathfinding method. It develops a path by setting current position on the surrounded position which carries lowest evaluating value until reaching the destination. The evaluating value is generated by the following function:

\[ f(n) = g(n) + h(n) \]

\( g(n) \) is a path-cost function, which is the cost from the starting position to the current position. In game development, the cost represents not only the distance in between, but also some game environmental attributes, such as effort required for climbing a hill, hostile rate, friction of the ground, etc. In this thesis, only distance is taken into consider.

\( h(n) \) is an admissible “heuristic estimate” of the distance from current position to the goal. This function provides directional information to guide path toward the goal. There are several heuristic methods introduced on website Amit’s A* Page (A-star-trap, Amit’s A* Pages). In game development, this function is developed in simple way because avoiding complicate computation without affecting presentation is the major concept to save resources. A game system won’t need any pathfinding method if its game world contains no obstacles. If obstacles do exists in a game world, the heuristic estimate applied with fixed tuning value could never fit all game maps. In this thesis, heuristic estimate is the sum up of the vertical distance and the horizontal distance between current position and the goal.
In addition to evaluating function, A* algorithm carries two lists: open list and close list. Open list contains all visited positions which are assigned with a cost value, a heuristic estimate and its previous step. One position would be moved out of the open list into the close list when all of its surrounding positions are assigned with evaluating values.

Pathfinding function sets current position on starting point at the beginning and puts all surrounded position into open list with their cost, heuristic estimate and previous step generated according to current position. After all surrounded positions being evaluated, pathfinding function sets the current position on the position stored in open list which carries lowest evaluating value. This process repeats until the current position reaches the goal. The final path is built by tracing back previous steps from the goal toward the starting position.

Two-dimensional game maps developed in coordinate system with integer values look like grid-maps. We will use the term “A* grid” to represent the pathfinding method implemented in an A* algorithm based on a pure coordinate system.

**Feature**

Although the A* grid may not be the ultimate solution for game pathfinding, it is definitely one of the more popular ones. Dating back to older games, game maps were small and assembled by tiles. The viewport of the game was similar to looking at the world from the sky (Fig 2-1). While restricted by RAM memory and the speed of the computer, the map structure was expanded to contain game object information. Therefore pathfinding AI was allowed to plan an accessible path by referencing map data.
In theory, vertexes are what A* grid is based on to evaluate pathfinding details. Starting with a vertex on a simple two-dimensional map, movement in all directions should be allowed. However, when it is implemented on a coordinate system, each step has only 8 possible directions, moving upward, downward, rightward, leftward, and towards the four angles diagonally. It would take the object the same amount of time to move horizontally and vertically, and the same amount of time to move diagonally.

The way an A* grid works is very similar to a man walking in the dark. Eyesight is no longer enough to lead his direction, he has to move around with both hands stretched out to make sure that next step is clear of obstacles and is safe. Pathfinding AI implemented in an A* grid selects one optimal step from surrounding grids. A path is built by tireless grid-checking from the starting point to the destination.

**Advantage**

An A* grid method uses a distance and moving cost to evaluate the next step (A* algorithm, Wikipedia). In order to achieve the best next step, the AI sums up the
cost of moving from the starting point to the current location and adds it to the distance between the current location and the destination. The distance estimation highly depends on the coordinate system which not only contains the distance measurement but also the direction. Compared to Dijkstra's algorithm (Dijkstra's algorithm, Wikipedia), which is generally used in Internet routing services, the A* algorithm avoids most unnecessary checking and saves time.

Figure 2-2 A* algorithm used on simple map

This image shows the path built by A* algorithm and the grids that were checked during pathfinding process (A-star-trap, Amit's A* Pages).

Figure 2-3 A maze like map (Maze, Wesg ca)

On a simple map (Figure 2-2), directional movement helps greatly with the pathfinding. On the other hand, with a more complicated map (Figure 2-3), it inevitably takes the AI more time to resolve a task. Since responsiveness is the
highest priority to game system, the designer usually sets a limit on the length of time for processing before aborting the pathfinding task to prevent the task from occupying the system resources too long. When pathfinding takes excessive amount of time which might force the game system to abort the process, the NPC might appear as silly by not reacting much unless the player does something to it. Other than the aborting technique, the game designer can also solve this over-time issue fundamentally by simplifying the game map. After all, the game world is an imagination, its content is definitely negotiable, unlike the paths specified by the GPSs that cannot be changed freely since they have to be based on actual roads and highways.

The A* grid methods is still popular in the game industry. As game content is getting more complicated and as various pathfinding methods are being developed, the A* algorithm is usually where most pathfinding methods are derived from.

**Disadvantage**

A disadvantage is that there are only eight directions allowed for each step in an A* grid method. If one game object has to move over a long distance at a direction other than those allowed, it usually ends up moving in a zigzag motion and wastes time when turning. This problem is not obvious if a map is small and less complicated, and when each grid can represent a physical object or a relatively large region.

As hardware continues to improve, the game system is now designed to show a more refined visual presentation with each grid representing a smaller area. This way object should appear to not move grid by grid but point-to-point. As a result, each grid, while covering a much smaller area, is no longer regarded as representing an object or location, but used more as a reference point to calculate distance.
Furthermore, the measuring unit of each grid would also have decreased since each grid now covers a smaller area. To produce a map containing the same amount of objects and space as the older hardware, a designer using the newer hardware would require more grid and therefore more resources.

More grid and more resources mean bigger game map, which is exactly what the A* grid method is not suitable for.

### 2.2 Waypoint Method

When movements are without a grid, the moving direction becomes more important for the object at each step. The Waypoint Method (Waypoint Method, Wikipedia) uses links and nodes as additional information to accelerate the A* pathfinding work.

Waypoint Method is very similar to the A* algorithm on a high level. The object starts its movement from the closest node, goes through nodes and links toward the node closest to the destination, and then moves from there to the target location. There are two phases to validate Waypoint method: (1) the design of waypoint net, and (2) the planning of a route by the pathfinding AI using the waypoint net.

Waypoint Method is primarily based on the waypoint net. A waypoint net is composed of the selected accessible points, which are called the waypoints, and the links between those points to form a set of paths. It usually looks like a net and guides the object moving along the links to deliberate waypoints. Waypoint net is created to reduce the number of possible moving direction and the amount of time to make direction decisions. It is unlikely for the pathfinding request to be always located exactly on the waypoint nodes. Therefore, during runtime, it is AI’s responsibility to identify the nearest nodes around the starting point and the destination.
After the tuned locations are identified, the pathfinding AI tries to build a path based on the links that connect two arbitrary nodes. The link contains distance information between two nodes. In other words, the information provided by a waypoint net include the points, the direction and the distance. This is sufficient for A* algorithm to perform pathfinding. Therefore, Waypoint Method is essentially a method using the A* algorithm, assisted by coordinate system and waypoint net.

**Feature**

Waypoint Method uses waypoint net to assist the pathfinding process. How a waypoint net is designed is an important issue. Unlike the A* grid method which is able to identify its grids quickly by referencing to a coordinate system, there is no simple conversion for the Waypoint Method to convert nodes from a coordinate system to a waypoint net. The pathfinding AI has to scan its surrounding area for both the start and end points to identify the closest nodes.

Furthermore, the A* grid uses measurement to estimate the moving cost, whereas the waypoint retrieves the distance information from links. If a waypoint net is designed intensively, it may require longer processing time and occupy more memory resource than an A* Grid Method when resolve a task. If the waypoint nodes are designed loosely (Figure 2-4), the waypoint may detour round an object for a longer path.

The A* algorithm is implemented so that the object stops at the first occurrence it finds the destination, making it unnecessary to scan all irrelevant nodes. Under the Waypoint Method, if the player is in the middle of two waypoints, the order of checking the direction may affect the outcome (Figure 2-5). If an obstacle is allowed to be dynamic, it may block the path by being on the links. This can happen
even if there is still room to bypass the obstacle (Figure 2-6) The qualities of the waypoint net design highly affect the performance of the Waypoint Method

Figure 2-4 An example of how Waypoint net detours NPC

Mob's path would be disturbed by Waypoint nodes (red path), as the green path is the best solution. Original image comes from Neverwinter Nights (Neverwinter Nights, BioWare)
Figure 2-5 An example of waypoint evaluation affected by player’s location

AI uses the waypoint behind the NPC as start point. The distance from start point to both waypoints besides the player seems the same to AI. AI would choose the waypoint that was evaluated first while the waypoint on player’s right side is more optimal. Original image comes from *Prince of Qin* (*Prince of Qin*, Beijing Object Online Technology Corporation).

Figure 2-6 AI blocked at the bottleneck of Waypoint

If a “random obstacle” is possible, an obstacle which falls on the node at the center of bridge would block the path of the Waypoint. Original image comes from *Baldur’s Gate II* (*Baldur’s Gate II*, BioWare).
Advantage

Waypoint Method is very efficient on a map with less passable area, like the streets in a metropolitan area, or a complicated map (Figure 2-3). The AI only makes the decision when the object reaches a node, instead of at every step. If nodes are properly designed and tuned, this method is much quicker than the A* grid in runtime and generates human-like movement. The pathfinding AI can find all required data from the waypoint net. Other than identifying the starting and ending nodes, it is not necessary to scan an entire map to build a path.

Disadvantage

There is an essential difference from a game map to real world map. The major composition of a game map is a large passable field whereas in the real world map it is mostly comprised of obstacles. When we reach a large passable area, such as a forest, we tend to follow the path built by others to ensure that we will not get lost. But when we play a game and our characters confront monsters in virtual forest, we expect monsters to move straight toward us instead of moving to the closest road first and then following the path toward us. The game map may contain much more accessible area, not only for the convenience of design, but also for higher flexibility and easier control for users. As the game map expands even larger nowadays, keeping the nodes dense enough without spending too much time looking for required nodes and links in runtime would be a challenge.

2.3 Navigation Mesh

Navigation Mesh Method expands the concept of a step from strictly refined location to loosely defined area. This concept was evolved around the times of the dot-com bubble (Dot-com bubble, Wikipedia) when Internet accessibility was being
heavily invested in Multi-user online services became popular, and capacity was another critical issue besides visual presentation.

As massively multiplayer online games became possible, game maps were also expanded for entertainment purposes. Under multiplayer platforms, it is impossible for the game to secretly sacrifice lower priority AI tasks to improve performance without the users noticing. For pathfinding tasks on a large map, the A* grid is very slow because a large map contains a larger search space. Waypoint Method has similar problems on large maps as well. However, as the A* algorithm has proved its reliability for years in the game industry, game designers wanted to use the same algorithm. As a result, instead of using another more accurate but complicated method, designers would tend to increase the system performance by reducing AI selection.

