IMPROVING THE SURVIVABILITY OF AGENTS IN A FIRST-PERSON SHOOTER URBAN COMBAT SIMULATION BY INCORPORATING MILITARY SKILLS

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Chair

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Abstract

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The exhibition of intelligence while selecting paths in a combat setting should be based upon the right balance of the risk involved and the traversal time. In this work we propose an algorithm that finds strategic paths inside an urban combat game map with a set of enemies. The strategic path calculation is based upon the hit probability calculated for each enemy's weapons and the risk vs. time preference. Ultimately, the strategic path calculation minimizes both time and risk as per mission objectives. The strategic path planning concept can be applied to both Real Time Strategy (RTS) and First Person Shooter (FPS) games.

We propose evaluating a map at two levels of abstraction: Area level and Grid level. Area level strategic path computation can be done at run-time, because Areas are far less in count compared to Waypoints. When the agent reaches the computed Area, the strategic path is computed over the Grid Points of that Area. Thus, the calculation of the hit probability can take into account the real-time movements of the enemies as the agent traverses the Grid Points of an Area.

Secondly, in addition to the computational savings of calculating strategic paths at the Area level, rather than the Grid level (or using Waypoints), there is also the issue of not knowing visibility details within an Area until the agent arrives at that Area, especially in urban combat settings. Thus the agent exhibits intelligence (in strategic path computation) in a more realistic way.

We performed out-game and in-game experiments on our proposed model of strategic path computation and found that the computed strategic paths based upon a high risk vs. time preference are significantly safer.

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CHAPTER ONE

INTRODUCTION

In a combat scenario where there are enemies, the shortest path towards the goal is not always the best path, especially when it is well guarded. Thus, if an agent follows an unknown path that has been considered as the best path and in this path an enemy spots the agent and shoots him, the goal remains unachieved. Instead depending upon the mission objective if the agent can afford to take a safer path that takes advantage of areas hidden from the enemy to provide cover, then the agent can achieve the goal and maintain good health. This type of path planning is useful for Military Operations on Urban Terrain (MOUT) tactics. We have developed a strategic path planning algorithm that is based upon in-depth risk evaluations along all the possible paths that can lead to the goal. For that we use the Hit probability for calculating the risk involved on a path. The risk calculation takes into account all the enemies.

We also propose a 3D volume organization technique which we call the *Heuristic Search Space (HSS)* technique (discussed in a later chapter). For the visibility calculation we propose a *Brush Collision Detection* algorithm (discussed in [14] and that has been used with Binary Space Partition (BSP) trees in Quake3 [18]) to be used with our *HSS* technique. We implement and test the strategic path computational model using these techniques in the context of a MOUT scenario within the Quake3 first-person shooter computer and video game.

Quake 3 Arena is a multiplayer FPS game released on December 2, 1999 [24]. The game was developed by id Software. In Quake3, a player collects points (called frags) by killing other players. Quake3 Arena features Deathmatch, Team Deathmatch, Capture the flag, and tournament, in which players test their skills against each other in one-on-one battles and an elimination ladder [24]. See Figure 1 for a snapshot from the game. On August 19, 2005, id

Software released the complete source code for Quake III Arena under the GNU General Public License [24].

Figure 1: Quake3 Arena

We performed an empirical analysis of our strategic path computational model based on our MOUT modification of the Quake3 game. In our experiments we defined 50 random experiment sets. Each experiment set has a defined RiskVsTime factor, agent's start location, agent's goal location and enemy's location. For each of 50 experiments we evaluated all three paths, Shortest Path, Strategic Path at Area level and Strategic Path at Grid level, using both out-game and in-game trials.

In out-game trials we used the real world weapon details [5] to compute the *hit probability (HP)* across the traced path between the start and the goal location.

We used the Urban Combat Testbed (UCT) for our *in-game trials*. The UCT is an Urban Environment based modification of Quake3. The agent program interacts with the UCT using shared memory access. Here, the hit probability for each experiment is computed by computing the average *hit probability* over 10 runs.

On experimentation, we found the paths generated by the strategic path computation were safer (the difference between the risks was statistically significant) with a trade-off of longer distance to walk. In out-game trials, we found the Strategic path Grid level performed consistently better than the Strategic path at Area level by further reducing the distance of walk.

In chapter 2, we have compared our work with the research work done in this field. Chapter 3 discusses our Testbed environment and addresses how an agent interacts with the Testbed environment. In chapter 4, visibility algorithms have been discussed. Chapter 5 describes the conceptual definition of risk that we address in our work. It also discusses our algorithm for strategic path computation at Area level. Chapter 6 discusses our algorithm for strategic path computation at Grid level and explains how the strategic path computation at Grid level is connected to strategic path computation at Area level. Chapter 7 discusses our out-game and in-game trial setup. Chapter 8 contains our experimental results. Chapter 9 discusses MOUT strategies and tactics that can be implemented using this work. And chapter 10 contains the conclusion and also addresses the possible enhancements and the significance of this work to Real Time Strategy (RTS) games.

CHAPTER TWO

RELATED WORK

2.0 Overview

This chapter discusses how the simple path planning problems are related to the strategic path computation. This chapter also discusses previous work done in this field, compares our work and discusses our contribution.

2.1 The Shortest Path

Path planning and collision prevention for single and multiple players has been extensively studied [6]. But strategic path planning is a relatively new area of study. Shortest path planning can be done on waypoints by applying the A* algorithm [10]. But this approach neglects the strategic importance of waypoints.

2.2 Previous work

Various strategies and tactics for Military Operations on Urban Terrain (MOUT) depend upon the visibility among waypoints. In this direction by using the *BitStrings* technique [1] used by Liden for strategic path planning to exhibit a potential for MOUT tactics like *flanking* [1]. *BitStrings* decreases computation and storage requirements for visibility computation at run-time. In the *BitStrings* technique a bit represents visibility information between two waypoints. Each waypoint maintains a Bit String that contains visibility information of all the waypoints from that waypoint (in form of *true* or *false*). Therefore computation about the visibility from an enemy's waypoint does not need to be computed at run-time.

In their work risk has not been studied in detail. Risk is defined by the ability of an enemy to kill the agent. It makes the following assumptions.

(I) A far distant enemy has been considered equally risky compared to short distant enemy.

(II) A variation in fire power of an enemy has not been considered. For example Sniper and Sub-Machine Gun have not been considered separately.

(III) *BitStrings* can only be used for a fixed set of waypoints. In real 3D environments, the visibility complexity increases and the set of fixed waypoints cannot address strategic importance of visibility accurately.

2.3 Our contribution

We extend this work to find a strategic path with the help of weight and path matrices and also prioritize these paths on the basis of a risk vs. time factor. Instead of using a large number of waypoints we have abstracted it to a smaller number of polyhedron areas [3] and inside these areas we calculate visibility by using a *checkpoint* approach discussed in chapter 5. We also present an efficient Line of Sight (LOS) algorithm that can be significantly optimized by using the *Heuristic Space Search* technique. We also conducted various tests on a realistic MOUT based environment with the real visibility computational challenges.

Our work features,

(I) We compute the risk from the realistic hit probabilities [5] computed for all the enemies based upon the distance from the enemies. Thus, our risk calculation addresses all the components of risks (type of weapon and its lethality).

(II) First, the strategic path is computed over the set of Areas (an abstraction of walk-able areas). They are far less in count compared to Waypoints. Thus the risk computation can be done at run-time and it takes into account all the dynamic changes.

(III) Secondly, while walking over the selected Areas the strategic path is computed at Grid level (the Grid level, a higher level of detail). This computation gives the within-area Grid Points to walk through after reaching a selected area. Thus, the calculation of the hit probability can take into account the real-time movements of the enemies as the agent traverses the Grid Points of an Area.

(IV) Thus, by doing the strategic path computation at two levels the computational burden gets linearly distributed. As Grid level can go into a more detail than the fixed set of Waypoints and therefore it covers more strategically significant locations.

(V) Secondly, in addition to the computational savings of calculating strategic paths at the Area level, rather than the Grid level (or using Waypoints), there is also the issue of not knowing visibility details within an Area until the agent arrives at that Area, especially in urban combat settings. Thus the agent exhibits intelligence (in strategic path computation) in a more realistic way.

(VI) The *Areas* can be computed automatically (in Quake3 they are similar in concept to clusters separated by cluster portals [19]) and further *Grid points* are also automatically computed. And on the other hand optimal distribution of Waypoints does require intervention of level designers [19].

CHAPTER THREE

THE TESTBED ENVIRONMENT

3.0 Overview

This chapter discusses our Testbed environment. And later in this chapter agent's percepts have been discussed. They are categorized into Static and Dynamic percepts. And later types of actions the agent can perform have been discussed.

3.1 Urban Combat Testbed

Our experiments were performed on the Urban Combat Testbed (UCT) [3]. UCT is a modification of the Quake3 [18,19] first person shooter game.

The agent program interacts with the UCT using a shared memory interface exchanging percepts and actions. The shared memory is used to read and write percepts and actions with lower communication latency and lower computational burden on the game engine. Figure 2 contains a snapshot of UCT's heads-up display (HUD).

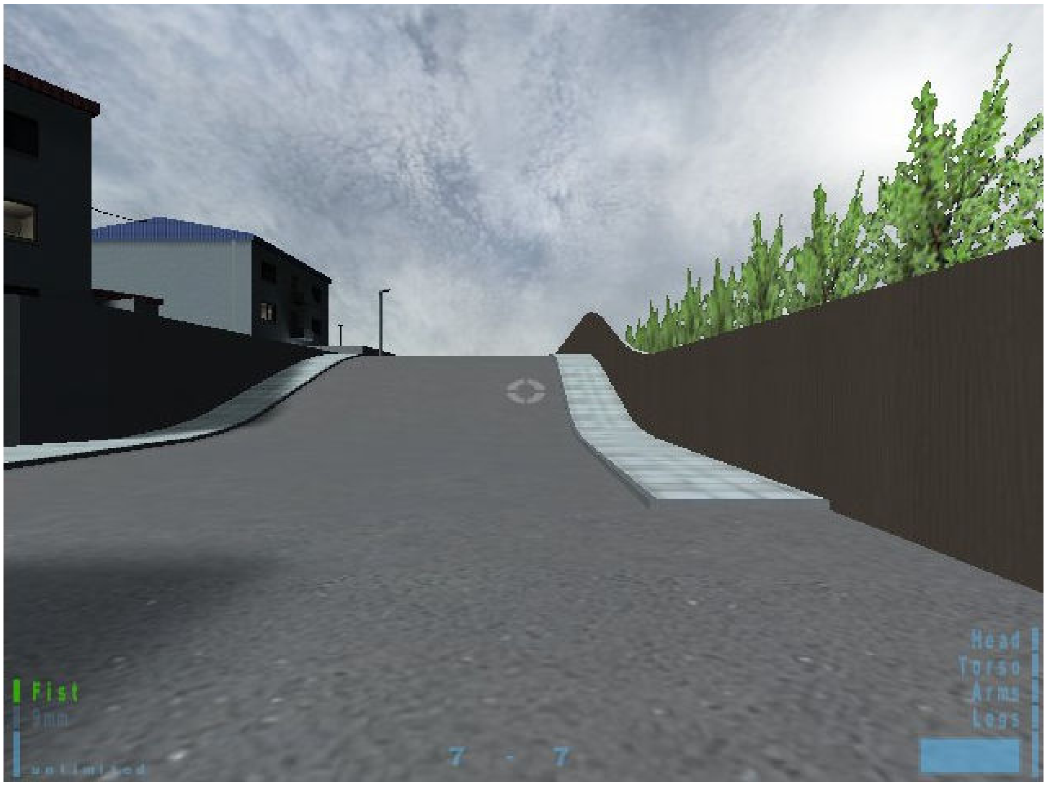


Figure 2: The UCT HUD

The Reykjavik map (figure 3) is a model of an urban area. It contains four small building structures connected by streets. It also contains other urban features like garage, walls, pallets, a bus-stop, street-lights, trees, crates. Areas inside this map vary in latitude. The size of the map is 3376 x 2976 x 640 inches (85.75 x 75.59 x 16.25 meters).

Figure 3: Top view of the Reykjavik map [20]

3.2 Areas and Gateways [3][21]

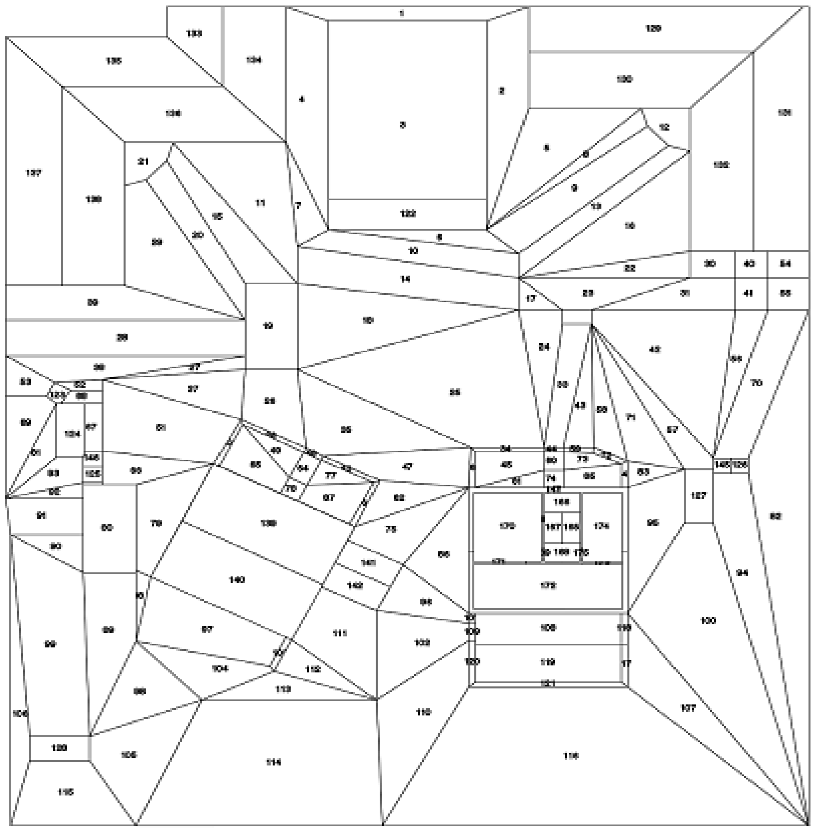


Figure 4: Formalizing into set of Areas and Gateways

The walkable surfaces in the map have been defined as *Areas*. In Quake3 *Areas* are similar to clusters concept and the *gateways* are similar to cluster portal concept [19]. These areas are 3D boxes made up of convex polygons (6 or more). Areas have been constructed from the 3D *brushes* used to define a map in Quake3. Figure 4 shows the areas computed for the map in figure 3. All walkable areas are connected using *gateways*. Gateways also contain information about the type of action required to cross the gateway from one area to another area (actions like Jump, Walk, Fall, etc.).

3.2.1 Area and Object Construction [3][21]

All the 3D volumes are classified into positive and negative spaces. A 3D volume like a wooden-box where an agent cannot walk-in is called as a positive space (called *Objects*) and on the other hand an open surface like a ground area where an agent can stand or walk-in has been classified as a negative space (called *Areas*). A building by itself is an *Object* but inside it also contains floors where an agent can stand, these floors are *Areas*. Using Quake 3 map editor (GTKradiant [22]) one has to manually box all the 3D volumes as positive and negative spaces. And by using the *Sarge* application [3,21] 3D coordinates and normals of planes boxing all the 3D volumes are computed and recorded into an XML file.

3.2.2 Gateway Construction [3][21]

An *Area* can be traversed to its neighboring *Area* by actions like walk, jump, fall or none between the connections (openings) of the two *Areas* that will be a polygonal surface (called *Gateway*). Using the *Sarge* application the connection between every two *Areas* is computed and recorded into the same XML file.

3.3 The Agent's interface

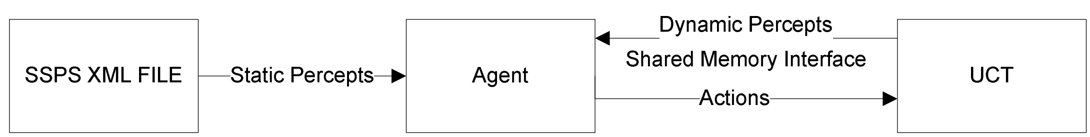


Figure 5: The agent's interface

The percepts are of two types: dynamic and static. As shown in figure 5, the agent retrieves the Static Percepts from a Static Spatial Perception Service (SSPS) XML file. And it receives Dynamic Percepts from the UCT and after processing the percepts it sends its Actions back. This communication is done through the shared memory interface (as shared memory has a very low latency).

3.3.1 The Dynamic Percepts

The dynamic percepts include information about current location (X, Y, Z coordinate form), yaw, pitch, roll, health, weapons and ammunitions, in other words these percepts are meant to change with the game play. The dynamic percepts consist of 33 different percepts related to the player, 11 different percepts about entities which include opponents if they are present and all the different dynamic objects, and 4 different percepts about weapons.

3.3.2 The Static Percepts

The static percepts contain the map information. The static percepts are the information about the static entities in the map like walls, areas, objects etc. The static map information is passed to the agent using an XML description [3][21]. The XML file contains plane coordinates, normals and a unique ID for all the Areas and Objects. It also contains connectivity information about those Areas called Gateways and type of action required to traverse from one Area to another neighbor Area.

3.3.3 The Actions

The agent program can choose from 29 different actions that can be sent to the game. The actions are of very primitive form (WALK_FORWARD, TURN_RIGHT, TURN_LEFT, WALK_BACKWARD, RELOAD, FIRE, STRAFE_LEFT, STRAFE_RIGHT etc). These actions are categorized into four categories and written into the assigned shared memory. The agent program can write together a set of four actions. These four actions can be performed together. The UCT reads these actions and executes accordingly. Thus, an agent can perform multiple actions together, e.g., Strafe and Shoot (the agent can move to a safe location while shooting). Similarly, it can Turn and Walk together making its path smoother.

CHAPTER FOUR

VISIBILITY AND 3D VOLUME SEARCH ALGORITHM

4.0 Overview

An Area at a higher height can block visibility between two of its neighboring Areas at lower heights. Therefore, Areas and Objects both must be considered for visibility computation. This chapter discusses how the information about an Area retrieved from a SSPS XML file is used for both visibility and location reasoning (for retrieving Area connectivity). We used *Heuristic Search Space (HSS)* technique to get to a small set of probable 3D volumes that could obstruct the visibility between two points. Then we applied Quake3's brush collision technique to determine whether the two points are really blocked by a 3D volume out of all the probable 3D volumes (algorithm 4).

And similarly for searching the 3D volume for a given XYZ point, *HSS* reduces the number of 3D volumes to search to a very small list of probable 3D volumes (algorithm 5).

4.1 Visibility between Areas

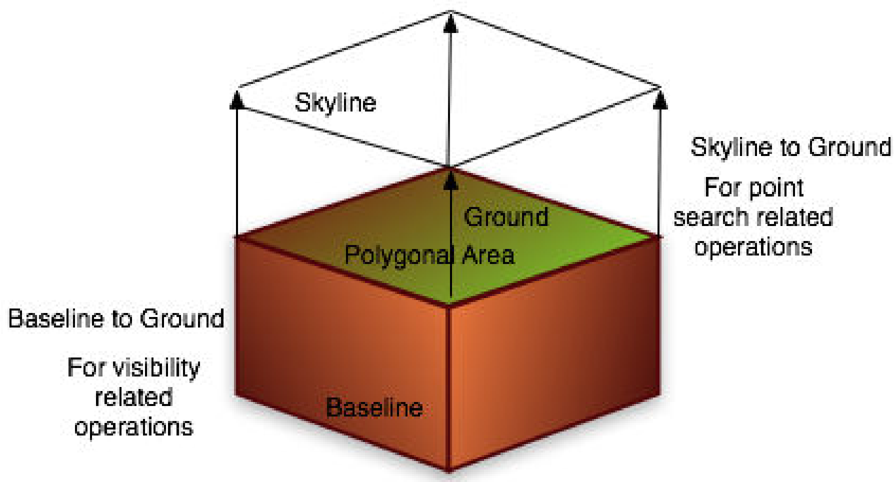


Figure 6: Double use of polygonal areas

As shown in figure 6, polygonal areas are used both for visibility calculations as well as walkable path calculations (that require locating an area for a given point). For visibility tests these polygonal areas are considered to be 3D volumes starting from the base of a map. Thus an area at a higher height could block visibility among two adjacent areas. And for other 3D calculations (like searching an area on the basis of a known point) these polygonal areas are considered to be 3D volumes starting from its skyline.

World coordinates of *areas*, *objects* and *gateways* are initially parsed using an XML file. From the dynamic percepts and the static percepts the agent calculates the current *area* information. For traversing into another area the agent finds the *gateway* information corresponding to the present *area* and the desired next *area*. The agent sends the relevant actions in order to cross the found *gateway* to the next *area*.

4.2 Heuristic Search Space Technique

With the help of this technique, we can limit the number of visibility tests to a very small number of visibility tests and this count is independent of the total 3D volumes. And also this technique efficiently finds the list of probable 3D volumes occupying a given XYZ location by searching through the 3D volumes associated with that *HSS* element instead of the total count of 3D volumes.

4.3 Indexing 3D Volumes

In this technique we index the complete 3D map to a small 3D array. Each element in that array points to a list of 3D volumes (Areas and Objects) in the corresponding 3D space of the map. For example when *HSS edge length* is 100 each 3D space of 100x100x100 will be associated with one element of the *Heuristic Search space (HSS)*, and it will store the list of Areas and Objects occupying (may or may not completely) that 3D space. Thus, areas and objects that could exist inside that 3D space of the map will be addressed by a very small 3D array. For example a 3D map of size 4000x4000x1000 in the *Heuristic Search Space* can be efficiently indexed into a 3D array of size 40x40x10.

To efficiently calculate the set of *HSS* elements that will store a 3D volume, we just need to find two extreme points (x_{min}, $y_{min,,}$ z_{min}) and (x_{max}, $y_{max,,}$ z_{max}) of that 3D volume and step through all the points inside this space in multiples of *HSS edge length*. These computed points are listed accordingly with appropriate *HSS* elements.

4.4 Visibility Test

For the visibility test between two points we search between these points for any 3D volume that could block the visibility. Thus, if a line segment joining these two points gets intersected by a 3D volume then it will be considered as a visibility blockage (refer Algorithm 1)

We transform the visibility problem in the original map to a visibility problem in *HSS*. Since *HSS* uses a more abstract and a more simple representation of the original map, it produces a list of probable 3D volumes that could block the visibility between the points of the original map. For example, in *HSS* a line segment between points {(1200, 1200, 40), (3000, 2000, 100)} will be indexed as {(12, 12, 0), (30, 20, 1)}. Thus, in *HSS* all the 3D objects that are associated with the line joining these points will be computed for visibility tests. This technique minimizes the potential 3D objects for visibility tests.

The Binary Search Partition (BSP) technique in the Quake3 engine keeps record of all the 3D *brushes* even when smaller *brushes* have no strategic significance. The BSP technique can be applied directly to SSPS 3D volumes. Whereas, the *HSS* technique meant for SSPS 3D volumes will directly reach the potential candidates in a constant time (independent of the total count of 3D volumes inside the map, but it varies with the map's dimensions). On the other hand the BSP technique searches through the root node to the potential set of *brushes* (polyhedral volumes) by comparing log(n) partition planes where n is total partition planes. For cases where two points are separated by a small distance the *HSS* technique will perform better than the BSP technique because BSP will go through log(n) partition planes and on the other hand *HSS* will list 3D volumes that are associated with the *HSS elements* along the line joining the two points.

But, the *HSS* technique cannot be a better choice for all the cases. For cases where a 3D map is poorly indexed the *HSS* technique will produce a large list of probable 3D volumes. Thus, it will increase the number of visibility tests before reaching the correct 3D volumes for decisive visibility tests.

Algorithm 1: LOS algorithm

INPUT: Two points, the static percepts and indexed HSS.

OUTPUT: Result of blockage in visibility as true or false.

SYNOPSIS: This algorithm checks visibility between two locations for strategic path planning. The given two points are mapped to *HSS* and the appropriate two *HSS* locations. And among these two *HSS* locations a line is drawn. And all the visited *HSS* elements are searched for their associated 3D volumes. These 3D volumes and the given two locations are the reduced test-cases for the brush collision algorithm [14] (of Quake3 engine) and on any successful blockage return *true* else continue with other listed 3D volumes.

ALGORITHM:

1**:** Locate *HSS* element for both the points.

2: Construct a line segment between above two *HSS* elements in *HSS*. And obtain all the *HSS* elements on that line.

2: For each 3D volume associated with the above *HSS* elements. Perform step 3.

3: Input two points and a 3D volume [14].

- 3.1: Locate sides of the two points for each face of the 3D volume.
- 3.2: If both the points are outside of any of the face. Then reject this 3D volume else continue with other sides.
- 3.3: If both the points are inside of any of the face. Then continue to step 3.4.

3.4: If both the points are on the opposite sides of at least two faces of a 3D volume.
Then, check the order in which the line is intersecting the two faces.
3.4.1: If the line is entering a face and leaving another face then return *true* (two points are blocked)
3.4.2: Else reject this 3D volume and continue with other 3D volumes.
4: If none of the listed 3D volumes are blocking the visibility then return false.

4.5 Locating 3D Volume for a Given Location

The algorithm 3 searches the Area ID for a given XYZ location, each of the XYZ coordinates is divided by the *HSS edge length*, this results in the *HSS* location (an XYZ value pointing an *HSS* element) to search for the list of probable 3D volumes. Now, each listed 3D volume is checked to determine the correct 3D volume occupying the given XYZ location.

Algorithm 2: 3D volume search algorithm
INPUT: A point, the static percepts and indexed HSS.
OUTPUT: Area ID or -1.
SYNOPSIS: This algorithm finds a given location inside the map by mapping it to the appropriate HSS element and then searching through the probable Areas.
ALGORITHM:
1: Locate the *HSS* element for the given XYZ point.
2: For each 3D volume associated with the above *HSS* element.

Test whether the computed point is inside the 3D convex box by doing dot product calculations [13] using the plane normal, a point on the plane and the computed point

$$(C.N_{ormal} >= P.N_{normal})$$

3: If the above is *true* for all the planes of the above 3D box, it means the point is inside the considered 3D box and thus return its Area ID.

4: If none of 3D volumes are found to contain the given point then return -1.

CHAPTER FIVE

STRATEGIC PATH PLANNING AT AREA LEVEL

5.1 Overview

This chapter discusses the conceptual definition of risk that we address in our work. It also discusses our Testbed environment and describes our algorithms.

5.2 Definition of Risk

A path that takes the agent to areas closer and visible to an enemy is a risky path. Risk is defined as the ability to shoot the player in terms of Hit Probability (HP). Each weapon has a different hit accuracy, rate of fire and hit ratio per bullet fired. We used weapon details [5] to obtain a hit probability based upon distances from a set of enemies. Each weapon has a different Hit Probability and the distance between the agent and the enemy is almost inversely proportional to the hit probability. The enemy's ability to shoot the agent depends upon three factors:

(I) The agent's visibility from the enemy's location.

(II) The distance from the enemy.

(III) The lethality of the enemy's weapon.

A strategic path is a trade-off between the time of traversal and the risk along the path. Not all the areas along all the possible paths are completely covered (no risk along the path because none of the enemies can see it). Therefore the risk evaluation must carefully consider all of the three components of risks.

5.3 Formalizing Areas and their Connectivity as a Graph

Areas and their connectivity can be formalized as vertices and edges of a graph. Thus, finding a path among areas becomes a problem of finding a path in a graph. The connectivity between areas resembles connections between vertices. The Euclidean distances between areas become weights on the edges (in our case we measured the distance between the area centers going through the *gateway* center when *"walk"* is the action of the *gateway* between areas).

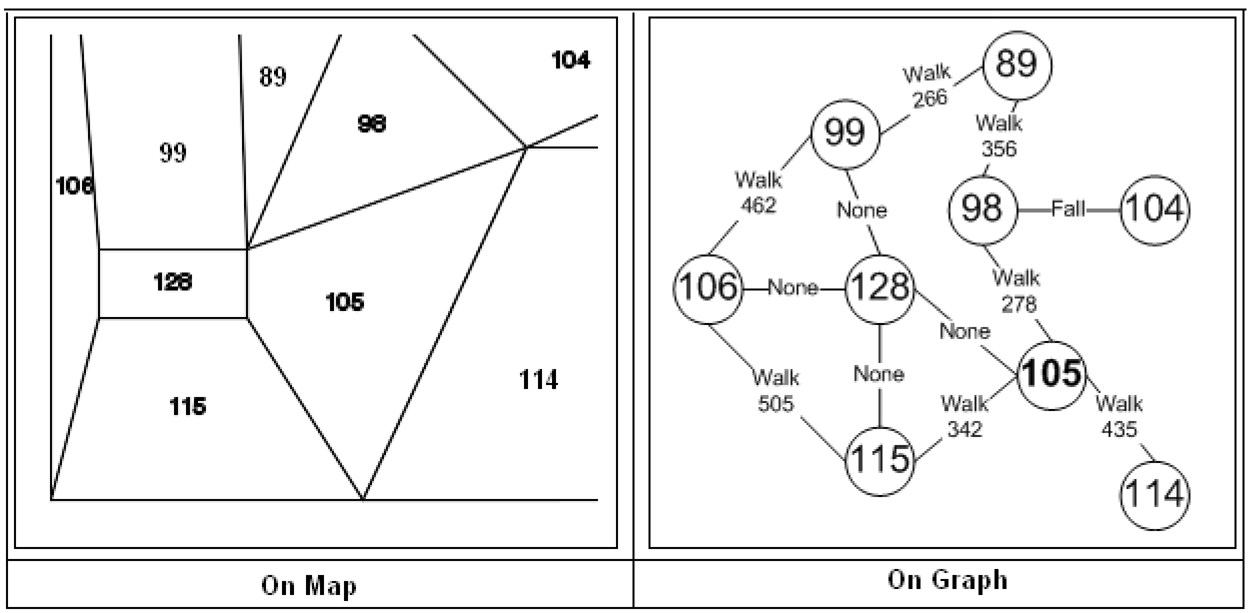


Figure 7: A portion of the map converted to a graph

As shown in figure 7, a portion of the map has been converted into a graph. Here, the action "*Walk"* on the *gateway* between two areas enables the agent to walk between the areas. The action *"None"* prevents the agent from moving into the next area because the next area is at higher altitude (beyond jumpable height) and the action *"Fall"* represents the next area is at lower altitude.

In our strategic path calculation we modify these weights to incorporate risk, and then use the same shortest path algorithm to find a strategic path.

5.4 Strategic Path Calculation

Our strategic path calculations have been done by modifying the weights in the weight matrix of the connectivity graph and then using the *Dijkstra's* algorithm to compute the shortest paths. Each weight initially represents the *Euclidean Distance* between the area centers and it is penalized for being exposed to an enemy. For this process we compute *Meta-Weight* for each *Weight*.

The *Meta-Weight* is computed by computing the *Hit Probability* and the *RiskVsTime* factor. The *RiskVsTime* is determined by the priority to safety for the agent in terms of mission objectives. The *Hit Probability* is computed over the path connecting two area centers and that is done by using *checkpoint technique*.

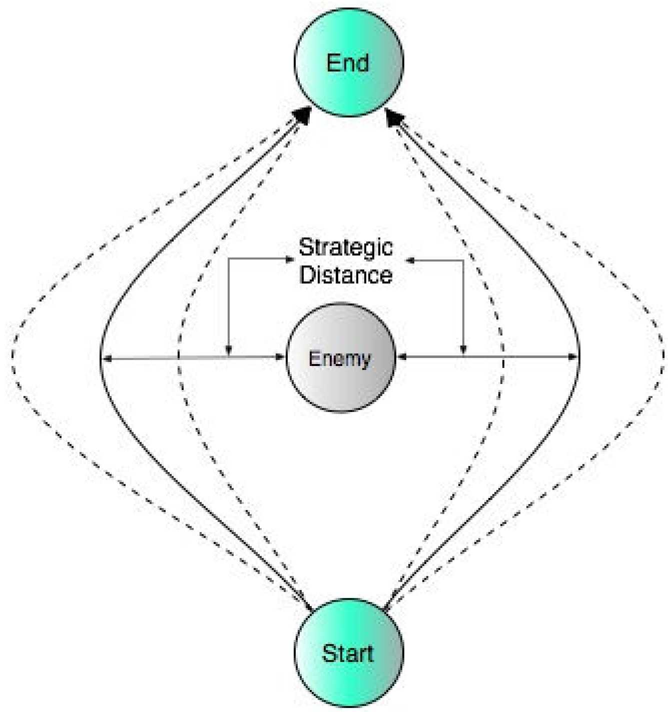


Figure 8: Strategic Distance is a trade-off between Risk and Time

In figure 8, the strategic path to the goal area is influenced by various factors like the fire power of enemy's weapon and priority given to survival over the time as per mission objectives. A smaller *RiskVsTime* value (the smallest value is 0) means the safety has no priority. And similarly a high *RiskVsTime* value means safety has a high priority and therefore any exposure to enemies will be minimized. Thus, the strategic distance from an enemy will vary for an exposed area.