Navigation Mesh Method (Navigation Mesh Method, Wikipedia) is one of the newer methods invented under this concept.

Navigation Mesh Method is more of a game-specific pathfinding method for AI. Waypoint Method is sufficient for humans as it is easy for us to bypass obstacles with a pathfinding result on hand. For the AI, it is a different story. AI does not “see” things. It never chooses shortcuts other than the ones given. Therefore, the Navigation Mesh is designed to give the AI freedom to choose any location within a chosen area, and will not make the path different even if the AI chooses another location in the same mesh.

Feature

Navigation Mesh Method uses a pre-processed map. A designer defines convex polygons to cover entire passable areas. Unlike pathfinding methods introduced previously, this method shifts most of the address checking work to
boundary calculations. This change would be valuable only if the game map is large enough to make the calculation cost less than address checking. The game system also needs the relationship between conjunct areas. At runtime, when pathfinding tasks are triggered, the game system looks for convex polygons, so-called meshes, which the starting and ending points belong to. It sets a start area as a checking base, picks the best candidate from all surrounding neighbors, and then sets it as a new starting area. This process is repeated until reaching the ending area. After a mesh path is confirmed, the game system should polish it into final movement path as the final result (Figure 2-7).
There are commercial products that help designers to place meshes, such as Source SDK (Source SDK, Valve Developer Community), which is developed by Valve Developer Community. This tool predefines basic mesh shapes so that a designer can fill them in on a game map. After the game map is completed, this tool processes the game map to merge all shapes into fewer convex polygons. The designer reviews the result and can attach or detach merged polygons to assist the game AI. Though the mesh generation tool hardly creates perfect maps, it does simplify the designer’s work significantly.
This method simplifies the choice of pathfinding and indirectly increases pathfinding performance. All resource saved by less selection is invested into geometry calculation. It is excellent for pathfinding on large maps.

**Disadvantage**

Navigation Mesh Method still uses the A* algorithm. As an attribute of this algorithm, the AI evaluates the next step by analyzing surrounding nodes. For the navigation mesh, there is no fixed node within a mesh to be the basis of evaluation. The game system generates one reference node for each mesh to help the evaluation process. No matter how much effort the AI spent in generating an ideal reference node, there would be at least a few detours caused by unbalanced mesh design.

Take Figure 2-7 as an example, the meshes on the left are quite large while meshes on the right are relatively small. The AI sets reference nodes on the center of each mesh. The path built by reference nodes on the left side (green path) is much longer than the path on the right (blue path). But the final path, the red line, built from the blue path, is much longer than the path built from the green line (Figure 2-8). This could be avoided by reconfirming the built path. Nevertheless, reconfirmation and redoing the path doubles the AI loading. The path length built during the pathfinding process of the Navigation Mesh Method is not as straightforward as that built by Waypoint Method.
Additionally, the way meshes are defined greatly affect the performance of pathfinding. If the map is too complicated or meshes are too small, the geometry calculation may consume even more system resource than address scanning.

After going through these popular pathfinding methods, we have developed a better concept of what the game industry really needs in pathfinding, how it is practiced in current available products, and why they are not compatible in certain conditions. We will now focus on our Heuristic Path Finding Method.
Chapter 3 Heuristic Path Finding Method Approach

3.1 Overview of Heuristic Path Finding Method Approach

Our method targets the online hosting service. Specifically, Heuristic Path Finding Method is a method that should be implemented on a server. By breaking down the structure of the system and the components of a request, the Heuristic Path Finding method efficiently moves a part of the tasks out of runtime, thereby reducing processing time and increasing efficiency. Many other pathfinding AI, such as those used in GPS, emphasize accuracy, however, they are highly inefficient to be applied in a game setting. On the other hand, we have designed our method with efficiency as the highest priority, while minimizing any possibilities to sacrifice accuracy. Under our structure, the system is very capable of dealing with massive pathfinding requests and still works effectively. This is apparent especially when comparing with other methods mentioned previously over a long term basis.

The process of the pathfinding work can be divided into two parts. The first is preparation. Heuristic Path Finding Method uses processed map information which contains ordered vertex sets and relationships of all passable areas. The map data is supposed to provide minimum, well-structured and sufficient information that can be understood and processed efficiently by the game system. Before the main system provides service, it loads the processed map information, analyzes and rebuilds the relationship of the passable areas. According to the map information, our method builds a path prototype for each pair of two different passable areas based on A* algorithm, and stores the path template in a database system. The database system is an independent system located on server side.
The second phase is runtime execution. After initialization, the server goes online. Requests would be sent as pairs of starting and ending points. The game system identifies corresponding areas for each pathfinding request and then sends a query to the database to retrieve a matching path. The database will perform a data search, and then sends a set of path template back to the game system. In the end, the game system optimizes the path template to fit the request as the final path.

In the following content, we use "database" as the abbreviation of "database system". And we will use "main system" to represent the major purpose of the system on server side. If it is a game server, "main system" represents the game system, if it is out testing system, this term is an alias of the testing system.

### 3.2 Heuristic Path Finding Approach

In this section, we are going to demonstrate step by step how Heuristic Path Finding works. Let's take Figure 3-1 as a sample game map for illustration.

![Figure 3-1 Sample game map](image)

#### 3.2.1 Pre-processing
1 When we receive an online game map shown as Figure 3-1, we would rule out the area that has obstacles in it (Figure 3-2) and then create convex polygons to hover over the entire passable area.

2 We would identify vertexes of all the polygons and denote their relationship. After the data recognition, we would deposit everything into a database (Table 3-1).

<table>
<thead>
<tr>
<th>ID</th>
<th>Vertexes</th>
<th>Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(0,0), (300, 0), (284, 197), (194, 243), (0, 58)</td>
<td>B, C</td>
</tr>
<tr>
<td>B</td>
<td>(300, 0), (560, 0), (618, 107), (377, 244), (284, 197)</td>
<td>K, E, A</td>
</tr>
<tr>
<td>C</td>
<td>(194, 243), (195, 243), (228, 322), (205, 511), (188, 597), (137, 682), (0, 641) (0, 58)</td>
<td>A, D, H, I</td>
</tr>
<tr>
<td>K</td>
<td>(560, 0), (1023, 0), (1023, 108), (618, 107)</td>
<td>B</td>
</tr>
</tbody>
</table>

Table 3-1 Polygon information

3 We would then execute the pathfinding program and obtain a list of path templates (Table 3-2).
3.2.2 Online Path Finding

1. After all the preparation is complete, the game server is ready to provide online service to satisfy requests. Let’s assume that we receive an AI request for a path from (380, 730) to (740, 60).

2. The pathfinding AI would first identify where these 2 points belong. They are area-J and area-K.

3. The AI would retrieve the path template from the database. The path is J-G-F-E-B-K. The path built by the reference nodes is shown in Figure 3-3.

<table>
<thead>
<tr>
<th>ID</th>
<th>Path</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AB</td>
<td>AB</td>
</tr>
<tr>
<td>2</td>
<td>AC</td>
<td>AC</td>
</tr>
<tr>
<td>3</td>
<td>AD</td>
<td>ACD</td>
</tr>
<tr>
<td>66</td>
<td>JK</td>
<td>JGFEBK</td>
</tr>
</tbody>
</table>

Table 3-2 Area paths

Figure 3-3 Path built by reference nodes
The AI would optimize the path template by adjusting the intersections on the edges. The resulting path is (380, 730), (414, 677), (452, 547), (448, 502), (618, 106), (740, 60). It is shown in Figure 3-4.

3.3 Design Details

As mentioned, Heuristic Path Finding Method is a method for online service. It reduces the runtime workload by using a distributed structure. We will describe how it is designed, the role each part plays, and the contribution made by each part to the overall performance.

3.3.1 Creating Map Data

Heuristic Path Finding Method is a pathfinding method with an overview of graphical information. The format of the map information is essential to our method. Heuristic Path Finding Method creates a path prototype before the game system is ready to provide service. Efficiency is the first priority for a game system. Even if
longer initialization time is allowed in the online game business model, the game system maintainer would always want to make the loading time as short as possible. Therefore we need to make the map data used by Heuristic Path Finding Method as compact as possible with sufficient information.

**Convex Set**

The first decision that should be made is how detailed the map information should be. Take Figure 3-5 as an example, it is a simple map, 4x4 units in size. One unit represents one step, moving across this map takes 4 steps at the most. If there is a request to build a path from A1 to D4, there would be 22 checks for step-checking among candidate steps under the A* grid method (Table 3-3).

If we use Heuristic Path Finding Method, the pathfinding AI would create 120 path templates to cover all possibilities. The A* Grid Method only creates storage memory as large as the size of map and each grid is assigned with a number, it requires a space for only 16 integers in this example. Heuristic Path Finding Method takes at least 240 integers in storage space to denote the starting and ending location, excluding path details (Table 3-4).

For execution time, the A* grid method takes 22 times of step checking for path A1 to D4. For Heuristic Path Finding Method, if the path templates are stored in a binary tree, it takes O(log 120) for an average case to search for a path, or O(120) in the worst case (Binary search tree, Wikipedia).
Figure 3-5 Sample map

<table>
<thead>
<tr>
<th>Confirmed path</th>
<th>Candidates in open list</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>a2, b1, b2</td>
</tr>
<tr>
<td>a1, b2</td>
<td>a2, b1, a3, b3, a3, b3, c1, c2, c3</td>
</tr>
<tr>
<td>a1, b2, c3</td>
<td>a2, b1, a3, b3, c1, c2, d2, d3, d4, c4</td>
</tr>
<tr>
<td>a1, b2, c3, d4</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-3 Path finding for the map on Figure 3-5

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Middle steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>a2</td>
<td></td>
</tr>
<tr>
<td>a1</td>
<td>a3</td>
<td>a2</td>
</tr>
<tr>
<td>a1</td>
<td>a4</td>
<td>a2, a3</td>
</tr>
<tr>
<td>a1</td>
<td>b1</td>
<td></td>
</tr>
<tr>
<td>d2</td>
<td>d4</td>
<td>d3</td>
</tr>
<tr>
<td>d3</td>
<td>d4</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-4 Path template generated by Heuristic Path Finding Method for Figure 3-5

If we divide this map into 4 groups (Figure 3-6) and apply it to Heuristic Path Finding Method, the pathfinding AI would create 6 path templates for it. We expand steps into areas in order to reduce the amount of path templates to be created, nevertheless, we do not want this expansion to break a pathfinding task into several minor and cross-referencing tasks. Passable areas should not overlap each other. Each area should guarantee that one object within its range has direct access to.
another point in the same area. The area should be a convex set (Convex set, Wikipedia).

With processed map, Heuristic Path Finding Method uses 12 integers to store path templates. The maximum searching time is $O(6)$. $A^*$ grid method does not use a processed map. Thus, its storage space and execution time remains the same. For this reason, Heuristic Path Finding Method becomes attractive.

![Figure 3-6 processed map](image)

![Figure 3-7 Simplified map](image)

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Middle steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>a2</td>
<td></td>
</tr>
<tr>
<td>a1</td>
<td>b1</td>
<td></td>
</tr>
<tr>
<td>a1</td>
<td>b2</td>
<td></td>
</tr>
<tr>
<td>a2</td>
<td>b1</td>
<td></td>
</tr>
<tr>
<td>a2</td>
<td>b2</td>
<td></td>
</tr>
<tr>
<td>b1</td>
<td>b2</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-5 Path-template for Figure 3-6

Since the sample map is a square without any obstacles, it could be taken as one single passable area (Figure 3-7). Within one passable area, our method will not require any path to search. With direction and destination provided by pathfinding AI,
The A* grid method is uncompetitive at all in this case.

**Polygon Shape**

The second decision is the description of boundary. Boundary helps to identify the area where the specific location belongs to. Heuristic Path Finding Method uses a processed map. When the pathfinding AI receives a pair of starting and ending points, it has to identify their location by checking through convex sets. If a convex set is formed by random curve (Figure 3-8), the system should go through each step to confirm that the requested point is within the boundary.

Take Figure 3-9 as an example, it takes 20 units to surround an area of 4x4 units. A larger area will require a longer boundary. In the worst case scenario, requested point will be located on the last checked area. The time saved during the pathfinding process by using convex set may be consumed by area identification. Therefore, we need a boundary description, which is simpler than recording every passable location around an area.
The simplest way to describe a passable area is to use it as a convex polygon. When dealing with a graphical calculation, a straight line is always easier than a curve. Map designers only need to call out vertexes of convex polygons, which the main system is based on in order to reverse back edges and relation of those polygons.

**Data Structure in Runtime**

To meet the efficiency requirement, the map is simplified into vertex polygons to describe the passable areas. The system would load the polygon vertexes, rebuild the graphic structure, restore the relationship and keep the information in memory. Checking the boundary of a passable area should be done in a routine manner, rather than allowing the AI to frequently allocate and release the memory then retrieve the data from the database, keeping the required information in memory of a gaming system will shorten the checking time.
We have vertexes used to form the polygon boundary, these vertexes can also be used to identify the relationship of the polygons. The map used by Heuristic Path Finding Method is partitioned into convex polygons (Figure 3-10). Adjacent areas share the same edge, such as edge Va1-Va2 of polygon A. Edges that belong to only one polygon are taken as adjacent to non-passable area, like edge Vb1-Va1 of polygon B.

According to this rule, the system can identify adjacent passable areas by scanning through polygon vertexes. Since the vertexes are checked so frequently, we can keep the relationship of the vertexes in memory while tracking the adjacent areas and corresponding edges during map loading process.

![Figure 3-10 Sample map in convex polygon](image)

```
Struct Map
{
  Polygon1
    Vertex 1 {x1, y1}
    Vertex 2 {x1, y1}
    Vertex 3 {x1, y1}
    Neighbor 1
      Neighbor ID Polygon 3
      Edge Vertex 1 & Vertex2
```
After the map is completely loaded, the map information would be kept in memory as the structure illustrated in Table 3-6

### 3.3.2 Preparing Path Prototype

With the loaded map information, the system is capable of building a path prototype. In order to increase pathfinding efficiency at runtime, Heuristic Path Finding Method prepares a path prototype for every pair of two different passable areas that are accessible to each other, and stores them in the database. When a pathfinding request is received, the system retrieves the path within the corresponding areas based on the starting and ending points, finally, it adjusts the path to fit the current conditions. When the passable area is properly divided, this process helps the system cut down on task processing time without losing accuracy.

Heuristic Path Finding Method uses the A* algorithm to build a path prototype. One important attribute of the A* algorithm is that it evaluates the candidate points based on the cost accumulated from the starting point and distance estimation from this point to the destination. When we said that “we are going to build path from area-A to area-D”, we do not have any specific location that could be called as “step”, we do not even have starting and ending points. Without a specific location, we cannot provide the pathfinding AI distance information, which the A* algorithm bases its evaluation on.
In order to make the A* algorithm work under ambiguous map information, such as the passable areas used by our method, we have to create temporary reference points and adjust it gradually to a better location, which allows the following evaluation to benefit from (Figure 3-11 and 3-12)

We call a gradually changing reference point as “dynamic reference point”. Since the reference point would be changed anyway, we set the reference point as an average vertex point which only needs a simple calculation (Table 3-7) and is always within a passable area due to the attribute of convex polygon.
struct point {
    int pX,
    int pY,
};

point pVertex1, pVertex2, pVertex3, pVertexN,
PtTemp = (pVertex1 + pVertex2 + pVertex3 + pVertexN) / N;

Table 3-7 Rule of average vertex location

Having a processed map and rule of reference point generation, Heuristic Path Finding Method is ready to build a path template. We now use Figure 3-13 as an example to illustrate how a dynamic reference point helps our method generate a path template.

Figure 3-13 is a map with 4 passable areas C, D, E and F. Heuristic Path Finding Method is supposed to build area path CD, CE, CF, DE, DF and EF. The following steps show how our method builds the path template for CF.

Step 1 The pathfinding AI generates reference points according to the rule in Table 3-7 as the starting point in area C, denoted as P_start, and the ending point in area F, denoted as P_end (Figure 3-14 (a)).
Step 2 By looking at the relation list, the pathfinding AI establishes that area C has 2 neighbor areas area D and E. The AI puts both areas into an open list according to the rule of the A* algorithm, and generates a reference point for each area, denoted as P_dTmp and P_eTmp (Figure 3-14 (b)).

Step 3 Heuristic Path Finding Method evaluates paths from P_start to P_dTmp and P_eTmp by A* algorithm. The evaluation would suggest that P_dTmp is closer to P_end. The AI sets area D as the next step and creates a new reference point, dTmp2, on the intersection of the path from P_start to current P_dTmp and the line Edge_CD of polygon D (Figure 3-14 (c)).

Step 4 The AI puts area C to close list according to the rule of the A* algorithm. By looking into the relation list, the AI establishes that area F is the only neighbor to area D, which is still out of close list. The AI puts area F into open list.

Step 5 Knowing that the ending point is located in area F, the AI takes ending point P_end as the reference point. The AI has referenced a point before the path has entered area D, P_start in this case, and a reference point after the path has gone out of area D, P_end in this case. At last, the AI adjusts the reference point for area D to its final location.

Step 6 The AI builds a line from P_start to P_end as LineCE and extends the edge D_Left to D_Right to infinite line, LineD. The AI finds the intersection of LineD and LineCE on P_dTmpF (Figure 3-14 (d)). If P_DTmpF is out of section D_Left and L_Right, the AI can use the closest vertex to replace it.

Step 7 With reference point P_dTmpF and P_end, the AI modifies the reference point of area F to P_fTmp2 (Figure 3-14 (e)).
Step 8 Area F is the final area. The AI has routed a real path which starts from P_start, goes across P_dTmpF, P_fTmp2 to the ending point, P_end. The path template is CDF. The AI now stores the path template into database (Figure 3-14 (f)).

Step 9 Path template CE was completed.

From this illustration we can see that reference point has been modified twice and the final version is very close to the shortest path. Correct reference point is crucial for A* algorithm to build the information on the cost of an arbitrary point for path evaluation. At the phase of building path template, only area information is
stored in database. Other information such as P_start or P_dTmpF, in this case, is discarded.

The area path is stored in the database under the schema illustrated on Table 3-8 and Table 3-9. Splitting data into 2 parts shifts the sorting task from the game system to the database system, which also prevents the game system from reversing the order. Comparing with the other methods described earlier, our method takes more time for preparation. This would actually be intolerable if it were for one-time usage. However, since our method is aimed for a massive request processing, the time used for initialization will be redeemed gradually by the time saved during the runtime phase in the overall time consumption.

<table>
<thead>
<tr>
<th>Id</th>
<th>Identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>idStart</td>
<td>ID of start shape</td>
</tr>
<tr>
<td>idEnd</td>
<td>ID of ending shape</td>
</tr>
<tr>
<td>idPath</td>
<td>Path identity</td>
</tr>
</tbody>
</table>

Table 3-8 Map path description

<table>
<thead>
<tr>
<th>Id</th>
<th>Identity</th>
</tr>
</thead>
<tbody>
<tr>
<td>idFnd</td>
<td>Order of path</td>
</tr>
<tr>
<td>idPath</td>
<td>Path identity</td>
</tr>
<tr>
<td>IdMesh</td>
<td>Shape identity</td>
</tr>
</tbody>
</table>

Table 3-9 Single Path description

3.3.3 Processing the Pathfinding Request

When the game system starts to provide the hosting service, the pathfinding request would be passed as a pair of starting and ending points. The game system identifies the corresponding areas and then queries a path from the database. We define a map as a list of vertex of a convex polygon. This approach not only guarantees that two different arbitrary points within the same passable area have direct access to each other, but also simplifies the way to identify a point.
Being a convex set, any of its interior angles must be less than 180 degree. Therefore, for any point within it, the angle between the vector of one vertex to its neighboring vertex and a vector of same starting vertex to an arbitrary point within the convex polygon must be less than the interior angle of the start vertex, illustrated on Figure 3-15 (a). If one of these points meets this rule after checking through all the vertexes of one convex polygon, its area location can be confirmed (Figure 3-15 (b)).

![Diagram](image)

(a) Angle of inner point to edge is smaller than vertex angle

(b) AI checking through all vertex angles to identify a inner point

*Figure 3-15 Inner point identification*

The database selects one path template from the prepared data according to its starting and ending areas, and then it sends the path back to the game system in the correct order. Consequently, the game system will convert the path template into a
real path by gradually modifying the reference points in the same way it builds a path template without a pathfinding evaluation (Figure 3-16). If any 2 different areas have no accessible path to each other, there would be no record in the database and the game system is notified without wasting any time on the pathfinding process (Figure 3-17 and Table 3-10).