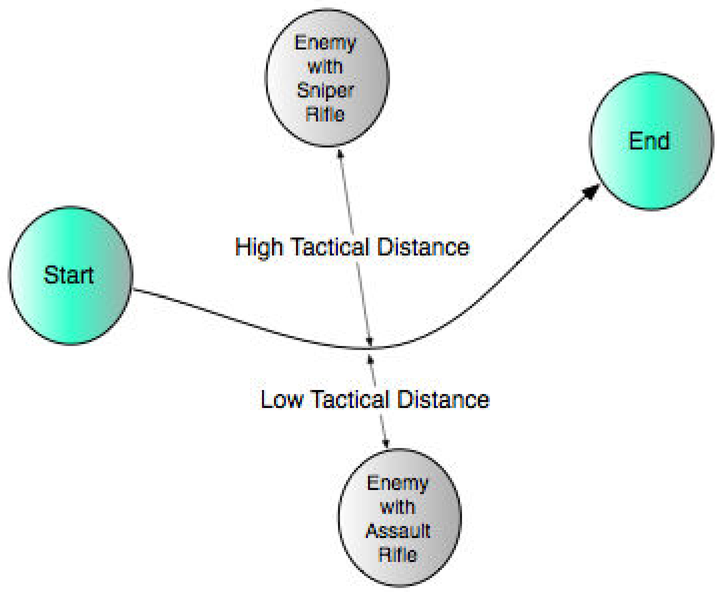


Figure 9: In Strategic path computation tactical distance from a more dangerous enemy is maximized

Due to *Hit Probability* computation the *tactical distance*s between a more and a less dangerous enemy is computed fairly. In figure 9, the strategic distance between an enemy and the agent depends on how dangerous the enemy is. For example an enemy with a sniper rifle is considered more dangerous than an enemy with an assault rifle.

5.5 Abstraction of map into Areas

All the walkable surfaces have been converted into a small set of large convex polygonal areas. There are a total of 227 areas out of which 169 areas are walkable (interconnected). And also there are 43 different objects (buildings, garage, walls, pallets, bus-stop, street-lights, trees, crates). Thus, for a small set of areas the graph representation and further application of shortest path algorithm is computationally feasible. For complicated maps the concept of abstraction can be further applied to a higher level. For example, we can define *Zones*, which are made up of *Areas* and at a more detailed level we will have *Grids*. For example, in a map that contains multiple buildings, to simplify details buildings can be considered as *Zones* and Floors can be considered as *Areas* and further rooms can be considered as *Grids*.

5.6 Hit Probability (HP) Calculation

From a start area to a goal area there can be many paths. A path is defined by a set of walkable polygonal areas. These areas can be visible to enemies. The risk factor of a path is determined by calculating the total hit probability for all the areas along that path.

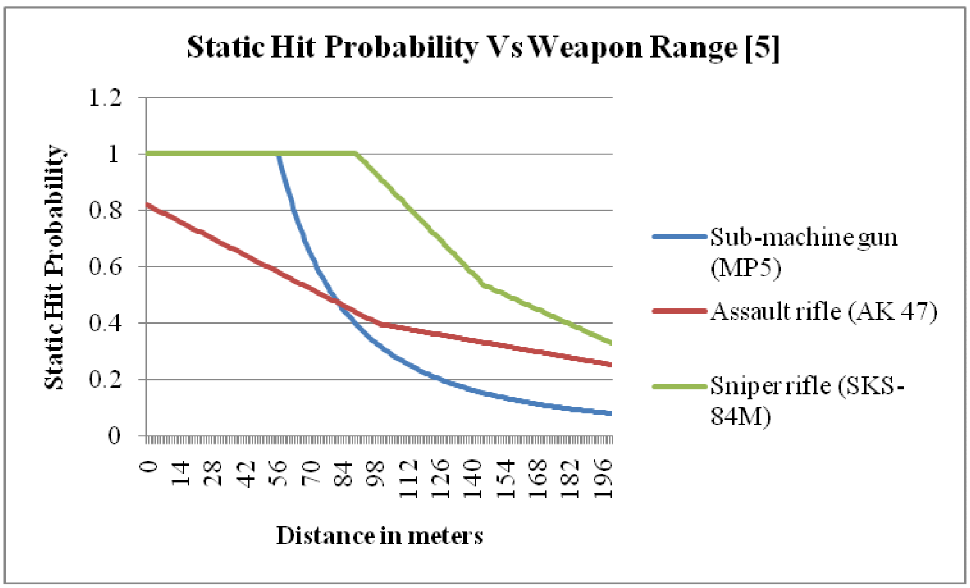


Figure 10: Hit probability based upon range modeled for three weapons.

The hit probabilities have been calculated from the realistic weapons data obtained from [5]. As shown in figure 10, we considered 3 types of weapons: assault rifle (AK 47), sniper rifle (SKS-84M) and sub-machine gun (MP5).

The realistic data gives a rough conversion of distances to static hit probability for various weapons computed for a standing soldier. We convert the given static hit probability to dynamic hit probability by considering it to be 0.25 (called *DynamicRatio*) times the static hit probability. When the agent will be be moving, it will be harder to hit him, thus use a fraction of the static hit probability to estimate the effects of the dynamics of the situation. If we don't consider *DynamicRatio* then it will be an unfair risk evaluation of a moving agent and also it will lead to situations where many exposed paths will be considered equally risky because the total hit probability over a path will consistently touch a high value (approx. 1.0) due to computational limitation of floating point preciseness. Thus, the strategic path planning will fail to distinguish between a less exposed and an over exposed path.

5.7 Checkpoints

A point on a path where the HP is computed has been defined as a *checkpoint*. In order to calculate the hit probability associated with a path made of a set of points, the *checkpoints* are linearly distributed along the path at a fixed Euclidean distance (called *checkpoint length*) and finally the end point gets included (if the distance between the last *checkpoint* and the end point was lesser than the *checkpoint length*). In the following equation HP_{total} represents the total *hit probability* over the given path and HP_i represents the *hit probability* for a *checkpoint*. The total *hit probability* is computed as:

$$HP_{total} = HP_1 + HP_2.(1-HP_1) + \dots HP_n.(1-HP_{n-1}).(1-HP_{n-2})\dots(1-HP_1)$$

Where $HP_1, HP_2 \dots HP_n$ are the HPs of the checkpoints $P_1, P_2 \dots P_n$ linearly distributed along the path separated by *checkpoint length*. Here for instance $(1-HP_1)$ means probability of not getting a hit on checkpoint P_1 and $HP_2.(1-HP_1)$ means the probability of only being hit on the checkpoint P_2. Similarly, $HP_n.(1-HP_{n-1}).(1-HP_{n-2})\ldots(1-HP_1)$ represents the probability of only taking a hit on the checkpoint HP_n (after surviving hits over the previous *checkpoints).* Here we focus only on the first hit, thus the probability of taking a hit only on a *checkpoint* is computed from the product of probability of not getting hit over all the previous *checkpoints* and probability of getting hit on that *checkpoint*. Thus, the *total hit probability* HP_{total} represents probability of getting a hit over all the *checkpoints*.

5.7.1 Checkpoints for Meta-weight computation

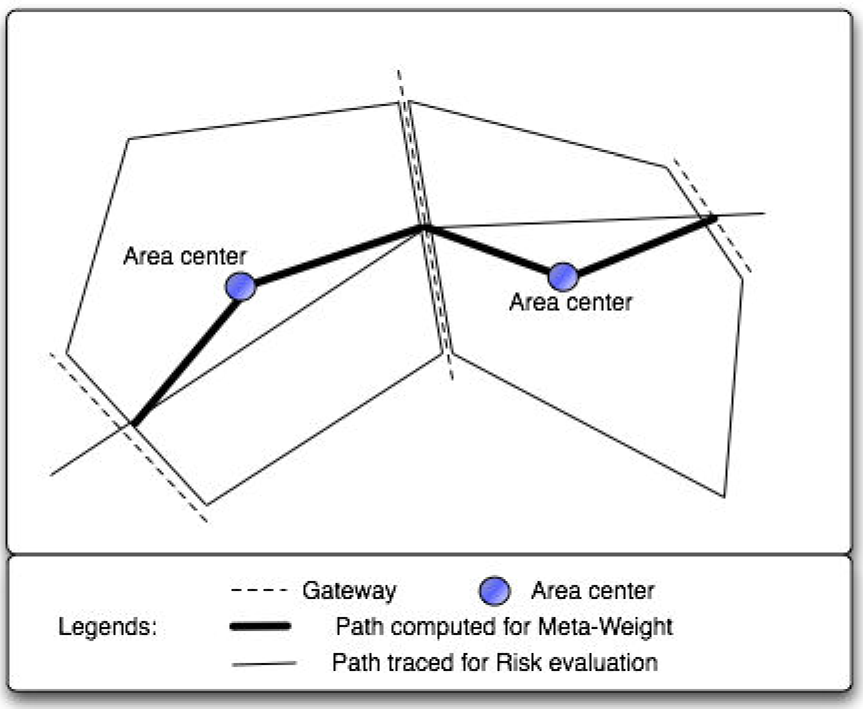


Figure 11: Checkpoint distribution along a pair of areas.

For the strategic path computation, each pair of neighboring areas is computed for the risk. Here, the risk is the total hit probability along the *checkpoints.* As shown in figure 11 along the thick dark line, the first *checkpoint* is allocated to the center of the start area, and the rest of the *checkpoints* are distributed linearly (e.g. 1 meter *checkpoint length*) along the path to the center of the stop area including the center of the stop area. This path goes through the connecting gateway of the two neighboring areas. The *hit probability (HP)* over this path is used for *Meta-Weight* computation. As shown in the figure 11 by the thick black marks.

5.7.2 Checkpoints for Risk Evaluation of a traced path

The path's safety is computed using the *hit probability* over the path. And it is evaluated by applying the *checkpoint technique* on the path. The shortest and strategic paths at Area level are shown in figure 11 by the thin line (they are connected between the *gateway* centers). A traced path is represented by a set of points. The start and the goal point are allocated a *checkpoint* each and the *checkpoints* are linearly distributed *at* a fixed length (*checkpoint length* 1m) and the total *hit probability* is computed over these *checkpoints* using the *checkpoint* technique as explained in section 5.7.

5.7.3 Comparison between Checkpoint techniques applied for Meta-Weight computation and Risk Evaluation of a traced path

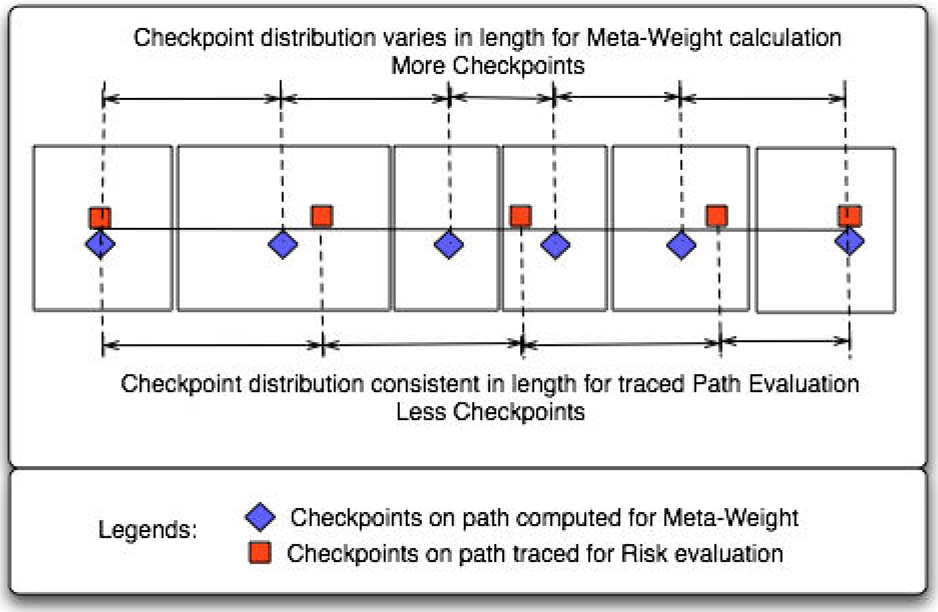


Figure 12: For paths traced the checkpoint count can be less

As shown in figure 12, It can be observed that the number of *checkpoints* computed during meta-weight computation for the same path will always be more (or equal) than the number of *checkpoints* computed in evaluating the risk on the path traced, because in the case of the meta-weight calculation the *checkpoint* distribution is restarted for each pair of areas. And when the *checkpoint* length is reduced, the correspondence between the total hit probability across the area centers of the chosen Areas and the total hit probability across the computed strategic path increases.

5.8 Visibility Constraints

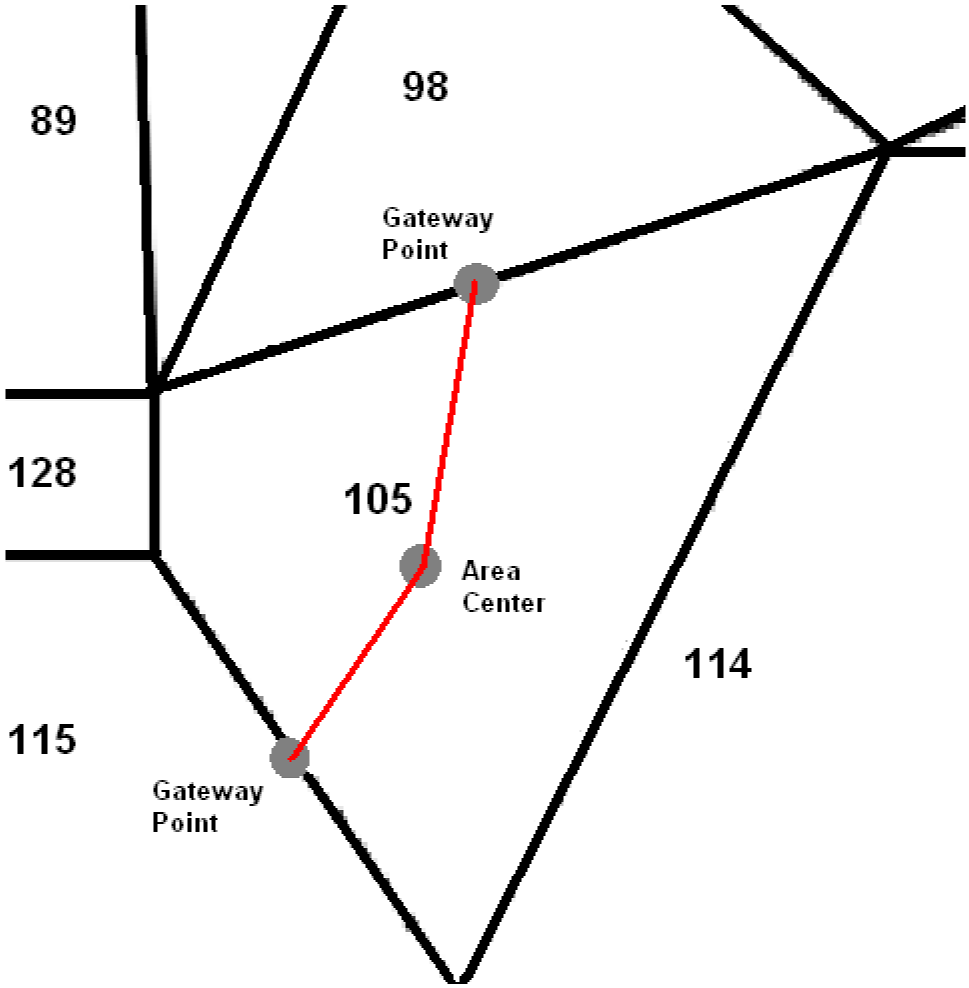


Figure 13: The strategic path at Area level for Area-105

The strategic path computation at the Area level does not consider visibility information within Areas at a great detail. In figure 13, Area-105 is considered on the basis of *checkpoints* over the line segment joining its center and the *Gateway* point. Here, we constrain the visibility considerations for the sake of reasoning that nobody can accurately predict the visibility information within an Area at a very high degree without reaching it. Thus, it adds to efficiency in the path calculations when an Area is considered at this abstraction, rather than reasoning about all the points within an Area.

5.9 Risk vs. Time Preference Factor

Risk is attributed to the probability of being hit. In order to succeed on a mission the agent must maintain a minimum health and minimize any health damage. This can be done by taking a route that keeps the agent hidden from most of the threats on the map. But not all the paths are threat free.

As per mission objectives the agent may want to reach a goal location as soon as possible. For that the agent must take the shortest route towards the goal. But the shortest route may contain threats. Thus, the agent must make a trade-off in selecting a path that can minimize risks and time. Depending upon the mission objectives the preference for the shortest route compared to preference for safety may vary. Thus, in order to maintain a good balance between the safest path and the shortest path the agent must define its risk vs. time preference factor. A high value will prioritize safety and a low value will prioritize time of traversal. For a higher the *RiskVsTime* factor the strategic path computation would tend towards more safety thereby decreasing the Output Hit Probability over the computed strategic path with a trade-off of a longer route to the goal.

It can also be seen when *RiskVsTime* factor is 0 or when there is no enemy the strategic path becomes the shortest path.

5.10 Meta-Weight Calculation

$$\text{Meta-Weight} = (HP * RiskVsTime + 1)$$

After determining the risk vs. time preference and the hit probability on the connecting distance across the neighboring *areas*, we can compute a meta-weight. This meta-weight represents a penalizing factor meant to symbolize the extra cost for being exposed to enemies.