Figure 3-16 Two final path generated from same area path

Figure 3-17 Request that is not able to get a path template from the database
Table 3-10 Path templates for Figure 3-16, 17

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Middle steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>C</td>
<td>B</td>
</tr>
<tr>
<td>A</td>
<td>D</td>
<td>BC</td>
</tr>
<tr>
<td>A</td>
<td>E</td>
<td>BCD</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>D</td>
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<td>D</td>
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<tr>
<td>D</td>
<td>E</td>
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</tbody>
</table>

From the entire pathfinding workflow, we can see that Heuristic Path Finding Method greatly simplifies AI's work by shifting a major portion of the pathfinding process from runtime to the preparation phase. Effort spent at searching for a path and maintaining the path information is not carried out by the game system, instead, it is accomplished by the database system, which is an expert for this type of work.

We can see that, Waypoint Method accelerates the A* grid method by switching the focus from estimate calculation to map simplification, Navigation Mesh Method for further simplifying the map by introducing the area concepts in passable steps. We further improves online pathfinding progress by converting the solo pathfinding progress into a distributed structure such that a resource costly portion of computations can be done off-line, the repetitive calculation of these computations can be avoided. Thereafter, by adopting our algorithm, not only the pathfinding efficiency is improved but also the entire gaming system achieves a better performance since the resources (time and memory) become predictable.

The system resources used for initialization are relatively heavier than other methods, but the workload is lighter at runtime. Heuristic Path Finding Method is free from complicated pathfinding with database support, its area of identification is

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simplified by the map definition. Heuristic Path Finding Method takes advantage of a
distributed structure, general functionality of operation system and characteristics of
data types to meet massive pathfinding requests instantly
Chapter 4 Implementation details and subjects of measurement

Pathfinding is not the most important AI functionality, but it helps computer controlled objects to move similar to humans and make virtual world more vivid. The first requirement for a game system is being responsive to user input. Accuracy of AI is not a major issue but it still needs to respond correctly when the computer controlled character faces the player.

Heuristic Path Finding Method targets the online game pathfinding functionality. As we mentioned in Chapter 1, online game provides service via internet. Comparing to console game, the number of concurrent users of online game is hundreds if not thousand times more than that of console game, and the demands for game functionality also expand greatly. Having many players logging on to the same virtual world, fairness and concurrency become important issues. The virtual world is not stationary, a game system does not have an infinite amount of time to calculate for the best solution. In order to resolve massive requests in a limited time, game system can choose either adapting more well-designed algorithm or managing system resource more efficiently. Our method is the second category. It breaks down the workflow of pathfinding process, and introduces database to assist management.

In order to prove that our Heuristic Path Finding Method has better performance on massive pathfinding environment, we have built a testing system which is able to perform all pathfinding methods mentioned previously and generate reports for performance analysis. In this chapter, we will describe the implementation of the testing system and subjects of measurement it focuses on.
4.1 Introducing Database to Pathfinding Functionality

Database is introduced to the world by business model. It is an excellent tool in dealing with a huge amount of data. Some of the main characteristics of a database include the ability to analyze data by specified rules, create the best structure to hold information, and specialize in selecting data efficiently.

Database is constituted by four basic functionalities: insert, update, select, and delete. When a user inserts a row of data into a database, the database would first try to find a proper location to store the data. If no proper location is found, database could expand current structure based on an efficient selecting process, build space to allow further incoming data, and adjust the maximum size limitation accordingly. Functionality of deleting data shares the same basic rules as insertion. The only difference lies in that database shrinks its structure according to the rules instead of expanding it. Usually updating data will not cause changes to structure, since data size and format are already defined when the table is created.

The most useful functionality of database to pathfinding in a game setting is selecting data. Database selects the required data according to query statements. The rules specified by the statements may be very complicated. The need to perform complex selection in a short time is the reason why a database should alter its structure during the insertion and the deletion processes. Database takes time to optimize data structure whenever a change is required, which helps database to select as efficiently as possible. Heuristic Path Finding Method adapts to this attribute by building all paths in the initialization phase and leaving path selection to runtime. By shifting time consuming work to the initialization phase, our method changes pathfinding work into data selection in the runtime phase.
Introducing new factor into existing mechanism always requires additional resources. If using Heuristic Path Finding Method comes with a cost, we need to know clearly what the cost is for using this new feature, and how it can be mitigated.

Online game host usually has at least one database to maintain user accounts. A game company always wants to gather user information as detailed as possible for business analysis. On the other hand, game map and path template are mostly defined in a compact format for reasons we mentioned earlier in chapter 3. Comparing to user information, pathfinding data occupies relatively less space but provides essential support for the game system. Schema of path template is designed in a straightforward manner for the database. Selecting one path from a path template table does not require complex functionality such as pattern recognition or data mining, which are used in business analysis. The workload that Heuristic Path Finding Method adds to database is nothing when comparing to what it can achieve for game hosting, such as user account management.

In the game world, player movement triggers AI pathfinding requests constantly. Game system is responsible of processing the requests and adjusting path template to each path used in the game. Therefore the game system decides the number of connection to spare for database connection. This means that our method will not be allowed to carry out any unexpected connection or to impair the workflow of game system. As a result, while introducing database into pathfinding functionality, our method will not affect the original budget and performance. It simply hands out part of its work to database, and relies on the database's specialty to increase total performance.
4.2 Map Information Storage

Our testing system contains four pathfinding methods: A* grid method, Waypoint method, Navigation Mesh Method, and Heuristic Path Finding Method. All methods are implemented under the same A* algorithm and storage preference. By unifying pathfinding functionality, the testing system ensures that any performance difference is caused only by the difference in the structure of the methods rather than by any potential self-optimization of the functionality of each method. Each method has its own data structure to hold map information. Here we will describe the attributes of these data structure for each method and illustrate how it is implemented in our testing system.

When game application starts, player sees a virtual world illustrated or described on screen. In the virtual environment, there might be grass, tiles, trees, walls, buildings, etc. Objects are not randomly put on the map, but by designers’ will to give soul to the virtual world. However, to the pathfinding AI, every object only means one of the two things: passable location or non-passable location.

Using A* grid method, one grid represents one step of movement. Pathfinding map could be set as a simple matrix to mimic coordinate system. Objects which occupy one or more grids on the map set flag on corresponding grids. Game system determines passable grid according to the flag on grid. Table 4-1 illustrates how map information is used. The final path built by A* grid method is continuous points linking the starting and the ending points.
enum _e_object_id_
{
    eObjectGrass = 0,
eObjectTile,
eDecorateStrip,
eDecorateCurtain,
eObstacleTree,
eObstacleWall,
},
unsigned int uiMapInfo[50][50],
uiMap[25][25] = eDecorateCurtain,
uiMap[23][25] = eObstacleTree,

location getNextPoint(location poGnd, location EndGnd)
{
    location poCheck = poGnd,
    location poNext = poGnd,
    unsigned int iCost = MAX_UNSIGNED_INT,
    unsigned int iTempCost,

    if (int idDirection = 0, idDirection < 8, idDirection++)
    {
        iTempCost = getCost(poCheck, EndGnd),
        If ( iCost > iTempCost )
        {
            poNext = poCheck,
            iCost = iTempCost,
        }
        poCheck = poCheck + locationShift[idDirection],
    }
    return poNext,
}
Waypoint method uses processed map information. Map is described as a series of waypoints with links to other waypoints (Figure 4-1). Every waypoint represents passable location and every link represents accessible path. Whenever a request is sent in as a pair of starting and ending points, testing system finds the closest waypoints to either point, and then Waypoint Method tries to find a path between these two waypoints. Table 4-2 illustrates the structure of map information and how it is used. The final path generated by Waypoint Method is a series of waypoints, corresponding links, and straight path between waypoints and the starting and ending points.
Table 4-2 Map data used by Waypoint Method

Navigation Mesh Method uses processed map as well. Its map information contains sets of convexes for passable areas to be described as convex polygons. In this regard, Heuristic Path Finding Method is similar to the Navigation Mesh Method in that it also uses area-based pathfinding estimation. To avoid testing system being in favor of either the Navigation Mesh Method or our method, we use the same structure as we described in chapter 3 for both methods. Table 4-3 shows how map structure is defined and used in the testing system. Whenever a request is sent to AI, the AI identifies areas where the starting and ending points belong to. Then the AI builds a path according to roughly created reference points and gradually modifies reference points to a final path. The process is similar to what is performed by Heuristic Path Finding Method during the preparation phrase.
class NmMapData
{
    public $lstVertex = array(),
    public $lstNeighbor = array(),
}

class NaviMesh
{
    protected $mapdata, // array of NmMapData

    protected function getNeighborList ( $meshId, array &lst = array() )
    {
        $meshData = $this->mapdata[$meshId],
        while ( list($key, $val) = each($meshData->lstNeighbor))
        {
            if ( isset($this->lstClose) && array_key_exists($key, $this->lstClose))
                continue,

            $lst[] = $key,
        }
        return count($lst),
    }
}

Table 4-3 Map data used by Navigation Mesh Method

Last but not least, our Heuristic Path Finding Method is a method that keeps game map during runtime. Its map is not used for pathfinding at all, but for area identification and path modification. Details of our method are described in chapter 3.

Heuristic Path Finding Method does not use brand new map structure, but it chooses the one that helps the AI to build better path in 2-phase process.

4.3 Territory Type

Our testing system implemented four pathfinding methods. Only the A* Grid method uses unprocessed map data. It honestly reflects the shortcomings of a map,
such as redundant data stored on the map, which definitely affects performance of the pathfinding. Every type of processed data is altered based on a set of specific problems that the process is designed to resolve. These solutions in general are to simplify complicated conditions or to skip repetition. Waypoint method focuses on accessible direction, Navigation Mesh method focuses on decreasing the number of choices, Heuristic Path Finding Method focuses on saving system resource for massive tasks processing. No matter how a method tries to simplify source data, the resulting path would inevitably be affected by the style of the map content. Every method has its pros and cons on different map types and this is what our testing system trying to reveal. Here we will discuss attributes of each map type which would be used in the experiments.

We define map type according to how obstacles are scattered around on a map. Taking a map with ten obstacles as an example, if obstacles cluster in the center, which could be taken as one single obstacle, the map could be described as less broken map (Figure 4-2). If obstacles spread evenly on the map, it is defined as highly broken map (Figure 4-3).

Figure 4-2 Less broken map
Upon this concept, we can define maps into four types

**Spacious map**

If one map contains only a few number of obstacles or obstacles crowded together, there is higher possibility for one object traveling through the map without hitting an obstacle. This kind of map is identified as spacious map (Figure 4-4). Pathfinding method is not really necessary on this map type.
Lightly obstructed map

A map has obstacles spreading around evenly with a potential to break accessible area into several small pieces of convex polygons, we define it as lightly obstructed map (Figure 4-5) Accessible portion of this map type is still large, but NPC need more indication from AI to avoid hitting obstacles

Complicated map
If a map has many obstacles which purposefully form paths that allow travelers to pass through, we define it as complicated map (Figure 4-6). Though it seems the obstacle here makes pathfinding work difficult, this map type has in fact simplified the work if the map data is processed. For example, if we process the map to waypoint map, illustrated as Figure 4-7, we could see that there is only one path to move object from \( \text{P}_{\text{startA}} \) to \( \text{P}_{\text{endA}} \), and there are only two directions for object on \( \text{P}_{\text{startB}} \) to move to \( \text{P}_{\text{endB}} \) by passing through either \( \text{P}_{\text{ref1}} \) or \( \text{P}_{\text{ref2}} \). Pathfinding AI is necessary and beneficial for this map type because even though this type of map is more complicated, it offers fewer choices in the available routes. Hence, as soon as the AI is able to determine the turning corners at each point, it will easily figure out the best route.
Broken area

Maps that match none of previous three conditions could be defined as broken area (Figure 4-8) Processed map data of this type only reduce redundant checking, but is of no help on simplifying pathfinding work

With the concept of map types, we now have a glimpse of what pathfinding AI confronts. In pursuit of large game environment and performance optimization, how to maneuver pathfinding AI with scarce resource is what our method wants to achieve.

4.4 Memory Usage

Performance of game system does not rely on the speed of Central Processing Unit (CPU) only, but also on data structure that stores constantly referenced static data. Memory is an important resource for game system. During runtime, memory cache is more convenient than disk storage. If game data is too large to be kept in cache, game system has to save it in storage device. Swapping data from storage device to memory cache is a time consuming technique and would obviously slow down system process. This is what game system designers desperately want to avoid. Pathfinding work consumes memory, too. There are three types of memory usage that
pathfinding method needs map data storage, runtime allocation and prepared information

1) **Map data storage**

In the very first version, a map was defined almost identical to a coordinate system, such as the map used by A* grid method. The bigger the map size, the larger memory usage required. With the intention to enhance performance, developers not only try to improve algorithm of pathfinding method, but also simplify the map it uses. Map information is constantly referenced to, and must be kept in RAM (Random-accessed Memory).

2) **Runtime allocation**

In runtime, most methods need temporary allocated memory to store all potential selections, so called “open list” in A* algorithm, and fully checked selections, so called “close list”, before the final decision is made. The temporary memory may become too large when consumed by temporary data, which may cause memory swapping in runtime. Open list is scanned repeatedly whenever evaluation for the next step is needed. This kind of memory usage is crucial to performance but highly unpredictable.

3) **Prepared data**

Only Heuristic Path Finding Method uses prepared data. Prepared data is used for assisting pathfinding AI. Prepared data consumes system memory in keeping its accessibility. Referencing to the prepared data takes additional processing time in runtime which is not necessary in other pathfinding methods. Preventing the prepared data from holding back system performance is therefore an
important task. Designers should take this into account before employing prepared data.

Minimum usage of both runtime memory and static data is an ideal that pathfinding methods should pursue. If large-sized static data is inevitable, minimizing memory usage for runtime allocation should have higher priority to guarantee better performance.

### 4.5 System Structure

In order to perform pathfinding task, there should be a map, a pair of starting point and ending point and specific pathfinding methods. Heuristic Path Finding Method requires additional database connection. There are 3 other pathfinding methods, A* grid method, Waypoint method and Navigation Mesh method, to be compared with our method. The testing system we use also implements tools such as image decoder for A* grid method and waypoint generator to simplify map generation. It also has record parser to translate result into analysis data.

We created our system under the server-client structure. Hypertext PreProcessor (PHP) provides comprehensive basic utility. Under Apache web host, PHP core functionality is good at memory management, technique sorting and database communication, which is good for us to concentrate on developing pathfinding method. We use BMP file as the source of map data. Instead of using PHP's external library to decode image files when executing pathfinding task, we convert image files by our simplified external executable file to text file, which is the format PHP excels at.
4.6 Testing Structure

Heuristic Path Finding Method is a method derived from A* algorithm, and so as the other three methods implemented in the testing system Our experiments focus on the difference in output between each method By avoiding difference in characteristics that all methods share in common, we wanted this testing system to reveal the difference in performance affected by designed structure Here are guidelines we followed when implementing the testing system

4.6.1 Hardware with medium capability

Hardware is an important element, together with operating system and pathfinding methods, to affect the overall performance Also, the hardware determines the level of complexity in the available mathematical calculation for pathfinding work A* grid method uses unprocessed map data, together with simple math calculation, to resolve a pathfinding request, whereas the other three methods use the processed map data with elaborate mathematical calculation One pathfinding task could be resolved by either numerous simple calculations or fewer elaborate calculations When using low-end hardware, difference in performance would be obvious especially when map data is changing On the other hand, when using high-end hardware, changes in map content may affect performance only slightly, or even unnoticeably Therefore, we built our testing system based on medium-leveled hardware to make difference significant

4.6.2 United version of A* algorithm

All methods, including Heuristic Path Finding Method, are based on A* algorithm It is important to develop all methods under the same version of A* algorithm There are existing open source codes for pathfinding methods available,
but each of them specializes in different aspects, such as data management, cache technology or order evaluation. To minimize the variation in core functionality, our testing system applies same technique at common functionality, such as sort, stack and data dump, on all methods.

4.6.3 Same pair of starting and ending points

Comparing pathfinding performance between two paths of different complexities makes no sense. The testing system generates and stores the same set of testing data for each map to be applied to all four methods. Every method completes all tasks and saves execution-related data as text file for performance analysis.

4.6.4 Amount matters

We want a pathfinding method to be capable of fitting into the modern game environment, which asks for immediate response in a highly interactive virtual world. It is an environment that is prone to trigger massive request in peak time. Massive amount of testing is requested for our experiment. In order to make difference in performance significant, each method processes and completes all tasks in one setting, and then another method does the same from beginning to end, rather than having each method processing one task only, then alternates until all methods complete all tasks.

4.6.5 Diversity in map types

We expect each pathfinding method to have its own specialty in some map types. We provide maps of all types to ensure our experiments were not in favor of any particular method. A variety of map types ensures result of our experiments to be neutral.
4.7 Disadvantage of testing system

During the development of our testing system, we have encountered an issue on Waypoint method, which was not able to be resolved fundamentally due to the shortage of manpower at that time. We have found a way to get around it, but the solution has affected the experiment result in a certain way.

When we were evaluating the testing result during development, we found that the Waypoint method relies too much on the design of the pre-processed map. It needs different plotting strategies for different maps. For example, waypoints cannot be too loose in the spacious map, and Waypoint method would sometimes detour to a longer path. Waypoints cannot be too intensive, either. Intensive waypoints cause redundant checking. The more links one waypoint has, the slower this method would be.

Waypoint is not only for eliminating unnecessary checking, but also for ruling out unnecessary selection. At that time, we were in the process of deciding map content. We wanted each map used in the experiment to correctly represent the map type it was supposed to be. Whenever we made a change to map content, waypoints would be reprocessed. After several times of resetting, we finally used a tool to generate grid-like waypoint-set (Figure 4-9). This tool saved us a lot of tuning time for plotting waypoints, but was not smart enough to solve the design problem. Here we
list the issues that we took into consideration when reviewing the output of the Waypoint method

1) **Pre-checking for starting and ending points**

In our design, the system tries to identify the closest waypoints to the starting and the ending points before pathfinding work begins. There are chances that the closest waypoint is not accessible to the requested points (Figure 4-10). Instead of spending time on tuning reference nodes, the testing system used unprocessed map to assist identification. During runtime, the testing system checked each step along the straight path between waypoints and the requested points to ensure that there are no blocking areas in between. This is a content design issue. Loading time and memory usage for path-checking should not be included as Waypoint Method's performance, but there is no proper way to split them out of the performance result of Waypoint Method. Accessibility checking in runtime may slow the performance a little. In our analysis, we named each result of Waypoint with postfix _No_Check to denote the accessibility checking was turned off.

![Figure 4-10 Closest node and valid node](image)

Figure 4-10 Closest node and valid node
2) Rounding total length

When we implemented the waypoint generating tool, we tried to minimize the number of links for one point to reach others, because the processed map information is supposed to reduce unnecessary checking. But it ended up giving improper selections to the pathfinding AI. A waypoint can only choose points at the top, the bottom, the left, and the right of itself. One of the advantages Waypoint Method has over A* Grid Method is that linking direction for each waypoint is pre-designed, and it helps to make better decisions from fewer selections. Under current structure, moving diagonally takes two steps to complete (Figure 4-11). In order to make the final path length closer to human design, we assumed that there were half chances for one step to move diagonally, therefore we estimated a realistic path length to be 80% of the final length (Figure 4-12). The estimated value is denoted as “Rounded” in experiment result.

\[
\text{Rounded Percentage} = \frac{(0.5 \times 1) + (0.5 \times 2)}{(0.5 \times 1) + (0.5 \times 2)} = 80\%
\]

Figure 4-12 Function of Rounded percentage

Although rounded value and the assumption it is based upon may not seem accurate, we do not consider Waypoint Method experiment as failed. When trying to
plot suitable waypoints, we found that density is a major issue for this method. If the density of waypoints is too low, path length would be doubled. In contrast, time spent for pathfinding may extend if density is too high (Figure 4-13, 4-14). Our waypoint generation tool was able to cope with density issue. Comparing to density, disadvantage in direction only affects performance in a minor way and the rounded value could help to adjust it. The length of the final path that could be rounded to a more realistic value by the rule we made is shown in Figure 4-12.

![Figure 4-13 Too few waypoints](image1)

![Figure 4-14 Too many selections](image2)
Chapter 5 The Experiments

This chapter describes the experiments we designed, discusses the testing results and analyzes the outcomes. For each experiment, we will explain the reason of the design, as well as the assumption and the expectations we have. If the result is different from our expectation, further analysis will be specified. A pathfinding report is also constructed containing three major columns: method name, length in total and time spent. Experiments that used maps other than spacious map, specifically the prepared maps, will have a fourth column showing the loading time.

The first column describes which method generated this record. “A-star grid” represents A* Grid Method. “Waypoint” represents Waypoint Method. Postfix of waypoint title in numeric format denotes the horizontal and vertical space between two waypoints. The postfix “_No_Check” denotes this execution skipped checking of accessibility, which is described in Chapter 4-7. “Navigation Mesh” represents Navigation Mesh Method. And “Heuristic” represents our method Heuristic Path Finding Method.