In the formula an exposed area with the *hit probability* = 1 will be penalized linearly by the *RiskVsTime* factor. So, the *RiskVsTime* = 1 factor will double the cost of traversal over that area, whereas the *RiskVsTime* = 0 factor will keep the cost of traversal over that area unaffected, thus any exposure will not affect any decision making.

5.11 Modification to the existing Weights

*Weight = Meta-Weight * Euclidean Distance*

The Euclidean distance is the distance between the centers of the areas passing through the connecting *gateway*. Thus, all the *weights* are penalized for being exposed to the enemies.

5.12 Use of Shortest Path Algorithm

These meta-weights are multiplied to the Euclidean distances between the connected areas. The computed weights are stored in an adjacency matrix. We use *Dijkstra's* single-pair-shortest-path algorithm, because the computational complexity of the algorithm is $O(n^2)$.

Strategic path planning can also be done by using the *Floyd-Warshall* algorithm which has the computation cost of $O(n^3)$. The main benefit for using the *Floyd-Warshall* algorithm is that for further path planning the re-computation of the strategic path will not be required for other pairs of areas as long as the enemy stays in the same location.

5.13 Strategic Path Calculation

The *Shortest-Path* algorithm is run on the above discussed computed weight and path matrices. For each pair of areas we retrieve path information. The obtained path is the strategic path, it balances the risk and the time as per mission requirements.

The algorithm 3 computes the strategic path at Area level. For each pair of areas it computes the *hit probability* over the path joining their area centers through the gateway center of their connecting gateway by using the *checkpoint technique* meant for computing *Meta-Weights* (refer section 5.7.1). And then based upon the *RiskVsTime* determined by the preference for the safety and then from the *hit probability* and *RiskVsTime* factor compute the *Meta-Weight.* Then compute the product of the *Meta-Weight* and the *Euclidean distance* as the weight of an edge. Compute all weights of the edges and use the shortest path algorithm to compute the strategic path.

Algorithm 3: Strategic Path Planning at Area level Algorithm

INPUT: The static and the dynamic percepts.

OUTPUT: A set of Areas.

SYNOPSIS: Compute HP for each area pair and compute the Meta-Weight. And for each edge take the product of Meta-Weight and the Euclidean distance between their area centers (going through their gateway center). The shortest path on this modified graph is the strategic path.

ALGORITHM:

1: Compute the *HP* from linearly distributed *checkpoints* across each pair of the *areas.*

1.1: Optimize the total number of visibility tests by using *Heuristic search space.*

1.2: By application of *LOS algorithm* compute visible *checkpoints* over the above pair of *areas* from all the enemies.

2: Determine *RISK_VS_TIME* and then compute *Meta Weight* for each visible enemy as:

*MW = HP * RISK_VS_TIME + 1*

3: Compute Weights of the *Weight Matrix*:

*W = MW * Euclidean_Distance_between_areas*

Here *MW* is 1 for completely hidden *areas.*

4: Apply *Shortest Path Algorithm*

5: Return the shortest path, which is a list of the selected Areas along the strategic path.

CHAPTER SIX

STRATEGIC PATH COMPUTATION AT GRID LEVEL

6.0 Overview

After the strategic path at the Area level is computed, the strategic path at the Grid level (higher level of detail) is computed for each selected Area while traversing the selected Areas computed by the strategic path at Area level. As shown in figure 12 a selected Area is further divided using a grid formation (a rectangle of *grid unit length*). Here a bigger *grid unit length* means more detail and more computational cost. This computation gives the within-area *Grid Points* to walk through for each selected area. Thus, it takes into consideration any enemy movement. A selected area is sub-divided using a Grid Formation, and a strategic path is computed over the *grid points*. This technique is applied over all the chosen areas and it gives the strategic path at Grid level.

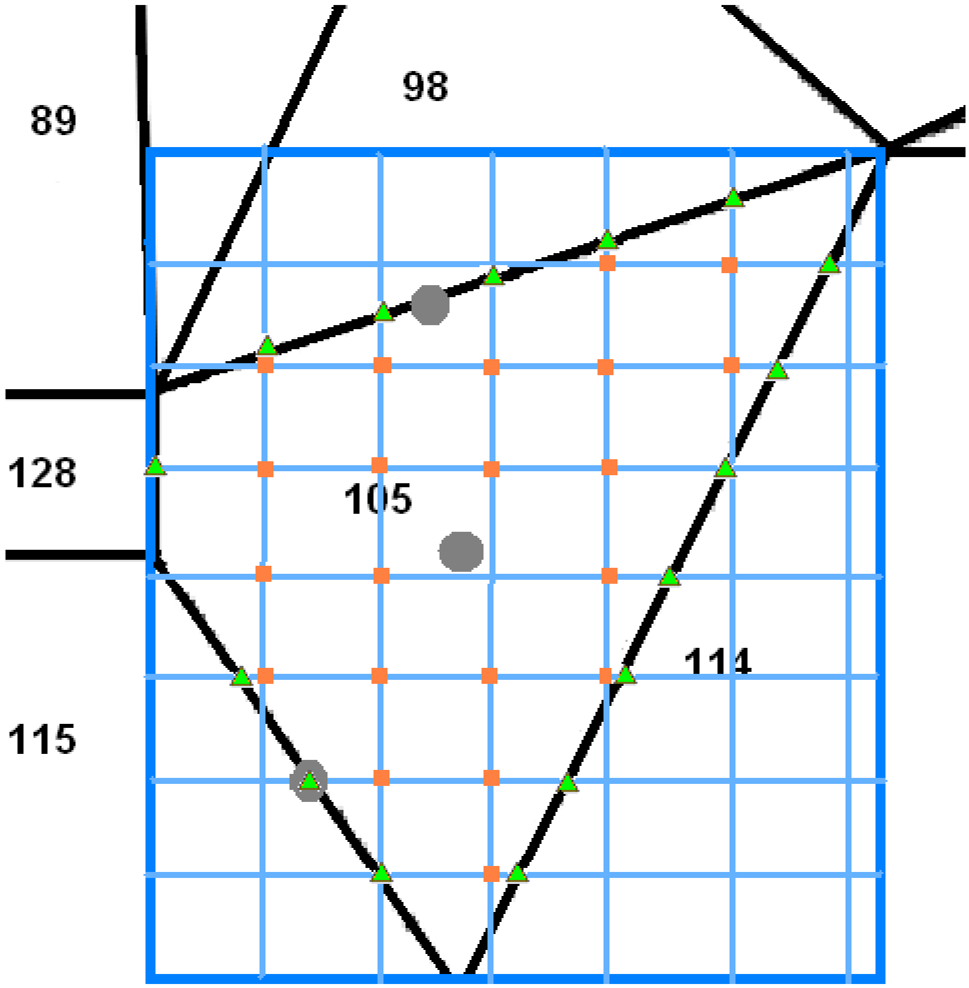


Figure 14: The strategic path at Grid level for Area-105

In figure 14, the strategic path at Grid level is computed for Area-105. The process involves computing first *gateway points* on the gateways shown as triangular Green points and then *grid points* inside the Area shown as square Orange points. Then the strategic path computation selects the appropriate Green and Orange points as per the strategic requirements for traversal.

6.1 Grid Point Calculation on the Gateway Side

The Areas selected to be on the strategic path are connected using *Gateways*. *Gateways* are rectangles in 3D extended between 4 points shared by two polyhedral Areas. A *gateway* on the

Gateway side is computed using the below discussed algorithm. The selected *Gateway Points* on the *Gateway* sides define the start and the end points of the strategic path at the *Grid level* for the selected Area.

The algorithm 4 computes the next *gateway point* by using the previously computed *gateway points***.** It uses the same strategic path methodology to penalize the distance from the goal and the previous *gateway point.* This way it prioritize the safety as per as *RiskVsTime* factor and also shortens the distance from the goal.

Algorithm 4: Gateway Point computation on the Gateways

INPUT: Area ID of two selected neighbor Areas, the saved *gateway point* of the previous area, the static and the dynamic percepts.

OUTPUT: A *gateway point.*

SYNOPSIS: This algorithm computes the next *gateway* by using distance from the goal and the previous area center. It uses the same strategic path methodology, thus the *gateway* point computed incorporates risk and tends to shorten the distance from the goal (of the strategic path at Grid level).

ALGORITHM:

1**:** From all the points of the obtained *Gateway* between the given two Areas find the lowest two points in Z-axis.

2: Divide the line segment joining the computed two points into a set of *gateway points* (*grid unit length*).

3: Between the second and the second-to-last *gateway points*.

Compute for each *gateway point*

$MW = HP * RISK\_VS\_TIME + 1$

$Weight = MW * (ED_{goal} + ED_{prev\text{-}gateway\_point})$

Where *HP* is the hit probability of the *gateway point*.

Where ED_{goal} is the Euclidean distance from the goal.

Where $ED_{prev\text{-}gateway\_point}$ is the Euclidean distance from the selected *gateway point* of the previous *Gateway* between the previous pair of two Areas on the same path.

4: Find the *gateway point* with the least *weight* among all the *gateway points* considered above and return the coordinates of the selected *gateway point.*

6.2 Grid Point Calculation inside the Selected Area

The strategic path at the Grid level produces a set of *grid points* that an agent can walk over to traverse an area. These points are expected to meet strategic requirements of the agent. From the above discussed algorithm a *grid point* is computed on the next gateway. Now, in between the current point and the next *gateway* point over the bounded Area, a set of *grid points* are computed by using the algorithm discussed below. This computation is done only when the agent reaches the selected Area. Thus, the strategic path computation over the Area level gets a list of selected Areas, and later while walking over these selected Areas, in accordance with the enemy's dynamic behavior, appropriate *grid points* are computed. As shown in algorithm 5.

The algorithm 5 computes the *grid points* inside an area. It takes two *gateway points* (computed using *algorithm 4*) and it does the risk analysis inside an area at a great detail with respect to any enemy's current location and generates the strategic path at Grid level.

Algorithm 5: Grid Point computation inside an Area

INPUT: An Area and the two *gateway points*, the static and the dynamic percepts.

OUTPUT: A list of *grid points*.

SYNOPSIS: This algorithm computes the strategic path at Grid level by using the computed *gateway points* and the complete risk information for all the grid points (by applying grid formation on the area). Then using the same strategic path methodology of penalizing the exposed edges, it generates the modified graph and by applying the shortest path algorithm a set of *grid points* are generated to represent the strategic path at Grid level.

ALGORITHM:

1: Find the ground face (the lowest *Z-axis*) and then find $(X_{min}, Y_{min}, Z_{min})$ and $(X_{max}, Y_{max}, Z_{max})$ of that face. And also find which normal's component *(X or Y-axis)* varies the most with *Z-axis*.

2: Store the sequence information of all the valid *grid points* that exists inside the given Area by stepping through the computed $(X_{min}, Y_{min}, Z_{min})$ and $(X_{max}, Y_{max}, Z_{max})$ in an optimized way inside a 2D integer array by:

2.1: Inside a rectangle formed by (X_{min}, Y_{min}) and (X_{max}, Y_{max})

2.2: For Y_{middle} between Y_{min} to Y_{max} iterate

2.3: Search for X_{start} by iterating between X_{min} to X_{max}

Such that (X_{start}, Y_{middle}) is inside the Area.

2.4: Search for X_{end} by iterating between X_{max} to X_{min}

Such that (X_{end}, Y_{middle}) is inside the Area.

2.5: For X_{middle} between X_{start} to X_{end}

2.6 Store (X_{middle}, Y_{middle}) as a valid *grid point*.

3: Formulate a graph where *grid points* are the vertices and their connection among their neighbors are the edges. Each *grid point* is connected with 8 neighbors (the nearest vertical, horizontal and diagonal neighbors). The connection between two *grid points* is computed as

$$MW_{Grid} = HP_{Grid} * RISK\_VS\_TIME + 1$$

$$Weight_{AB} = ED_{AB} * MW_{Grid}$$

Where HP_{Grid} is the hit probability across the two *grid points*. Computed as $HP_{Grid} = HP_A + HP_B * (1 - HP_A)$ where *A* and *B* are the two *grid points*.

4: Associate the two end points to the *grid point* graph.

4.1: Find the closest *grid point* from each of the end points.

4.2: Add both the end points to the *grid point* graph as another two vertices connected with the grid points computed from step 4.1 with weights computed using step 3.

5: Now use Shortest Path algorithm *(Dijkstra's algorithm)* to find the least-weight path between the two end points.

6: Along with the connected *grid points*, the two *gateway points* are also connected with $Weight_{Gateways}$ as its weight.

$$MW_{Gateways} = HP_{Gateways} * RISK\_VS\_TIME + 1$$

$$Weight_{Gateways} = ED_{Gateways} * MW_{Gateways}$$

Where $HP_{Gateways}$ is the hit probability across the two selected *gateway points* computed using *checkpoint technique* with *checkpoint length* as the *grid unit length.*

Where $ED_{Gateways}$ is the Euclidian Distance between the two selected *gateway points* computed using *checkpoint technique*.

7: Compute *grid point* coordinates of the *selected grid* points on the least cost path using slope information computed using step 1 and cache the processed path information with respect to the current enemy location for optimal future use.

The alternative connection between the two *gateway points* apart from the connection over the selected *grid points* addresses two important cases. For the case, when there is no grid point allocated to the Area and also for the case, when the Area is completely unexposed to any of the enemies. The direct connection between the *gateway points* guaranties the shortest route fairly computed with the alternative route through the selected *grid points.*

6.3 Risk calculation over the complete strategic path at Grid level

In the case of the strategic path calculation at Grid level. The path is tracked over the selected *grid points* and *gateway points* computed for the chosen Areas computed by the strategic path at Area level. This path can be evaluated for risk by using checkpoint technique between the start and the end point through the selected *grid points* and *gateway points*.

CHAPTER SEVEN

EXPERIMENTATION AND VALIDATION

7.0 Overview

This chapter discusses our experiments and their results of out-game and in-game trials. Section 7.1 discusses our experimental setups. Section 7.2 discusses one of the experiments with the plots of the chosen strategic paths. Section 7.3 discusses variations in hit probability for different weapons for out-game trials. Section 7.4 discusses an experiment with 50 runs of different start area, end area and an enemy area with *RiskVsTime* = 10 and *checkpoint length* = 1 m for out-game trials. Section 7.5 addresses the *hit probability* variation between the Meta-Weight computation and the traced path evaluation of the *checkpoint technique*. Section 7.6 discusses how the distances of the traced paths vary with RiskVsTime factor for the out-game trials. Sections 7.7 to 7.9 discuss our in-game trial results. Section 7.10 discusses the in-game trial results of the agent with shooting skills. Section 7.11 addresses some underlying assumptions and discusses some observations.

7.1 Out-Game and In-Game experimental setup

We performed the Out-Game trials using the realistic weapon details [5]. By using the *checkpoint technique* (refer section 5.7.2), we computed the *hit probability* of the generated strategic paths. The In-Game trials were done on the UCT (a modification of Quake3). We ran 10 experiments and we took the average. For example in an experiment where the agent got hit 4 times and successfully reached without getting a hit 6 times had the *hit probability* of 0.4. We performed the *in-game trials* to test the accuracy of the *out-game* computation.

7.1.1 Out-Game Trial Setup

Using the realistic weapon details [5], we used the *checkpoint* technique to evaluate the risk factor involved to traverse the computed path. We modelled the three types of weapons (an assault rifle, a sub-machine gun and a sniper rifle) and based upon the target distance, a hit probability is computed. This computation is done over the set of checkpoints. In this process the checkpoint distribution starts from the start location and ends at the goal location and between these two points these *checkpoints* are linearly distributed using the *checkpoint* length.

7.1.2 In-Game Trial Setup

A scenario with a start location, a goal location and an enemy location were defined as an experiment set. We ran 50 such experiments for the shortest path, the strategic path at Area level and the strategic path at Grid level. And for each experiment we ran the same trial 10 times and we computed the average *HP* for each of the three paths. The UCT is a modification of Quake3. It does contain an implementation of realistic physics calculation up to a certain degree. Thus, the gunshots were expected to have some realistic variations analogous to the real world. For the above experiments we controlled an enemy bot and programmed it to shoot the agent. We programmed the agent to walk between the start and the goal location along the computed strategic path (using the shared memory access between the agent and the game).

Along the path of traversal the enemy bot tried to aim and shoot the agent, and for that the enemy bot was given a very large count of ammunition (virtually infinite). We considered a hit as a failure and moving from the start location to the goal location without getting any hit as a success.

The in-game trials were based on the available shooting mechanism of the Quake3 game engine (its simulated physics and its implementation of real world variations). The enemy bot was controlled using the same shared memory mechanism (as of agent). Thus, the shooting accuracy suffered many implementation level constraints like the *yaw* (bot's angle on horizontal plane) alignment where the bot is turned left/right until it reaches a desired threshold. The weapon model we used to compute the *Meta-Weights* (the assault rifle) was different than the existing shooting mechanism of the Quake3 game engine and therefore any variation among them has a direct impact on the above in-game trials. The impact is subjective to how consistently and accurately it matches the real-world weapon models, if the Quake3 engine exhibits a poor range for a long range weapon then the strategic paths will meaninglessly take longer distances and for other-way round situations the computed strategic paths will be more risky than the computed risk values.

7.2 Experimental Results

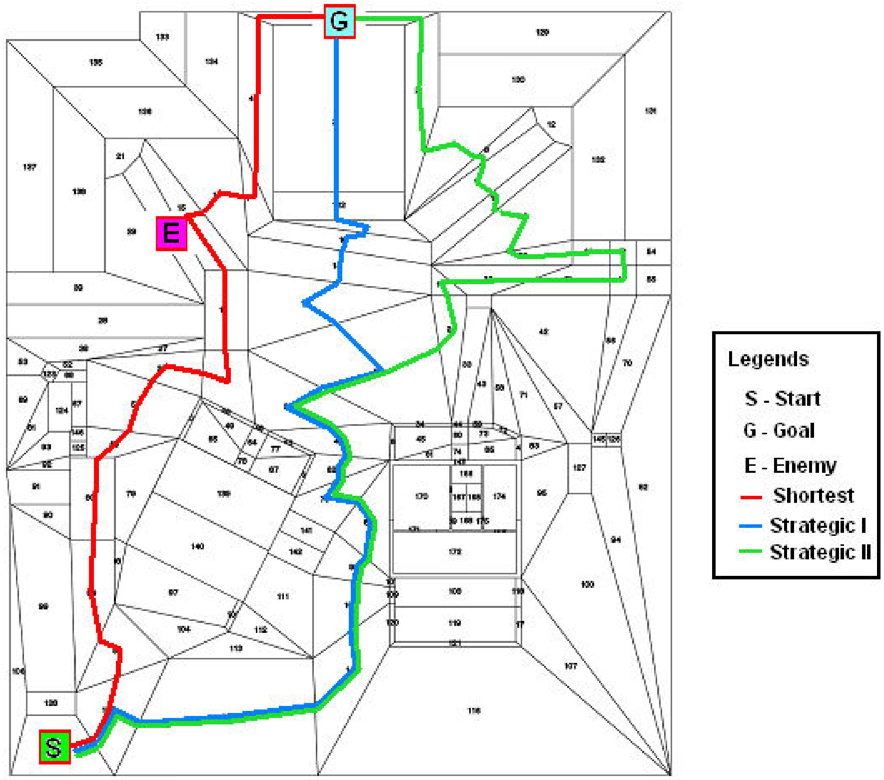
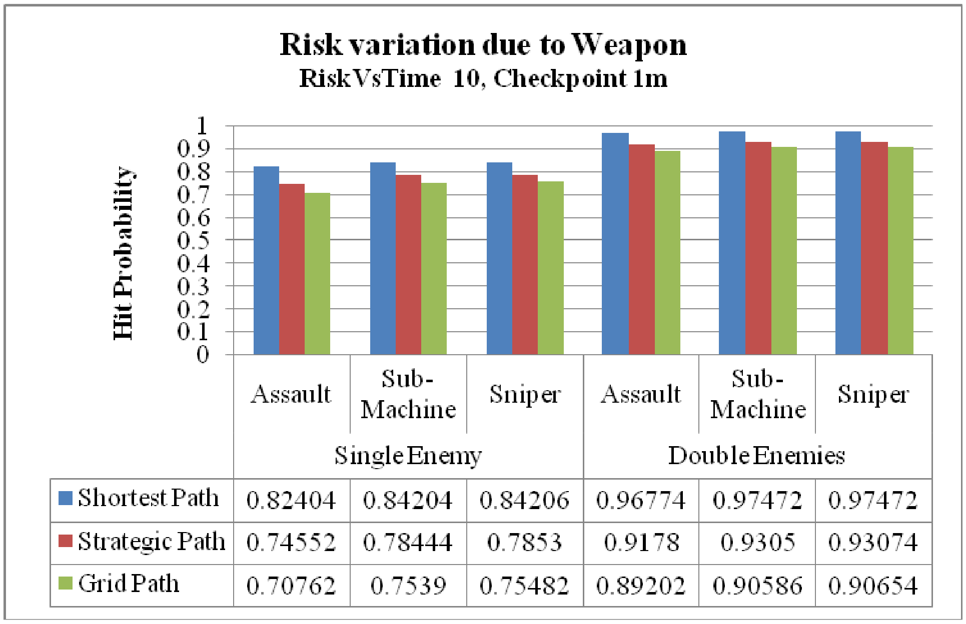


Figure 15: Strategic Path completely avoided the enemy

As shown figure 15 the start area is Area-115, the goal area is Area-1 and the enemy is in Area-15. The shortest path goes very close to an enemy, and therefore the total hit probability on that path is very high. On the other hand, the computed strategic paths minimize the risks. The strategic path I was computed using RiskVsTime factor = 2 and strategic path II was computed with RiskVsTime factor =10. Thus, based upon the time priority according to mission objectives the mission critical strategic path can be computed.

7.3 Risk variation due to variation in weapon

The hypothesis for this experiment was that the *out-game trials* will show the increase in the average *hit-probability* with the increase in the lethality of the considered weapon. And also the *out-game trials* will show the increase in the average *hit-probability* for all the three considered weapons with the increase in the count of enemies.



	Single Enemy			Double Enemies		
	Assault	Sub-Machine	Sniper	Assault	Sub-Machine	Sniper
Shortest Path	0.82404	0.84204	0.84206	0.96774	0.97472	0.97472
Strategic Path	0.74552	0.78444	0.7853	0.9178	0.9305	0.93074
Grid Path	0.70762	0.7539	0.75482	0.89202	0.90586	0.90654

Figure 16: Plots of variations in Avg. Output Hit Probabilities with different weapons

The figure 16 shows the average output hit probabilities due to different weapons. As discussed in chapter 5.6, the Assault Rifle has the lowest lethality in terms of hit accuracy. Thus, the average output hit probability computed is less than the other two considered weapons. For the case of two enemies, a significant portion of the map becomes risky, resulting in a higher average output hit probability. And we can also see the grid paths were consistently safer than strategic paths and shortest paths for all types of weapons.

The hypothesis for this experiment was confirmed. We found with the increase in the lethality of the considered weapon the average *hit probability* increased. And also found that with the increase in the number of enemy count the average *hit probability* increased. The hypothesis for this experiment tested the accuracy of the *out-game trial*.

7.4 Shortest Path vs. Strategic Paths at Area vs. Strategic Path at Grid level

The hypothesis of this experiment was that the difference between the shortest paths and the strategic paths is statistically significant.

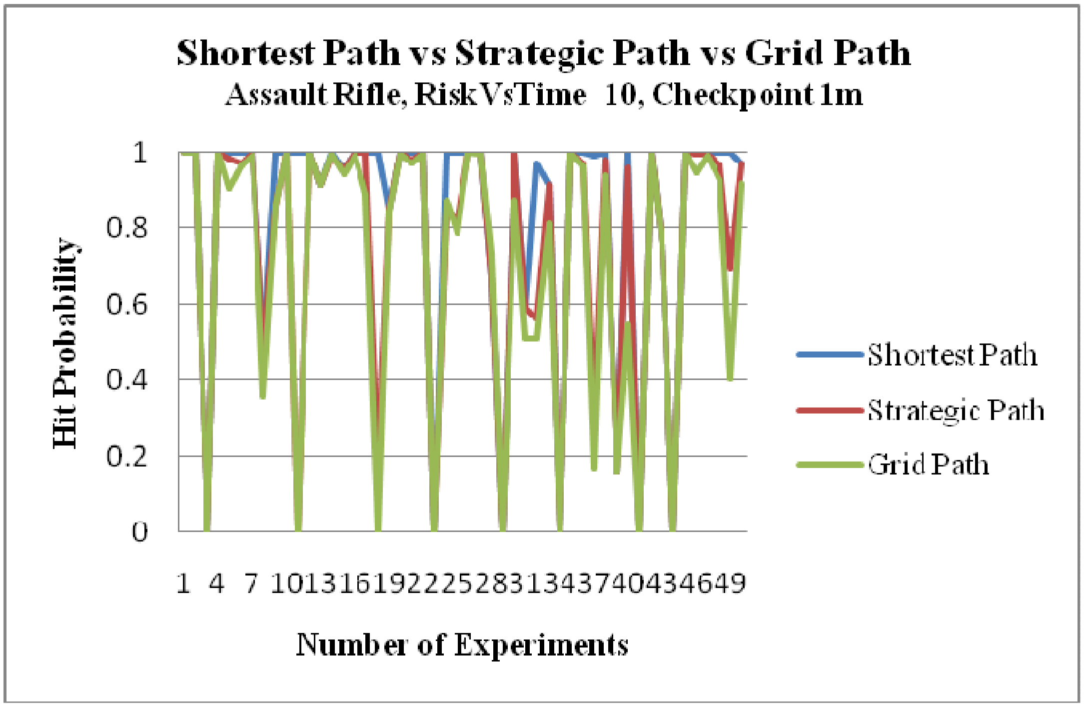


Figure 17: Plots of Hit Probabilities for one enemy situation with RISK_VS_TIME = 10

In figure 17, we computed the strategic path for 50 random experiments for situations with one enemy. In these experiments a start area, an enemy area and a goal area were randomly selected from available open areas. And the strategic paths were computed for *RiskVsTime* = 10 for a single enemy with an assault rifle. We found strategic paths computed were consistently safer than the shortest paths. We compared the shortest path and the strategic path at Area level (refer chapter 5) using a t-test and found that the difference in path safety was statistically significant at the p=0.0056 level and between the shortest path and the strategic path at Grid level (refer chapter 5) the difference in path safety was statistically significant at the p= 0.00076 level. Between strategic paths at Area level (see chapter 5) and Grid level (see chapter 6) we found the difference in path safety was statistically significant at the p=0.00085 level. This confirms the claim when seen in abstraction an Area gives a rough estimation about its safety and when that Area is reached and when the Grid Path is computed for that Area then it can be consistently traversed with same or lesser risk.

We can expect anomalies where the shortest path can be evaluated as less costly (i.e., safer) than the strategic paths. This is because for Meta-Weight computation, more *checkpoints* are distributed along the Areas and when the strategic path is obtained along the same set of Areas it contains lesser *checkpoints*. During safety evaluation if a portion of a computed strategic path is exposed and on the other hand if the shortest path gets lesser *checkpoints* exposed due to variation in *checkpoint* distribution along the exposed areas then this could result into a situation where a strategic path could get evaluated to have a higher hit probability compared to the shortest path.

The hypothesis for this experiment was confirmed. We also found the difference between the strategic path at Area level and the strategic path at Grid level was also statistically significant.

7.5 HP variation between Meta-Weight computation and Path traced evaluation

The hypothesis of this experiment was with the increase of the *RiskVsTime* factor the generated strategic paths will become safer and also with the decrease in the checkpoint length the difference between *hit probabilities* computed by the *checkpoint technique* for *Meta-Weight computation* and *risk evaluation* of the traced path will decrease.

The *checkpoint technique* computes the *Hit Probability* between the Area centers of each of the neighboring Areas for *Meta-Weight* computation. Both the Area centers get one *checkpoint* each and checkpoints are linearly distributed along the path joining the two Area centers through the *gateway center*. The number of *checkpoints* distributed using this technique is always more than the number of checkpoints distributed across the start and the goal point for the strategic paths.

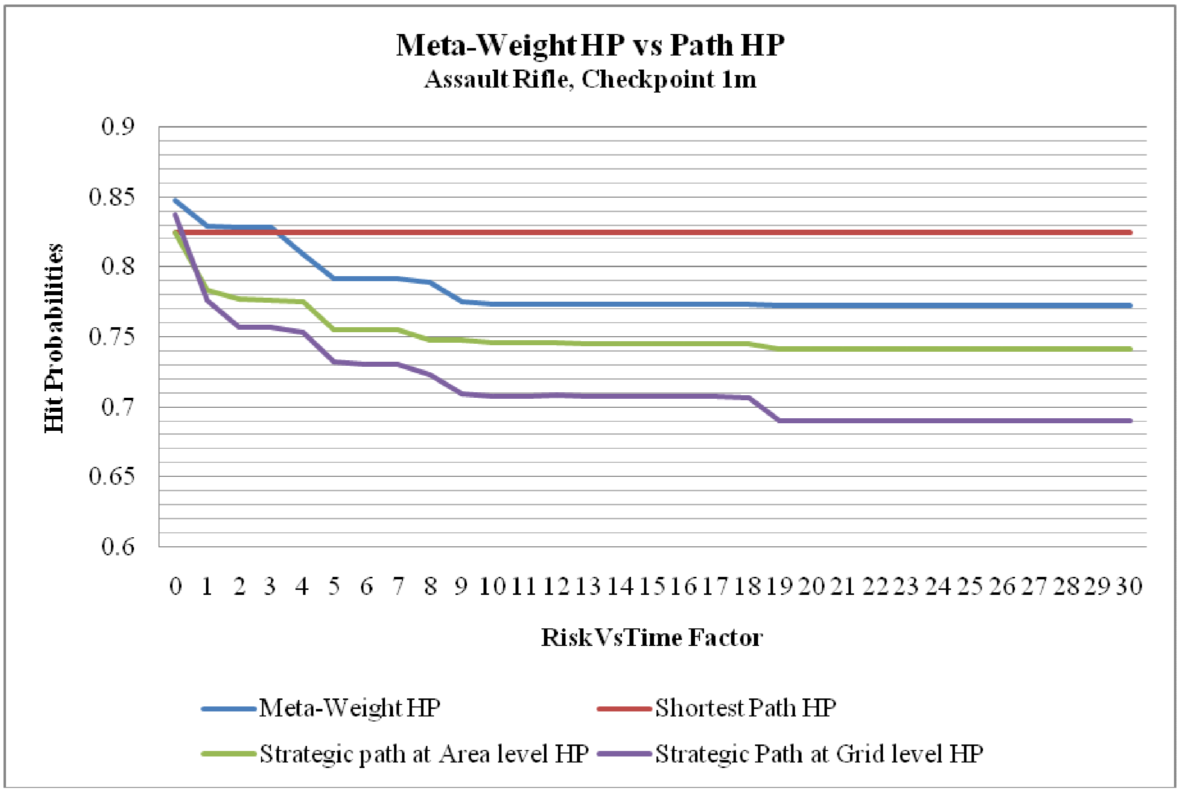


Figure 18: HP variation between Meta-Weight computation and Path's risk evaluation for 1m checkpoint

In figure 18, the relation between Meta-Weight HP and computed Paths has been plotted with respect to RiskVsTime factor. As RiskVsTime factor increases the hit probability (HP) decreases and thereby the computed path becomes safer. And it can be seen that Grid Paths are consistently safer compared to other paths. The RiskVsTime factor has no-effect on the shortest path.

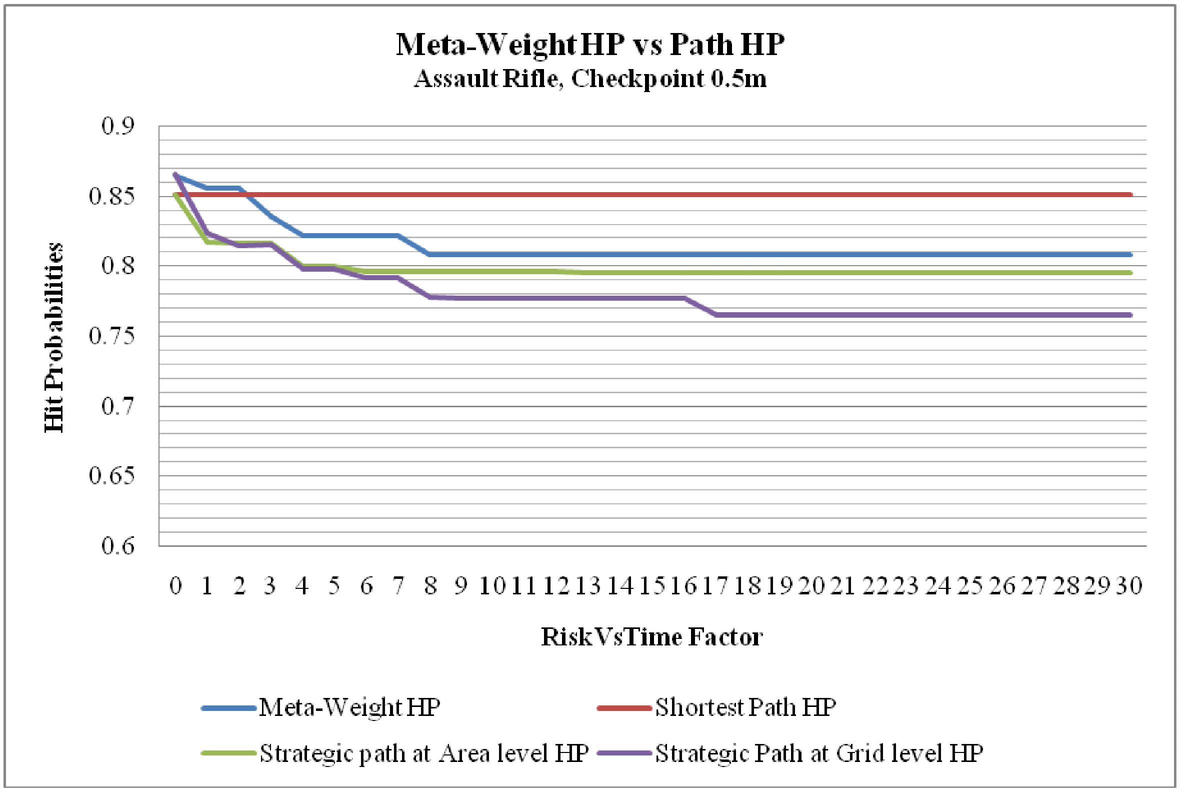


Figure 19: HP variation between Meta-Weight computation and Path's risk evaluation for 0.5 checkpoint

In figures 18 and 19, when checkpoints are of smaller lengths the difference between *HP* for Meta-Weight and Path's risk evaluation significantly reduces and they tend to approach higher values compared to shorter checkpoint lengths.