The second column, “length in total”, shows the sum of the path lengths for all resolved tasks. For Waypoint Method, there is a second record noted as “rounded” which is the adjusted value due to the defect of Waypoint generating tool. This issue was described in Chapter 4-7. The third column, “time spent”, shows the length of time each method took to resolve all tasks. The fourth column, “loading time”, represents the length of time the game system took to load prepared data. We do not have this record for spacious map because the time is immaterial to have meaning on its difference.
5.1 Performance on Simple Map

The simplest map is the spacious map type. Object travelling across this map type rarely runs into an obstacle. Almost all direction is correct, every step is valid. Pathfinding method has very few selections to choose from, if any. Result of this experiment should reveal how long a method needs to build a path when every decision is correct. We expect this experiment to give us a preview of all implemented methods. With this basic concept, we can adjust upcoming tests and corresponding assumption to be more realistic.

Expectation of this experiment is that A* Grid method would get the shortest final path, but longest procession time, whereas Heuristic Path Finding Method would get the shortest processing time.

Preparation

We have designed a map of size 250 * 250 with one blocking area on the map (Figure 5-1). We divided the map into five passable areas for area-based methods (Figure 5-2). For Waypoint Method, reference nodes are generated based on different densities. We generated 2000 sets of testing data for this experiment.

Figure 5-1 Testing map
Figure 5-2 Area map for 1st experiment

Result

<table>
<thead>
<tr>
<th>Method name</th>
<th>Length in total (pixels)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td>279097 87</td>
<td>1702.92</td>
</tr>
<tr>
<td>Waypoint_50</td>
<td>395471 513</td>
<td>16.32</td>
</tr>
<tr>
<td></td>
<td>(Rounded 316377 210)</td>
<td></td>
</tr>
<tr>
<td>Waypoint_40</td>
<td>383775 036</td>
<td>21.85</td>
</tr>
<tr>
<td></td>
<td>(Rounded 307020 029)</td>
<td></td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>373674 116</td>
<td>34.53</td>
</tr>
<tr>
<td></td>
<td>(Rounded 298939 293)</td>
<td></td>
</tr>
<tr>
<td>Waypoint_20</td>
<td>361022 793</td>
<td>79.34</td>
</tr>
<tr>
<td></td>
<td>(Rounded 288818 234)</td>
<td></td>
</tr>
<tr>
<td>Waypoint_10</td>
<td>348798 283</td>
<td>480.97</td>
</tr>
<tr>
<td></td>
<td>(Rounded 279038 626)</td>
<td></td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>264847 510</td>
<td>4.14</td>
</tr>
<tr>
<td>Heuristic</td>
<td>266564 490</td>
<td>4.15</td>
</tr>
</tbody>
</table>

Table 5-1 Result of first experiment

Analysis

For the very first time, we tried manually designing Waypoint reference nodes for this experiment (Figure 5-3), but the resulting path length ended up as 2.5 times longer than the shortest path generated by other methods. This forced us to use generated nodes with spreading distance of 50 pixels. Even when we tested this new approach...
waypoint set, total length is still a lot longer than that generated by other methods. Therefore we have decided to generate several sets of reference nodes in different densities and choose a comparable one to be representative (Figure 5-4)

![Manually designed nodes](image1)

![Generated nodes of Waypoint map](image2)

We already know that the total number of waypoints on a map affects the performance of Waypoint method. Choosing a representative at this early stage of the test is difficult. In fact, it was chosen after all the experiments were completed. We finally set a limit on total length for Waypoint; the total length should not be greater than 130% of the longest length generated by other methods. Since our waypoint generating tool could not generate waypoints as sophisticated as a human could, we accepted Waypoint Method generated path that is less accurate in order to reduce time.
spent on pathfinding. We chose the waypoint_30 which was generally accepted in other experiment as representative. Selected results show the following.

<table>
<thead>
<tr>
<th>Method</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td>279097 87</td>
<td>1702 92</td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>373674 116 (Rounded 298939 293)</td>
<td>34 53</td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>264847 510</td>
<td>4 14</td>
</tr>
<tr>
<td>Heuristic</td>
<td>266564 490</td>
<td>4 15</td>
</tr>
</tbody>
</table>

Table 5-2 Selected result for first experiment

From this result, we found that A-Star Grid method did not have the shortest total length. By analyzing its data structure, we found that the paths of this method are fixed on 8 directions. If targeted-point is not right on any of those direction, "A* Grid Method" detours object to longer path. The other attribute is that A* Grid Method checks all directions even when some of them are not accessible. In contrast, methods using processed map have fewer but more effective selections when choosing each next step. By reviewing the Waypoint Method, we know that it is a point-based method, similar to the A* Grid Method. However, since the Waypoint Method uses processed map, it spent a lot less time in completing all tasks when comparing to the A* Grid Method.

It seems that the Navigation Mesh method performed better than Heuristic Path Finding Method slightly. We found that our method did not have advantage on time efficiency even when it is supported by a database. The possible reason is that the map is too simple and the pathfinding procedure did not take much time in choosing accessible area. There is insignificant difference in total length between these two area-based methods. When checking the generated paths, we found that it was caused by path prototype which is generated based on presumed center location upon each passable area. We will describe this further at the end of this chapter.
Conclusion

With a simple map, area-based methods performed much better than point-based methods, but it is not the type that our method is best suited for. In addition, for Waypoint methods, we needed to prepare different set of waypoints to reveal the choice for best performance and rules to tolerate its defects in design.

5.2 Performance over Maps Different in Size

This experiment is to demonstrate how the size of the map affects the performance of pathfinding methods. We provided two maps of the same structure but different in size for the test. We assumed that since point-based methods resolve tasks according to real map data while the area-based methods simplify tasks into a description of shapes, the change in size should affect point-based pathfinding methods only.

Preparation

The map used in previous experiment was taken as the first map for this experiment. We then expanded this first map to four times larger in width and in height, and made it as the second map. Therefore, we have two maps with the same design, but of size 250 * 250 and 1000 * 1000 respectively for testing.

As we know that processed map with waypoints situated 30 pixels apart from each other in distance, in both horizontal and vertical direction, was sufficient to generate acceptable length of path, we have created for the second map another set of waypoints with 120 pixels apart in distance, denoted as Waypoint_120. The number of waypoints on the first map with waypoint set of Waypoint_30 and the number of waypoints on the second map with waypoint set of Waypoint_120 are the same. Also, the density of the waypoint set of Waypoint_30 on the first and the second maps are...
the same. Density is important on a waypoint map. In this experiment, we also wanted to figure out whether the same number of waypoints, or the same level of density, in two maps that differ in sizes, would achieve the same final resulting path in the two maps by using the Waypoint Method.

While the sizes of the map differ, we keep the shapes of the areas intact. The number of passable shapes and blocking areas are also the same on both maps.

**Result**

<table>
<thead>
<tr>
<th>Method name</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td>143613 26</td>
<td>686 93</td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>147687 436</td>
<td>16 68</td>
</tr>
<tr>
<td>Waypoint_30_No_Check</td>
<td>147804 903</td>
<td>11 48</td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>133821 463</td>
<td>4 41</td>
</tr>
<tr>
<td>Heuristic</td>
<td>134682 360</td>
<td>4 33</td>
</tr>
</tbody>
</table>

Table 5-3 Result of first map of second experiment

<table>
<thead>
<tr>
<th>Method name</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td>550411 114</td>
<td>24262 60</td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>692857 908</td>
<td>586 94</td>
</tr>
<tr>
<td>Waypoint_30_No_check</td>
<td>692856 678</td>
<td>450 07</td>
</tr>
<tr>
<td>Waypoint_120</td>
<td>751701 005</td>
<td>29 25</td>
</tr>
<tr>
<td>Waypoint_120_No_check</td>
<td>753483 978</td>
<td>10 90</td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>531761 404</td>
<td>4 22</td>
</tr>
<tr>
<td>Heuristic</td>
<td>535521 783</td>
<td>4 26</td>
</tr>
</tbody>
</table>

Table 5-4 Result of second map of second experiment

**Analysis**

Our original testing requests 2000 paths. Since the size of map greatly affects the performance of A-Star Grid Method, we have lowered the number of testing requests to half of original requests, which means 1000 paths in total only. Time spent
by A-Star Grid method to complete testing on the second map is 35 times longer than that for the first map.

For Waypoint method, we expected that time spent for Waypoint_30 on the first map to be similar to that spent for Waypoint_120 on the second map, since they both have the same number of reference nodes. To our surprise, Waypoint_120 consumed more than 175% times of processing time to complete the same number of tasks. By analyzing the structure of our testing system, we found the search of the closest waypoints was the cause. There are other sets of testing result with postfix _No_Check which disabled accessibility checking. Comparing with _No_Check records, processing time spent on the first map, (Waypoint_30 No check,) and that on the second map, (Waypoint_120 No check,) are very close, but we could not guarantee that the path is accurate, for the reason mentioned in Chapter 4-7.

In comparing the result of total length, the length for Waypoint_30 on the first map is within 111% times of the shortest path length, but 141% times of the shortest length for Waypoint_120 on second map. Even when we increased the number of reference nodes by using Waypoint_30 on the second map, the total length is still 130% times more than that of the shortest length. This means that the size of the map does affect the effectiveness of pathfinding for Waypoint methods.

Time spent by the Navigation Mesh method and the Heuristic Pathfinding method on both maps are similar. The difference is probably caused by the different location of testing points. Area-based pathfinding methods have the best performance as usual.
Conclusion

The size of map does impact point-based pathfinding methods. Though Waypoint method does not really use map data directly, the map size forces it to introduce even more waypoints in order to get proper accuracy.

5.3 Performance over Maps Different in Number of Passable Areas

The previous experiment proved that the size of map is not the differentiating factor distinguishing Heuristic Path Finding Method and Navigation Mesh method, while it has impact on point-based methods. We assumed that this is because area-based methods search path according to the setting of passable area. In other word, instead of the real data of the map, the number of convex polygons will affect the performance of area-based pathfinding methods. According to our hypothesis, with the support of a database, our method should perform better than the Navigation Mesh method in conditions that require more decisions to be made in processing pathfinding tasks. To test this out, we have designed a set of tests with maps different in structure and increase in complexity, to prove our method works the best in complicated maps.