The hypothesis of this experiment was confirmed. We found with the increase of *RiskVsTime* factor the generated strategic paths were safer and also with the decrease in the *checkpoint length* the difference between the *hit probabilities* computed by the *checkpoint technique* for *Meta-Weights* and *risk evaluation of the traced path* decreased. And we also found the overall *hit probabilities* for all the *traced paths* and for the *Meta-Weight* computation increased with the decrease in the *checkpoint length*.

7.6 Distance variation between shortest, strategic paths at Area and Grid level

The hypothesis of this experiment was with the increase in the *RiskVsTime* factor the distance of traversal will increase.

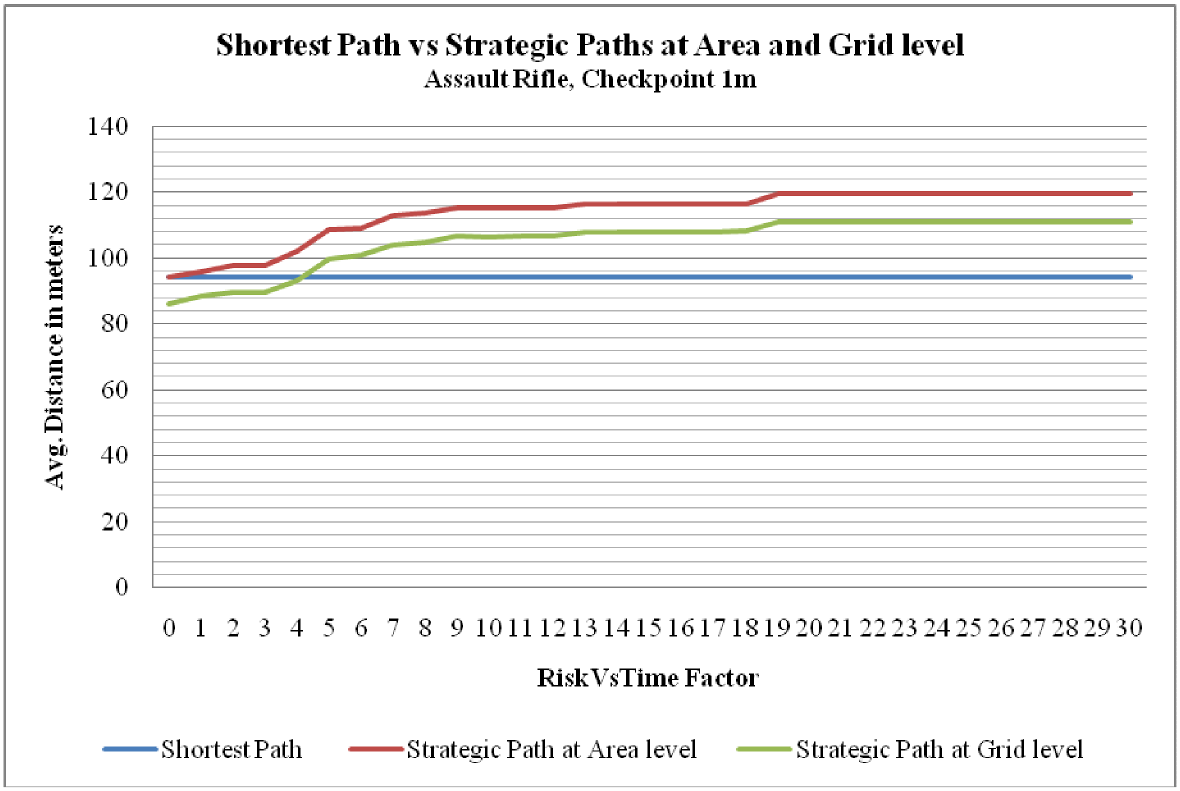


Figure 20: Avg. distance of shortest paths, strategic paths over Area and Grid level

In figure 20, for out-game trials as the *RiskVsTime* factor increases the strategic paths become safer at a cost of longer distances. The strategic path computation selects the shortest penalized path and in this process it tends to minimize both the risk and the distance of traversal. In the case of the strategic path at Area level the distance is the shortest distance between the *gateway points* lying at the centers of *Gateways*. And in the case of the strategic path at Grid level, these *gateway points* tend toward the goal Area and strive to remain smooth over the irregular Areas (using a similar A* technique). As a result the distance is further minimized.

The hypothesis of this experiment was confirmed. We also found the strategic path at Grid level was shorter than the strategic path at Area level.

7.7 In-Game trials for Shortest vs. Strategic vs. Grid paths for RiskVsTime = 5

The hypothesis of this experiment was the difference between the shortest paths and the strategic paths is statistically significant.

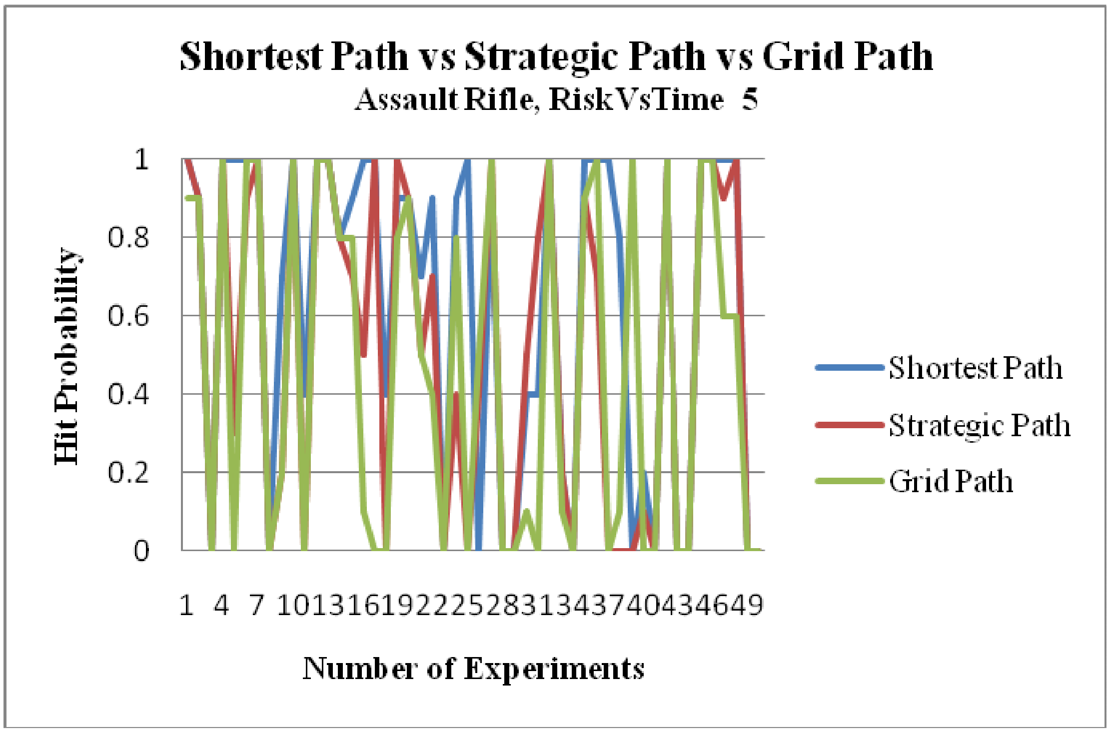


Figure 21: In-Game trial experiment results for RiskVsTime=5

The figure 21 shows results of the in-game trials. We performed the same set of experiments in the UCT. An enemy bot was programmed to shoot the agent (controlled by the shared memory access), and the agent was programmed to walk over the shortest path and the strategic paths at Area and Grid levels. In the above experiments we faced many programming challenges in keeping the agent out of the close objects. For preventing any unexpected collision with close objects we used the HSS technique to determine the set of objects associated with the HSS element representing the current Area, and we programmed the agent to walk along the close objects and walls by maintaining a small distance. We found that there were very few random occasions (1 in 500) when the agent or the enemy bot got stuck and could not recover. We marked those experiments as undecided.

For RiskVsTime = 5, we ran the same set of 50 experiments and compared the shortest path and the strategic path at Area level (refer chapter 5) using a t-test and found that the difference in path safety was statistically significant at the p= 0.0024 level for the in-game trials. Between the shortest path and the strategic path at Grid level (refer chapter 5) the difference in path safety was statistically significant at the p= 0.0013 level for the in-game trials. Between strategic paths at Area level (see chapter 5) and Grid level (see chapter 6) we found the difference in path safety was not statistically significant at the p= 0.119 level for the in-game trials.

The hypothesis of this experiment was confirmed. We also found the difference between the strategic path at Grid level and the strategic path at Area level was also statistically significant.

7.8 In-Game trials for Shortest vs. Strategic vs. Grid paths for RiskVsTime = 10

The hypothesis of this experiment was the difference between the shortest paths and the strategic paths is statistically significant.

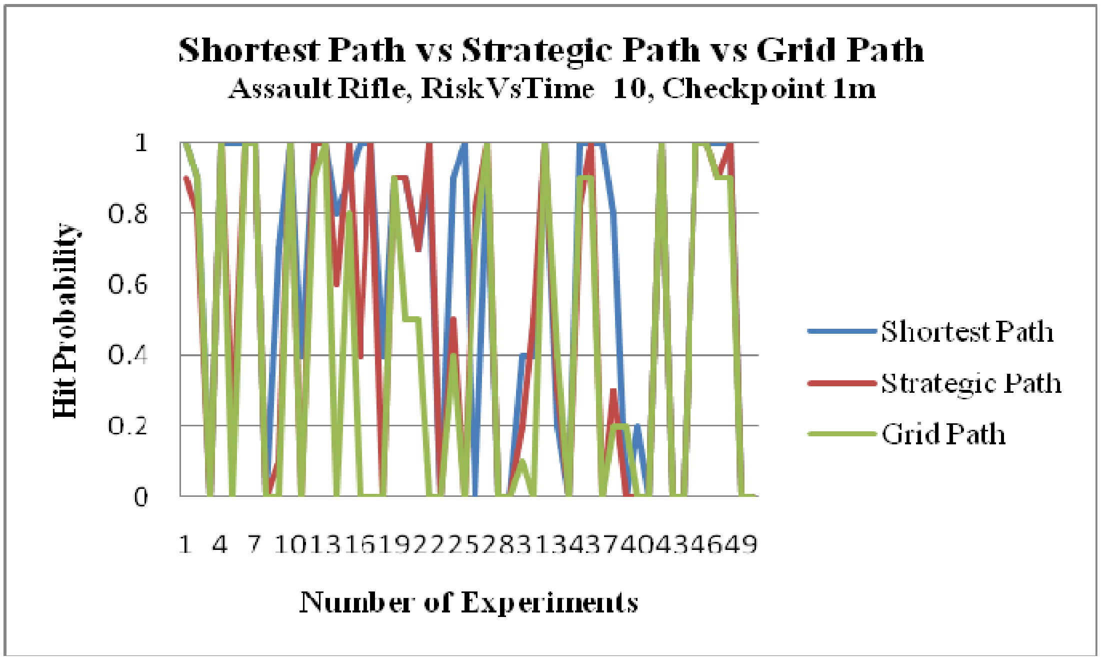


Figure 22: In-Game trial experiment results for RiskVsTime=10

As shown in figure 22, for RiskVsTime = 10 we ran the same set of 50 experiments and compared the shortest path and the strategic path at Area level (refer chapter 5) using a t-test and found that the difference in path safety was statistically significant at the p=0.006 level for the in-game trials. Between the shortest path and the strategic path at Grid level (refer chapter 5) the difference in path safety was statistically significant at the p=0.0001 level for the in-game trials. Between strategic paths at Area level (see chapter 5) and Grid level (see chapter 6) we found the difference in path safety was not statistically significant at the p=0.0036 level for the in-game trials.

During the in-game trials the shooting accuracy is based upon the angling calculations (weapon and the target), and the movement accuracy is based upon the bounding box [19] calculations (between objects and the agent). The movement computation tries to minimize any collision with the walls and the objects. Thus, the *in-game trials* contain many details where any technical inaccuracy could have a negative impact on the results. On the other hand for the case of *out-game trials* these game details are abstracted and do not adversely affect the analysis.

The hypothesis of this experiment was confirmed. We also found the difference between the strategic path at Grid level and the strategic path at Area level was also statistically significant. The importance of the *in-game trials* was to check the accuracy of the *strategic path computation model* and we found the model was consistent with the *in-game trials*.

7.9 In-Game trial analysis

We can see the strategic paths were consistently safer than the shortest path in analogy with out-game trials.

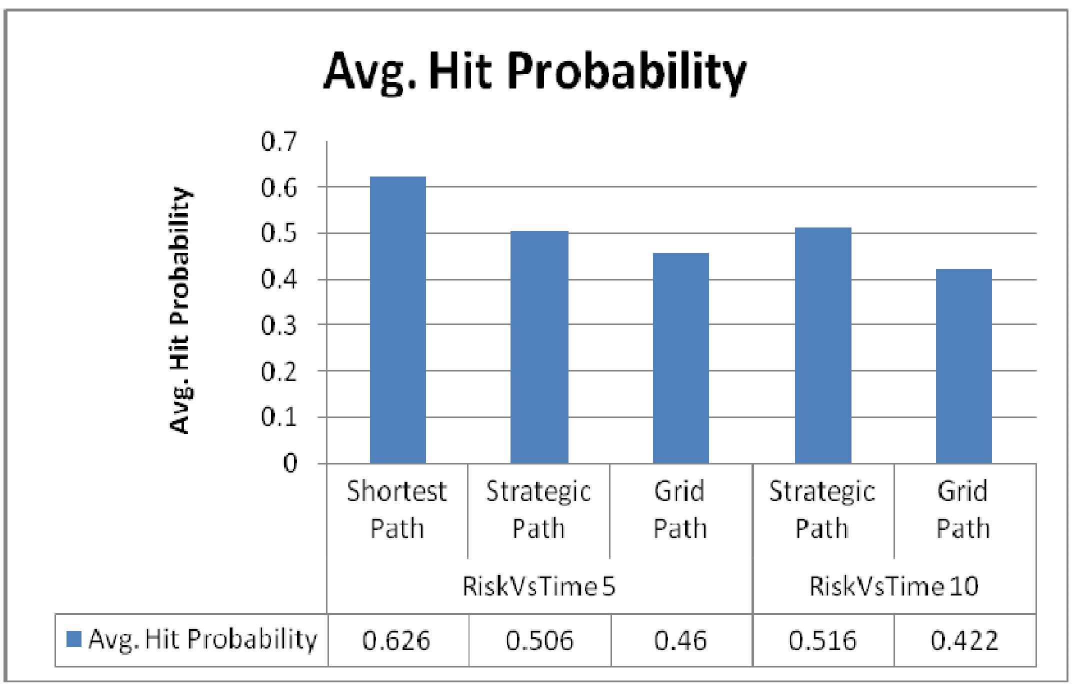


Figure 23: The average hit probability for the in-game trials

We can see in figure 23 that the Strategic Path at Grid level had the lowest *hit probability* for both the *RiskVsTime* factors. We also see when *RiskVsTime* factor increased from 5 to 10 the *hit probability* for Strategic Path at Grid level decreased from 0.46 to 0.422 in analogy to *out-game* trials. The average *hit probability* for Strategic Path at Area level increased when *RiskVsTime* increased from 5 to 10. We further analysed the above experiments and we learned that there were 6 cases where the paths (a set of Areas) suggested by *RiskVsTime* 10 was different from the paths suggested by *RiskVsTime* 5 and in these paths we found the path computed by *RiskVsTime* 10 were safer. The left 44 paths were the same for both *RiskVsTime* factors and we found the paths computed by *RiskVsTime* 10 suffered more hits compared to paths suggested by *RiskVsTime* 5. The Quake3 engine tries to follow the real-world variation through their projectile and simulated physics implementation and in above situation we can see for the same 44 runs the agent suffered a little variation as per their variation implementation.

We also see even though the Grid paths were consistently of shorter length than the Strategic paths (refer figure 19), we found that on the Grid paths the agent spent more time than the corresponding longer Strategic paths (as shown in figure 23). In figure 23, failed paths (where the agent could not reach the goal area) have been considered to take 0 seconds.

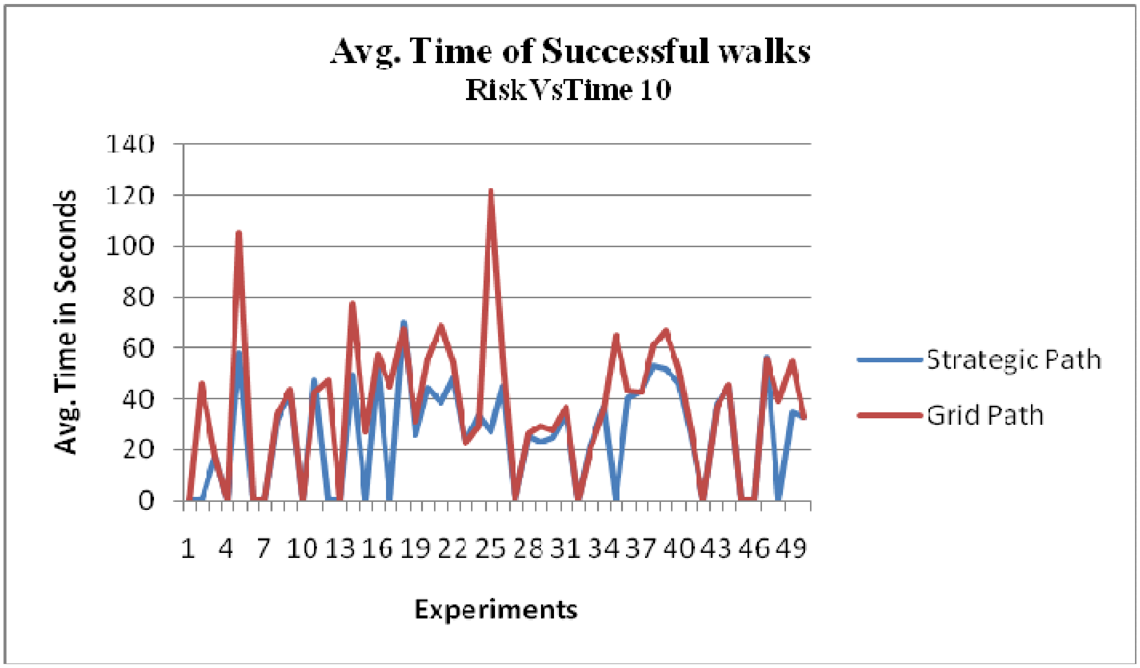


Figure 24: Avg. Time of Successful walks of Strategic and Grid Paths

In the Grid paths the agent tries to get closer to the walls to minimize exposure and maximize the distance from the enemy, but the technique we applied to prevent the agent from hitting the wall required the agent to change its movement angle continuously in order to avoid getting stuck. While the agent turns, it has the lowest or almost no speed and therefore it walks along the walls with a very slow speed (because of intermittent turns) and on many occasions this results in more time to traverse (as shown in figure 24).

7.10 In-Game Trials of Agent with shooting skills

The hypothesis of this experiment was the agent with shooting skills on the strategic path will perform better than the agent on the shortest path.

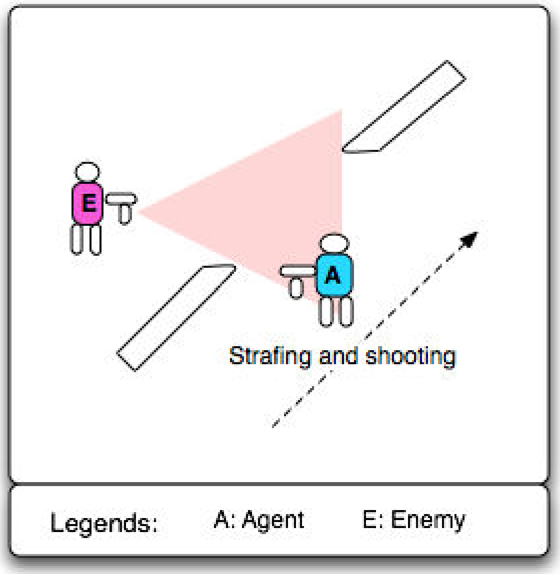


Figure 25: Strafing and shooting

We also performed 200 experiments, 10 experiment sets with 10 trials each for the shortest path and the strategic path (with RiskVsTime = 10) on the agent equipped with the shooting skills. Here the agent was able to shoot the enemy bot by strafing towards the goal when the enemy bot was visible (as shown in figure 25). Here we defined the shooting skill as the combination of strafing, aiming and shooting while moving towards the goal. In this mechanism the agent walks perpendicular towards the goal while aiming the enemy bot and shooting (without caring about perfectly aiming it). In implementation we performed three actions together one action each proposed by strafing, aiming and shooting skills. Here, the strafing skill aligns the agent to face the enemy bot and strafe on the path, whereas the aiming skill makes the agent to turn up/down (change pitch) and left/right (change yaw) when the enemy bot is visible and the aiming skill makes the agent to fire when the enemy bot is visible. The strafing speed is a lot slower than the normal walk towards the goal in the UCT. In Quake3 the yaw defines the aiming angle.When the agent strafes or moves, the yaw changes and the aiming is affected.

The enemy bot was programmed to aim and shoot the agent. On a successfully killing of the enemy bot the agent was programmed to switch to the shortest path to the goal area.

7.10.1 Agent with shooting skills

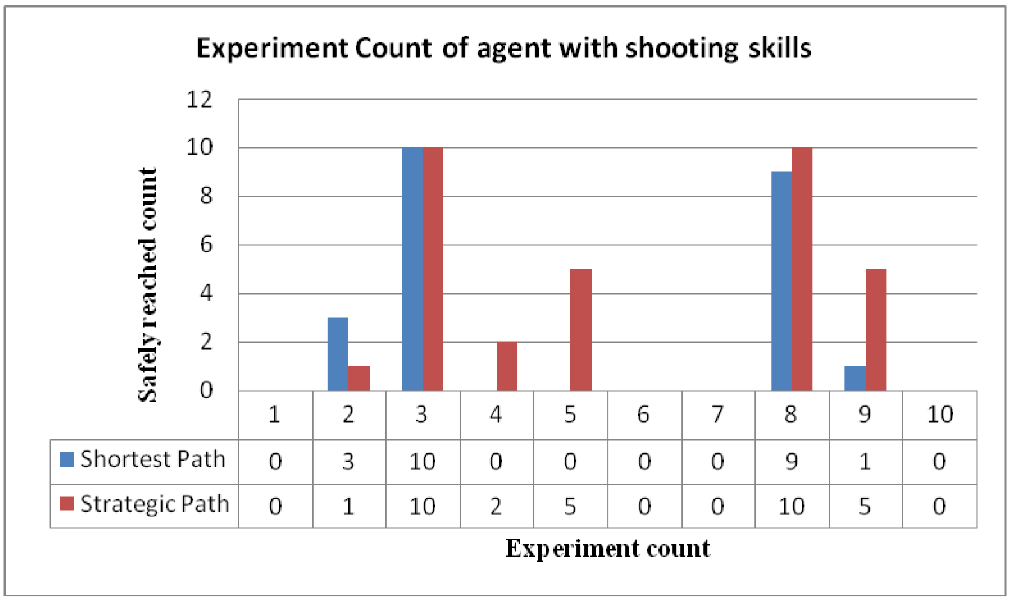
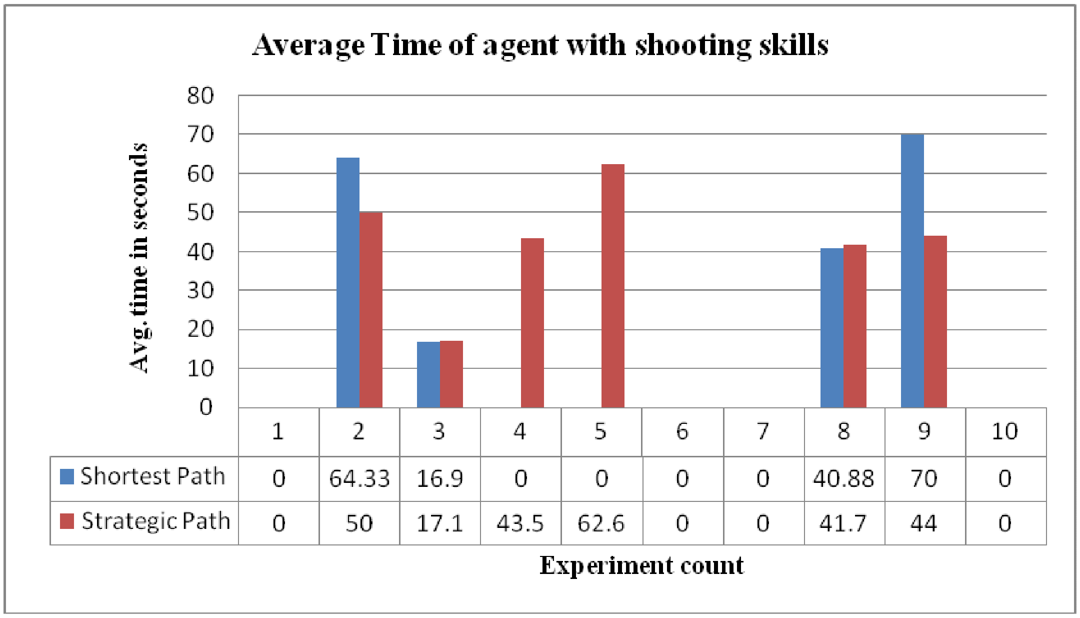


Figure 26: Safely reached experiment count analysis of agent with shooting skills

The strategic paths (Area level) were computed with *RiskVsTime* = 10. As shown in figure 25, on 23 occasions the agent safely reached the goal area while traversing the shortest path compared to 33 occasions while traversing the strategic path.



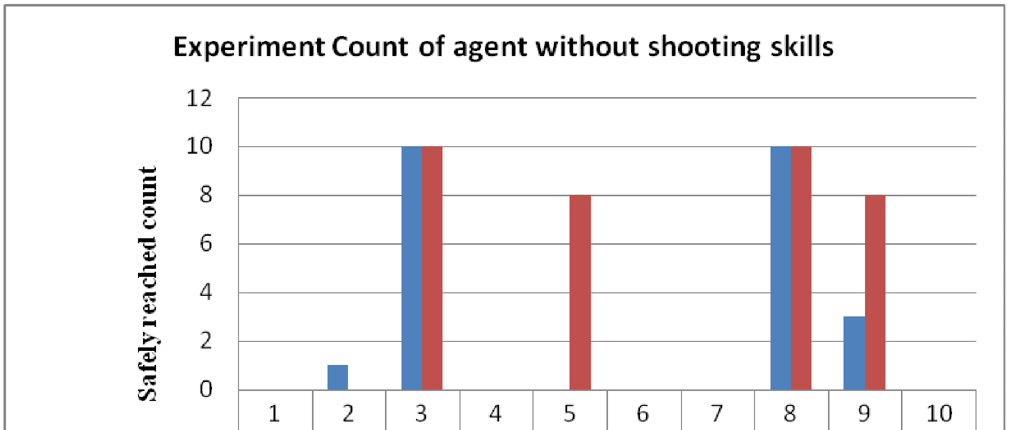
	1	2	3	4	5	6	7	8	9	10
Shortest Path	0	64.33	16.9	0	0	0	0	40.88	70	0
Strategic Path	0	50	17.1	43.5	62.6	0	0	41.7	44	0

Figure 27: Safely reached average time analysis of agent with shooting skills

In figure 24, average time analysis has been done for the experiments where the agent with shooting skills safely reached the goal area. For all the shortest path experiments the average time to safely reach the goal area was 34.77 seconds compared to 38.12 seconds of the strategic paths. Thus, it can be seen on the strategic paths the agent was safer but it took longer to reach the goal area.

7.10.2 Comparison with Agent without shooting skills

We also performed the above 200 experiments on the agent without shooting skills. Thus, the agent simply walked on its path. The shooting skill is equipped with the strafing skill and it is much slower compared to the normal walk's speed.



	1	2	3	4	5	6	7	8	9	10
Shortest Path	0	1	10	0	0	0	0	10	3	0
Strategic Path	0	0	10	0	8	0	0	10	8	0

Figure 28: Safely reached experiment count analysis of agent without shooting skills

As shown in figure 28, on 24 occasions the agent successfully (safely) reached the goal area along the shortest path area as compared to 36 occasions along the strategic path. When compared to the agent with shooting skills (equipped with the strafing skill), it explains the simple walk was safer than the walk with shooting skills. Since the strafing decreases the speed of movement towards the goal, the enemy bot had more time to properly aim and shoot the agent. Here, the agent could not successfully kill the enemy bot in spite of the shooting skills because of the constraints of the strafing mechanism in the Urban Combat Testbed. The strafing does allow the agent to face the enemy bot, but when performed in parallel with the aiming and shooting mechanism it does decrease the accuracy to a great extent. Hence the agent with the combination of strafing, aiming and shooting skills performed poorly.

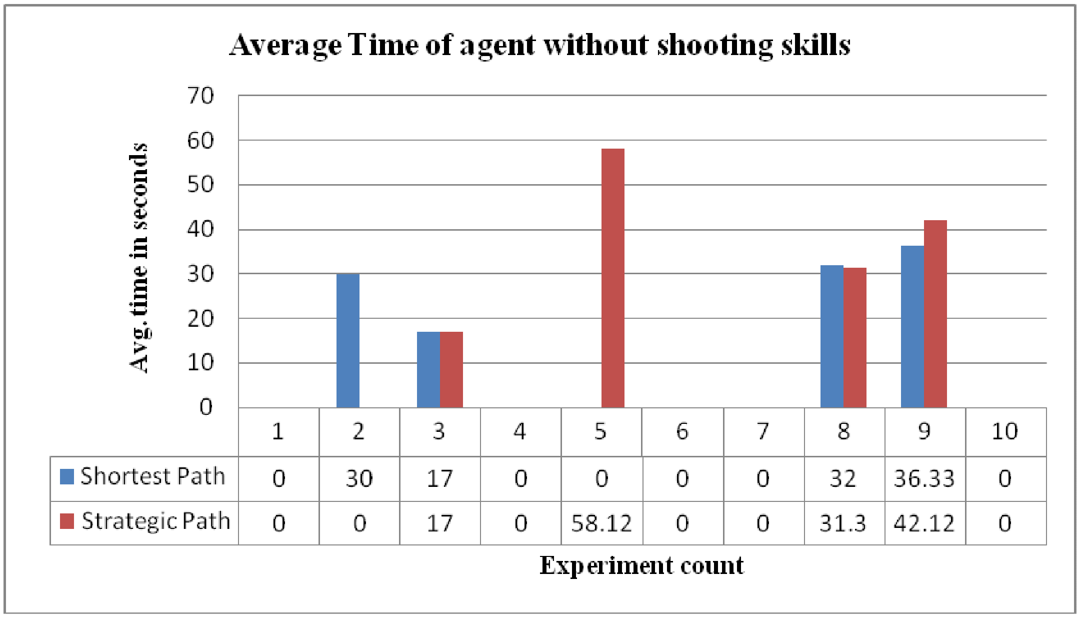


Figure 29: Safely reached average time analysis of agent without shooting skills

In the figure 29, average time analysis has been done for the experiments where the agent without shooting skills safely reached the goal area. For all the shortest path experiments the average time to safely reach the goal area was 26.2 seconds compared to 35.69 seconds of the strategic paths. Thus, it can be seen on the strategic paths the agent was safer but it took longer to reach the goal area. And when compared to the agent with the shooting skills we can see the slow speed of strafing caused more failures.

Since there is no separate aiming mechanism other than the yaw itself, any movement towards the right direction (strafing or forward walk towards the goal) requires the yaw to change and it affects the Aiming and the Shooting accuracy. Due to the limitations of no separate Aiming angle the two parallel actions Strafing and Aiming interfere with each other and decrease the shooting accuracy of the agent.

In above experiments, we have considered a stationary enemy bot. When the agent shoots the enemy bot it stays in the same location. Here, we can model the enemy bot to move to a safe location when the agent bot fires a few rounds. Thus, the enemy bot will get a short interval to shoot the agent, and if it misses, then it will take cover and stop shooting. For above experiments this modeling will improve the *hit probability* of the agent.