Preparation

We have prepared three maps of the same size, 250 * 250, for testing. The first one has three blocking areas and eight passable ones. The second map has six blocking areas and sixteen passable ones. The third map has nine blocking areas and twenty-four passable areas (Figure 5-5, 6 and 7) For Waypoint method, as it performed well with reference nodes spread 30 pixels apart, we applied the same setting for this experiment, denoted as Waypoint_30. 2000 pairs of testing points were generated separately for each map.
Figure 5- 5 Map with 8 passable areas

Figure 5- 6 Map with 16 passable areas

Figure 5- 7 Map with 24 passable areas
Result

<table>
<thead>
<tr>
<th>1st map</th>
<th>Loading time</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td></td>
<td>326223 478</td>
<td>9267 414</td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>0 027540</td>
<td>413958 696 (rounded 331166 957)</td>
<td>31 392</td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>0 032246</td>
<td>309288 714</td>
<td>10 547</td>
</tr>
<tr>
<td>Heuristic</td>
<td>2 475555</td>
<td>309205 525</td>
<td>10 847</td>
</tr>
</tbody>
</table>

Table 5-5 Result of first map for experiment 5-3

<table>
<thead>
<tr>
<th>2nd map</th>
<th>Loading time</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td></td>
<td>335569 048</td>
<td>12947 092</td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>0 018263</td>
<td>424859 793 (Rounded 339887 834)</td>
<td>28 918</td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>0 060433</td>
<td>319688 349</td>
<td>18 128</td>
</tr>
<tr>
<td>Heuristic</td>
<td>2 318125</td>
<td>323713 448</td>
<td>16 040</td>
</tr>
</tbody>
</table>

Table 5-6 Result of second map for experiment 5-3

<table>
<thead>
<tr>
<th>3rd map</th>
<th>Loading time</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Star Grid</td>
<td></td>
<td>337743 504</td>
<td>17298 147</td>
</tr>
<tr>
<td>Waypoint_30</td>
<td>0 020889</td>
<td>422145 153 (Rounded 337716 123)</td>
<td>29 060</td>
</tr>
<tr>
<td>Navigation Mesh</td>
<td>0 104791</td>
<td>320305 282</td>
<td>27 014</td>
</tr>
<tr>
<td>Heuristic</td>
<td>7 402034</td>
<td>313578 203</td>
<td>21 780</td>
</tr>
</tbody>
</table>

Table 5-7 Result of third map for experiment 5-3

Analysis

<table>
<thead>
<tr>
<th>Map ID</th>
<th>Number of links</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st map</td>
<td>76</td>
</tr>
<tr>
<td>2nd map</td>
<td>68</td>
</tr>
<tr>
<td>3rd map</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 5-8 Number of waypoint links on each map for experiment

Observing the result, we learned that with the increasing complexity of the map structure, the time spent by most methods for pathfinding have increased, but the Waypoint methods was an exception. We found that Waypoint method spent less time on the second map which has six blocking area, comparing to the time spent on the
first map. The time spent on the third map is longer than that on the second map, but still shorter than that on the first map. Comparing the result in total length, rounded length on the first map is 101.5% longer than the shortest result generated by the other methods, length on second map is 101.3% longer than shortest result, and length on third map is almost the same length as the shortest result. There is not much difference on path effectiveness between the three results.

Now let’s take a closer look at the number of links between the waypoints. The number of links for the first map and the third map are the same, but the time spent on the third map is shorter than that on the first map. This shows that Waypoint method works better on map with more blocking areas, and the way that waypoints are plotted produce greater impact than the structure of the map content.

By analyzing the result of Heuristic Path Finding Method and Navigation Mesh method, we found that the number of passable areas obviously affected the time spent on pathfinding for area-based methods. Time spent by our method to prepare data and to execute pathfinding tasks increased as the map structure gets more complicated. The condition is the same for Navigation Mesh method, but the increase in time spent is more than that of our method, although the difference of total length between these two methods is not significant.

In conclusion, the complexity of the map structure seems to have a reasonable amount of influence over the Waypoint method in particular, as well, it impedes the overall performance of area-based performance. According to the result, Heuristic Path Finding Method has better performance comparing to A-Star Grid and Navigation Mesh. Although it takes longer for our method to prepare area paths, the time spent for preparation can soon be redeemed when the amount of tasks performed is sufficiently large. Comparing our method with the Waypoint method, it is...
ambiguous which one gets most benefits from increasing the complexity of map structure

5.4 Performance over Maps of Different Style

In our assumption, we expected Waypoint method to have better performance with complicated map, and the same for our Heuristic Path Finding Method. Heuristic Path Finding Method targets on large sized map with massive requests of pathfinding job, which is suitable for the condition of online game server. We wanted to know if our method has better performance than Waypoint method, and how much better.

Preparation

According to our definition of “complicated map”, there are fewer choices for one point to reach destination due to the style of map. We designed two maps in different styles for this experiment. One has blocking areas setting similar to a maze, while the other spreads blocking areas randomly. Both maps have same number of passable areas and are the same size to minimize the potential disadvantage for either area-based methods or point-based methods (Figure 5-8, 9). We have also created the other set of maps four times larger in width and height for testing, since our method is expected to have better performance on large-sized map.

From experiment 5-2, we already know that A-Star Grid method is not competitive on large sized map, hence we have excluded it from this experiment. For Waypoint method, we know that path checking affects the total time spent on pathfinding procedure, therefore we tested the method under both pre-check and no-check conditions on large-sized maps. Then we went on to get the range of time it needed to complete pathfinding tasks.
Figure 5-8 Complicate map

Figure 5-9 Random map
### Result

<table>
<thead>
<tr>
<th></th>
<th>Loading time</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waypoint_30</strong></td>
<td>0.006858</td>
<td>715234 421</td>
<td>28.136</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rounded 572187 537)</td>
<td></td>
</tr>
<tr>
<td><strong>Waypoint_14</strong></td>
<td>0.021967</td>
<td>560692 137</td>
<td>139.038</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rounded 448553 710)</td>
<td></td>
</tr>
<tr>
<td><strong>Waypoint_Plan</strong></td>
<td>0.046915</td>
<td>567626 052</td>
<td>24.188</td>
</tr>
<tr>
<td><strong>Navigation Mesh</strong></td>
<td>0.205142</td>
<td>448676 985</td>
<td>70.683</td>
</tr>
<tr>
<td><strong>Heuristic</strong></td>
<td>0.246823</td>
<td>450705 093</td>
<td>47.427</td>
</tr>
</tbody>
</table>

Table 5-9 Result of Complicate map for experiment 5-4

<table>
<thead>
<tr>
<th></th>
<th>Loading time</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waypoint_30</strong></td>
<td>0.020342</td>
<td>417744 605</td>
<td>25.043</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rounded 334195 684)</td>
<td></td>
</tr>
<tr>
<td><strong>Waypoint_14</strong></td>
<td>0.022197</td>
<td>359095 704</td>
<td>106.722</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rounded 287276 564)</td>
<td></td>
</tr>
<tr>
<td><strong>Navigation Mesh</strong></td>
<td>0.219754</td>
<td>270937 143</td>
<td>58.119</td>
</tr>
<tr>
<td><strong>Heuristic</strong></td>
<td>0.094717</td>
<td>271165 358</td>
<td>46.926</td>
</tr>
</tbody>
</table>

Table 5-10 Result of Random map for experiment 5-4

<table>
<thead>
<tr>
<th>Complicate map (Large)</th>
<th>Loading time</th>
<th>Length in total (pixel)</th>
<th>Time spent (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waypoint_30</strong></td>
<td>0.124941</td>
<td>2169147 194</td>
<td>1241.953</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rounded 1735317 756)</td>
<td></td>
</tr>
<tr>
<td><strong>Waypoint_30_No_check</strong></td>
<td>0.075602</td>
<td>2168347 208</td>
<td>1025.128</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rounded 1734677 766)</td>
<td></td>
</tr>
<tr>
<td><strong>Navigation Mesh</strong></td>
<td>1.299509</td>
<td>1722141 686</td>
<td>75.229</td>
</tr>
<tr>
<td><strong>Heuristic</strong></td>
<td>0.591744</td>
<td>1720703 606</td>
<td>69.592</td>
</tr>
</tbody>
</table>

Table 5-11 Result of Enlarged Complicate map for experiment 5-4
Random map (Large) & Loading time & Length in total (pixel) & Time spent (sec) \\
Waypoint_30 & 0.218128 & 1388172.086 (Rounded 1110537.669) & 847.409 \\
Waypoint_30_No_check & 0.086802 & 1388175.473 (Rounded 1110540.379) & 738.894 \\
Navigation Mesh & 0.234787 & 1106868.213 & 57.971 \\
Heuristic & 48.348284 & 1098376.210 & 47.914 \\

Table 5-12 Result of Enlarged Random map for experiment 5-4

Analysis

During our experiment, we found that Waypoint_30 did not meet the requirement for length. After looking into the waypoints, we found that links to the generated nodes were broken (Figure 5-10). Waypoint set with 14 pixels apart from each other, which is denoted as Waypoint_14, were generated and taken as representative of Waypoint method. With new waypoint set, Waypoint Method was not as competitive as area-based methods in terms of time spent.

<table>
<thead>
<tr>
<th></th>
<th>Number of links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waypoint30</td>
<td>51</td>
</tr>
<tr>
<td>Waypoint14</td>
<td>283</td>
</tr>
<tr>
<td>Waypoint plan</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 5-13 Number of waypoints on each map for experiment 5-4

There is another set of waypoints created manually for testing, shown in Figure 5-11. We found that performance by the planned waypoints is satisfactory and total distance is within requirement. The number of links for Waypoint_30, Waypoint_14 and Waypoint Plan are listed in Table 5-13. From this test we learned that the waypoints affect the performance of Waypoint Method by the way they were plotted.
Observing the result of small sized maps while excluding the result of Waypoint Plan, we found that both Waypoint methods and Navigation Mesh methods had worse performance on complicated map than on random map. In the contrary, map style does not have obvious influence on Heuristic Path Finding Method during
pathfinding process, but does affect its time for preparing area path. Comparing this with the result of experiment 5-4, it seems that the performance of our methods is mainly affected by the number of passable areas, other attributes such as size and style have insignificant influence on its performance.

Comparing the result of small-sized maps with that of large-sized maps, Waypoint method performs worse on large-sized maps, as shown in the result of experiment 5-3. Our method had the best efficiency on all maps tested in this experiment. In conclusion, though Navigation Mesh methods and Heuristic Path Finding Method has comparable performance in total distance, our method has excellent performance on complicated map while the other area-based methods were undermined by the increased complexity in map types.

5.5 Analysis over Memory Usage

Memory usage includes map data, prepared data and runtime allocation. The first two are predictable as developers can design buffering technique to eliminate its impact on game system. The last one is unpredictable and may cause serious impact in runtime. In this experiment, we reveal how memory is consumed during the pathfinding process. We know that if the map type is too simple or if the path is too short, there is likely no pathfinding search required in some pathfinding methods. Therefore we decided to run this experiment on complicated map type with a path go across it.