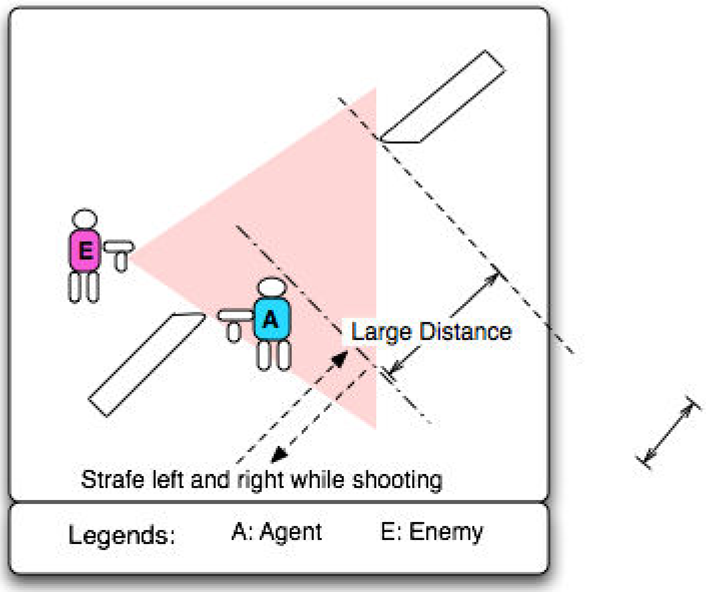


Figure 30: Strafe, aim, shoot and take cover.

As shown in the figure 30, we can also consider the agent to be stationary for a while and just perform aiming and shooting operations for a short interval and then take cover by strafing back to the previous location if the path towards the goal can be traced without getting a hit.

The hypothesis of this experiment was confirmed. And we also found the agent couldn't improve its performance with the shooting skills because of the limitations of the Quake3 engine (it uses *yaw* for both movement and aiming).

7.11 Observation

In this chapter we performed many out-game and in-game trials. We computed the variance between the *in-game* and *out-game* trials (*hit probabilities* for the traced paths) with

RiskVsTime 10 and Assault Rifle for the strategic path at Area level and it was found 0.17761 and for the strategic path at Grid level it was found 0.1896. The variances between the *in-game* and the *out-game* trials for the strategic paths are good considering the gap of real-world weapon performance and *Quake3*'s implementation of a similar weapon (similar but not the same). The *out-game* trials were based upon the realistic risk evaluation computed from available weapon details and it was free from the implementation details of the Quake3 game engine. We performed *out-game* trials with variation in *RiskVsTime* factor from 0 to 30. We observed that the computed strategic paths (Area and Grid levels) for a high *RiskVsTime* factor were consistently safer. We found the strategic paths at Grid level were safest among the three paths. And we also observed the Grid paths were of shorter lengths, but in *in-game trials* it took more time to trace these paths compared to the Strategic paths. We also analyzed the effect of variation in *checkpoint length* and observed for a shorter *checkpoint length* the *hit probability* computed for Meta-Weights was closer to the paths' evaluated *hit probability*. We performed experiments on the agent with shooting skills and observed the limitation that using the same yaw for aiming and movement caused the agent to perform poorly with the strafing/shooting skills.

CHAPTER EIGHT

OTHER APPLICATIONS OF STRATEGIC PATH PLANNING

8.0 Overview

This chapter discusses about the use of strategic path planning. The above strategic path computation can also be used for implementing various for Military Operations on Urban Terrain (MOUT) strategies and tactics. *Flanking* [4, 13] can be done by constructing a strategic path that minimizes exposure to other enemies while targeting a specific enemy. *Ambush* [4] can also be used by an agent by moving early to an area without being seen and waiting in anticipation of an enemy. Later this chapter discusses about possible further improvements in the strategic path planning and its implementation requirements. And this chapter also discusses how it can be used with Real Time Strategy (RTS) games.

8.1 Basic Strategic Tactics

In the basic strategic tactics (as shown in figure 31) the agent just targets a specific enemy without getting exposed to the other enemies.

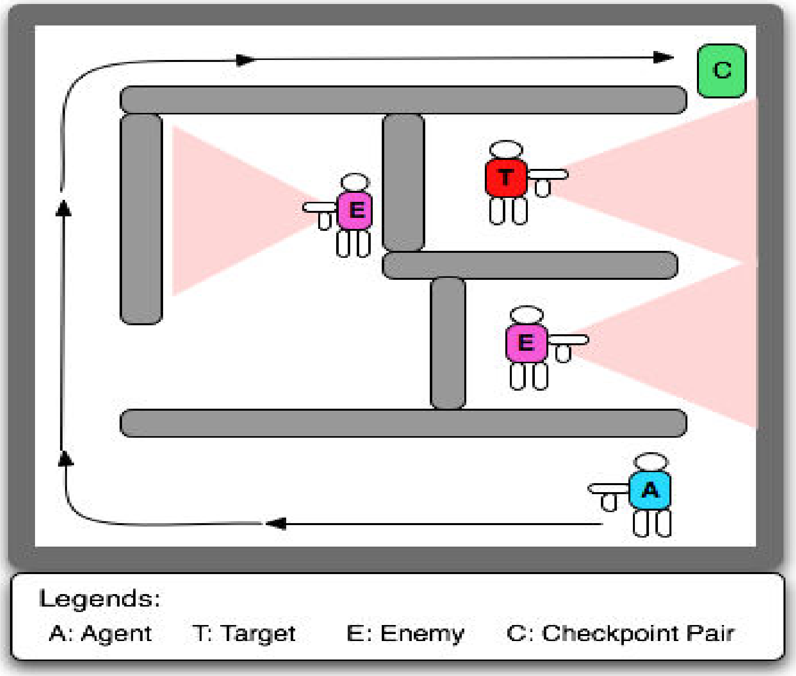


Figure 31: Basic Strategic tactics

Algorithm 6 Basic Strategic tactics

INPUT: World coordinates of areas, objects, agent and enemies with their weapon details.

1: Find an area pair with the following features among all the available areas

   i) A minimum of one *checkpoint* hidden from all the enemies and one *checkpoint* visible and within a good shooting range from the target enemy.

   ii) With the lowest modified weight (refer to chapter 5.4) of the path involved in getting there from the current location, i.e., along the computed strategic path.

2: Move to the hidden *checkpoint* of the above area pair by moving along the computed strategic path without getting exposed to the rest of the enemies.

3: Strafe and shoot in-between above discussed *checkpoints* by aiming the target enemy. Reloading in hidden *checkpoint* and shooting from the visible *checkpoint*.

4: Repeat step 3 until the target enemy is alive.

8.2 Shoot and Scoot

In Shoot and Scoot MOUT tactics (as shown in figure 32) the agent varies its shooting location from one point to another point without getting noted by other enemies. In this process the agent goes on changing the shooting location to prevent losses due to any heavy retaliation.

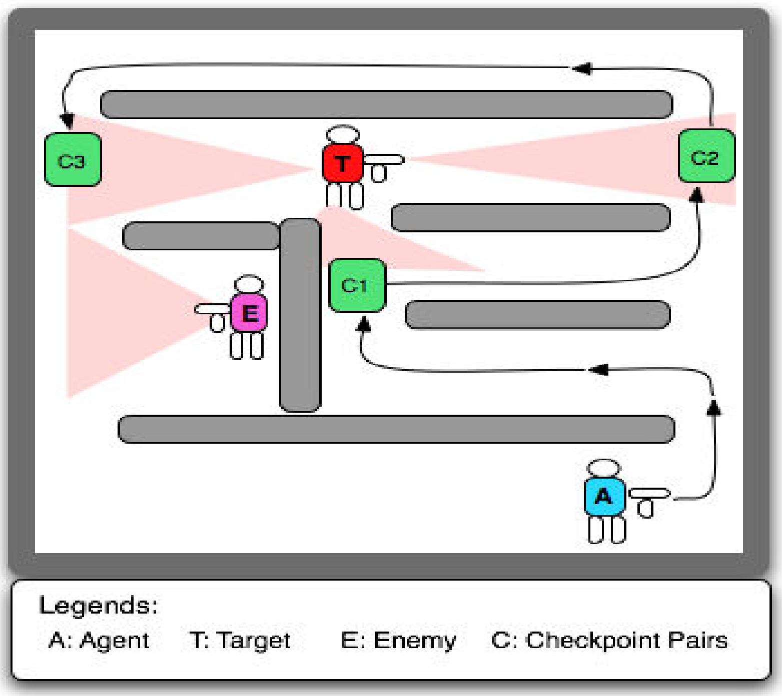


Figure 32: Shoot and Scoot tactics

Algorithm 7 Shoot and Scoot MOUT tactics
INPUT: World coordinates of areas, objects, agent and enemies with their weapon details.
1: Find an area pair with following features among all the available areas
i) A minimum of one *checkpoint* hidden from all the enemies and one *checkpoint* visible and within a good shooting range from the target

enemy.

ii) Farther than a threshold distance to confuse the target enemy.

iii) The lowest modified weight (refer chapter 5.4) of the path involved in getting there from the current location, i.e. along the computed grid path.

2: Compute two *grid points* (one hidden and one open) along the line joining the two *checkpoints.* Move to the hidden *grid point* of the above area pair by moving along the computed grid path.

3: Strafe between two *grid points* by aiming the target enemy. Reloading in hidden *grid point* and shooting from the visible *grid point*, here visible and hidden *grid points* are again computed.

4: Repeat step 1 to 3 until the target enemy is no longer alive.

8.3 Ambush

In the ambush MOUT strategy (as shown in figure 33) the agent hides in a location and anticipates the enemy in a strategic location and attacks the enemy with surprise. From the current location to the strategic location where the ambush is set, the enemy is left completely unaware about the agent's possible moves.

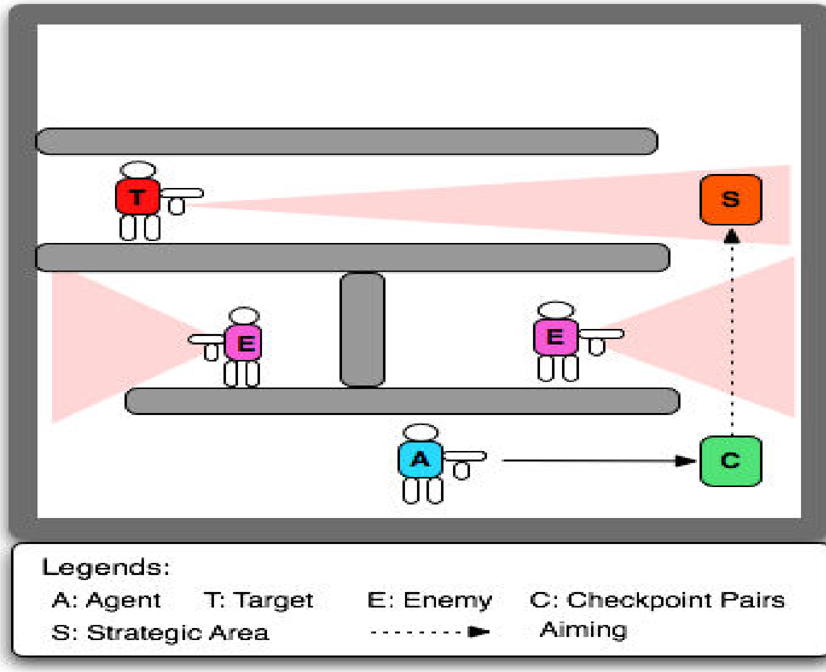


Figure 33: Ambush MOUT strategy

Algorithm 8 Ambush MOUT tactics

INPUT: World coordinates of areas, objects, agent and enemies with their weapon details.

1: Find the strategic area (an area with no nearby cover) where the target enemy is anticipated.
   i) It can be an area on a path towards power-ups or something important to the target enemy.
   ii) If the target enemy is returning from a locked area and this area exists on one and only one path.
   iii) This strategic area should also fulfill (2).
2: The agent should be able to reallocate to an area pair (as discussed below) within the walkable range from the agent's current location. This area pair should have
   i) A minimum of one *checkpoint* hidden from all the enemies and one *checkpoint* visible and within a good shooting range from the target strategic area.
   ii) The lowest weight (refer chapter 5.4) involved in getting there from the current location, i.e. along the computed strategic path. (To prevent any harm from other enemies).
   III) And it should be completely hidden from all the areas the enemy is expected to move along to reach the above discussed strategic area.
3: The agent should move to the hidden *checkpoint* by moving along a computed *grid path* (with a very high value of RiskVsTime) and wait until the enemy appears in the strategic area.
4: Strafe and shoot in-between dynamic *grid points* computed for above discussed *checkpoints* by aiming the target enemy. Reloading in a hidden *grid point* and shooting from the visible *grid point*.
5: Repeat step 4 until the target enemy is alive.

CHAPTER NINE

CONCLUSION AND FUTURE WORK

9.0 Overview

This chapter discusses about our conclusions and addresses how the concept of abstraction and concept of detailed dynamic visibility calculation at run-time for realistic risk calculation could be used to for both efficiency and more accurate risk analysis of a path. It also addresses issues related with using A* technique. It also discusses the applicability of our proposed strategic path computation algorithm in a more generalized for other computer science related fields and real world problems. And later this chapter discusses about the future work.

9.1 Conclusion

We studied three important components of risk on a path of traversal. It is not just an issue of exposure, but the distance from the enemies and their lethality also determine the real risk. A strategic path calculation must penalize paths by considering all three components of risk and making a proper trade-off between risk vs. time. We also studied how strategic path at Area level does the risk evaluation of an Area at an abstraction and in turn that adds to efficiency in computation. Therefore, the dynamic visibility calculation for areas is feasible at run-time and more accurate since it is based on the enemy's exact location. This also makes it possible to consider dynamic objects.

When the agent reaches the computed Area, the strategic path is computed over the Grid Points of that Area. Thus, the calculation of the hit probability can take into account the real-time movements of the enemies as the agent traverses the Grid Points of an Area.

By doing computation at two levels the strategic path computation is linearly distributed over the complete traversal process and therefore it does not become computationally intensive.

Secondly, in addition to the computational savings of calculating strategic paths at the Area level, rather than the Grid level (or using Waypoints), there is also the issue of not knowing visibility details within an Area until the agent arrives at that Area, especially in urban combat settings. Thus the agent exhibits intelligence (in strategic path computation) in a more realistic way.

The strategic path planning at Area level can be further abstracted to a more abstract concept called *Zones* (discussed in chapter 5.5) for more complicated maps. Thus the strategic path planning will perform at three levels of abstractions.

9.2 MOUT tactics and strategies

The MOUT strategies and tactics as discussed in chapter 9 can be implemented by using the strategic path planning technique. As the core philosophy of MOUT strategies and tactics is to maximize the damage to adversaries and minimize the return damage. And therefore, by using the strategic path planning technique the agent can minimize the risk or self damage in traversing the areas.

9.3 A generalized algorithm for problems in other fields

The strategic path planning in a more generalized form can be used in other fields where we need to plan a path with respect to undesired (or hostile) elements. For example in the field of *computer networks* for a problem of wiring an area with cable wires and where we need to prevent noise induced by certain noise producing elements, then it would need to maximize a minimum distance from these disturbing elements depending upon their noise producing capabilities. Thus, the wiring must be done in analogy to strategic path planning at Grid level.

9.4 Real world problems

In Military operations, a soldier can communicate with a satellite and acquire in abstraction the area information (abstract information about architectural structures, stairs, pathways etc.). And using military sensors [23] it can detect enemies' exact locations. Thus, a soldier can make use of devices that do strategic path computation to perform safe and strategically more efficient military operations.

9.5 Further optimization of strategic path planning at Area level

The strategic path planning can be further improved in terms of efficiency by using a hybrid approach to the *BitStrings* technique for strategic path planning at Area level. So, we will need to modify the *BitStrings* to contain distance values and also adapt to dynamic visibility. The dynamic visibility test will require testing any changes in visibility between area centers and checkpoints across area centers for all the dynamic entities at run-time using the *HSS technique* (indexing done only for dynamic entities). Thus, the total number of visibility tests will reduce for strategic path at Area level computation. But by using the above technique we would compromise with visibility accuracy, because we would assume the enemy is standing exactly at its Area center. On the other hand, this technique will not significantly improve the strategic path at Grid level computation, because Grid points are in large quantity.

9.6 Automated Area and Object construction

Using the Area Awareness System (AAS) technique [19], the construction of Areas, Objects and Gateways can be automated. Thus, the manual boxing of 3D volumes using map editors will not be required.

9.7 Significance for Real Time Strategy games

In RTS games the number of dynamic entities is significantly greater than in the FPS games. In RTS games players can build walls and defend these walls using turrets. Thus the area connectivity cannot be pre-computed. In RTS games areas analysis will be done on the basis of self-damage and damage-to-cause (destructing walls) to cross an area to another neighboring area. This computation of cost must be abstracted for each area; here areas could be of fixed size and shape. A graph can be formalized where the vertices are the areas and the edges are the cost to cross the area. Thus, to reach an enemy's base a rough estimation of the required unit military strength can be computed. And the strategic path planning algorithm can be applied for the computation of the best affordable path. This computation will make it possible to guess roughly the amount of resources and military units required to win the game.

9.8 Next step of Research

The next step of the current research would be to further minimize the gap between the real world and the UCT simulation. Thus, the UCT could be used to analyze the risk in executing a set of complicated moves that can involve strategic and tactical moves for computing the risk and the effectiveness in a more complicated environment.

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