We picked one representative path to run our experiment. We used the complicate map of size 250x250 which was used in experiment 5-4 test, (Figure 5-8) and picked one randomly generated request, point (1, 77) to (209, 247), as representative to run memory logging process. We used manually designed waypoint
map (Figure 5-11) for Waypoint Method, as it has reasonable plotting strategy. The results are shown as follows:

<table>
<thead>
<tr>
<th>Used for loading Map file *</th>
<th>A Start Grid</th>
<th>Waypoint</th>
<th>Navigation Mesh</th>
<th>Heuristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8000 Bytes (7% in total)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Used by processed map *</td>
<td>1784 Bytes (52 points and 114 links) (70% in total)</td>
<td>3188 Bytes (51 shapes, 264 vertexes, 109 neighbors) (93% in total)</td>
<td>3188 Bytes (51 shapes, 264 vertexes, 109 neighbors) (97% in testing system, 2% in total)</td>
<td></td>
</tr>
<tr>
<td>Used to record prepared path **</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>140976 Bytes (10473 notes, 1275 paths) (0% in testing system, 98% in total)</td>
</tr>
<tr>
<td>Maximum size of open list</td>
<td>14467 Bytes (629 structs)</td>
<td>207 Bytes (9 structs)</td>
<td>80 Bytes (5 structs)</td>
<td></td>
</tr>
<tr>
<td>Maximum size of close list</td>
<td>91839 Bytes (3993 structs)</td>
<td>437 Bytes (19 structs)</td>
<td>80 Bytes (5 structs)</td>
<td></td>
</tr>
<tr>
<td>Number of steps</td>
<td>2448 Bytes (306 points)</td>
<td>104 Bytes (13 points)</td>
<td>88 Bytes (11 points)</td>
<td>88 Bytes (11 points)</td>
</tr>
<tr>
<td>Memory allocated in runtime *</td>
<td>108,754 Bytes (93% in total)</td>
<td>748 Bytes (30% in total)</td>
<td>248 Bytes (7% in total)</td>
<td>88 Bytes (3% in testing system, 0 0006% in total)</td>
</tr>
<tr>
<td>Total memory used in testing system *</td>
<td>116,754 Bytes</td>
<td>2,532 Bytes</td>
<td>3,436 Bytes</td>
<td>3,276 Bytes</td>
</tr>
<tr>
<td>Total memory usage</td>
<td>116,754 Bytes</td>
<td>2,532 Bytes</td>
<td>3,436 Bytes</td>
<td>144,252 Bytes</td>
</tr>
</tbody>
</table>

Table 5-14 Sample of memory usage of one path on complicate map (Figure 5-8)
Memory usage was allocated in testing system
Memory usage was allocated in database system

From Table 5-14, we can see that the total amount of memory used by Heuristic Path Finding Method is relatively large comparing to other methods, but most of it was located in database. The amount of memory allocated in runtime is the least among all, this saves the engine from spending effort on maintaining memory. A Star Grid method dynamically allocated huge amount of memory in runtime. In general condition, this sometimes causes memory swapping that triggers even longer delays on overall performance of the game system.

Memory allocated for open list and close list is used by A* algorithm when performing pathfinding tasks. Both may dramatically increase due to the complexity of map content and path. Waypoint Method allocated larger memory during pathfinding but required less total memory usage than Navigation Mesh Method, because, on this particular map, processed map data used by Waypoint Method was a lot less than that used by Navigation Mesh Method. As we know that map size undermines the accuracy of Waypoint Method since more waypoints are needed in large-sized map. As a result, when this experiment runs on a large map, memory usage by processed map could be very different from the result of this particular experiment.

This is a memory log of one pathfinding task. For massive pathfinding requests, memory allocated in runtime for A Star Grid method would clearly exceed the memory usage of other methods, and hence probably not allow other tasks to be performed smoothly. On the other hand, our method uses relatively less resource in the testing system and has high possibility of completing its own task without delaying other threads, such as keeping up frame rate and processing user input. Among all the methods, Heuristic Path Finding Method occupies the least testing
memory usage in the testing system, our method is the most resource friendly to game
system

5.6 Analysis of A* Algorithm Detouring

A* algorithm is a directional pathfinding theory. It is supposed to build the
shortest path in the shortest time by avoiding unnecessary checking without
compromising in accuracy on a grid-like map. But when an adjacent step extends to
linked step, such as waypoint in Waypoint method, or extends to an adjacent area,
such as passable area in Heuristic Path Finding Method, accuracy of A* algorithm
drops. Figure 5-12 illustrates this defect by a Waypoint map. When A* algorithm tries
to build path from P_start to P_end, it chooses path above the obstacle. When AI
checks adjacent points of P_start, it would always select point R1_2. The crucial point
R_unused, which could end the pathfinding process even more quickly and correctly,
would never be selected due to the directional characteristic of A* algorithm.

![Figure 5-12 Defect of A* algorithm in processed map](image_url)

AI does not have infinite time to pursue the best solution. Heuristic Path
Finding Method breaks pathfinding work into two phases. This not only increases the
ability of instant response in runtime, but provides more potential options for AI to
5.7 Analysis of Why Heuristic Path Finding Method Got Detoured

When we analyzed the testing result, we found that Heuristic Path Finding Method sometimes built longer path than Navigation Mesh Method. They both were defined under the same map information and shared the same path-refined technique. The only difference in building path is that Heuristic Path Finding Method used presumed starting and ending points and applied path template to requested points, whereas the Navigation Mesh build a path according to requested points directly.

Here we describe how terminal points make a difference.

In the preparation phase, Heuristic Path Finding Method tried to mimic the starting and ending points to meet general requests by setting them to average convexes location. However, under certain conditions, presumed terminal points are not convincing. Take Figure 5-13 as an example, when Heuristic Path Finding Method tries to build path template for area-A to area-B, it always builds the path as Figure 5-13 (a). During runtime, if there is a request from Ps to Pe, our method applies path template to these two points and builds a path shown on Figure 5-13 (b). But Navigation Mesh Method could correctly build a path shown on Figure 5-13 (c).
Figure 5-13 Path detoured by Heuristic Path Finding Method
This detour under Heuristic Path Finding Method would be obvious when there is relatively large passable area on the map and there comes a request where terminal points are very close to the edge. After figuring out the cause of this condition, we found that there is potential solution to resolve this problem.

(a) List all adjacent areas

<table>
<thead>
<tr>
<th>Area</th>
<th>Neighbor areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B, D</td>
</tr>
<tr>
<td>D</td>
<td>C, D</td>
</tr>
</tbody>
</table>

(b) Evaluate path template selected for neighbor areas

<table>
<thead>
<tr>
<th>Template</th>
<th>Path detail</th>
<th>Reason of being eliminated</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>BC</td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>BAD</td>
<td>Eliminated Path route back to starting area</td>
</tr>
<tr>
<td>DC</td>
<td>DABC</td>
<td>Eliminated Path route back to starting area</td>
</tr>
<tr>
<td>DD</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>
If Heuristic Path Finding Method is able to locate the neighboring area of the starting and ending points (Figure 5-14 (a)), determine all the path templates surrounding both points (Figure 5-14(b)), and calculate the distance between the two points of each path template (Figure 5-14(c)), it would be able to derive a path just as correct, or even better, than the Navigation Mesh Method. This is because using path templates gives pathfinding method more selections, which is omitted by the A* algorithm. This is described in Chapter 4-2 Map information storage.

This idea was not implemented in our testing system. The first reason is that we realized this issue too late and it would require major change to the current system. The second reason is that because we needed to run test over A* grid method, we needed to use small-sized map in case this method is not able to complete pathfinding task on large map. However, area-based method does not work well on small-sized map. If we implemented path selection to our method, all the experiment would be unfair to our testing method because it would need to prepare relatively more information for small areas, which only produce relatively minor difference on path length.
Chapter 6 Conclusion

6.1 Summary

We have introduced database into our Heuristic Path-Finding Method and used a testing system to test the method to reveal how the system performance was improved by shifting memory usage and management to database. We have also discussed the method in details and analyzed the concept of how our method works and why it is better than other methods. Finally, we have created a testing system to prove our assumption about the performance of our method is correct.

Based on our experiments, we found that Heuristic Path-Finding Method costs the least system resources on processing massive pathfinding tasks on large-sized maps with medium to high level of complexity. This pathfinding method's performance improves in a consistent manner as the number of areas increased on a map, regardless of the map category. Although at current stage of implementation, our method sometimes builds a path longer than the Navigation Mesh Method does in certain situations, it can easily be seen that such weakness can be avoided by simply searching a few more paths surrounding both points as shown in Chapter 5-7. Navigation Mesh Method guarantees a faster pathfinding progress comparing to Waypoint Method and A* Grid Method, because it has smaller searching space. But Navigation Mesh Method does not provide a predictable time and memory usage which is one of the features of our Heuristic Pathfinding Method. Most of online games in the market are still using Waypoint Method, since it is generally understood that Navigation Mesh Method does not have a significant advantage over Waypoint Method. Therefore, there is enough reason to believe that, it will be attractive enough.
for gaming industry to move toward the predictable method, Heuristic Pathfinding, directly from the unpredictable method, Waypoint Method.

Waypoint method may outrun our method on complicated maps, but plotting waypoints is quite challenging, which definitely impact the performance of Waypoint Method. Heuristic Path-Finding Method requires time to build path templates and communicate with the database, both of these slow down the processing time. However, the multiple path templates produced by our method in the preparation phase allow it to save time by changing pathfinding work to data selection at runtime. On the contrary, other methods will need to run their pathfinding process continuously.

Since our targeted system is the online game server, resource used on a single task should be limited whenever possible. Our method is proved to use steady amount of resource and require relatively less memory maintenance for performing massive pathfinding tasks. Hence, the characteristics of our Heuristic Path Finding Method include being system resource friendly on modern technology, communicating effectively in the highly interactive online environment, and processing efficiently massive requests.

6.2 Further Research

We have proved Heuristic Path Finding method out-performed other methods but there are still issues that should be addressed for further research. As we know, for area-based methods, when locating the areas a particular point belongs to, pathfinding tool would scan all edges of all shapes on a map until successfully finding an appropriate area. It would be more efficient to keep a map in memory with grid.
information addressing mesh ID. This solution consumes system memory but is stable and could greatly boost the efficiency of locating starting and ending points.

The other issue is the potential path options, which we have addressed in Chapter 5-6. Giving our method more path selection could lead to better path within shorter time, comparing to the Navigation Mesh Method. We would need further improvement on the testing system to prove this assumption.
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