Terrain Reasoning for 3D Action Games

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Terrain Reasoning

the AI capability to take into account terrain in its planning, decisions, actions, and communication

terrain = indoor + outdoor
Aim

why
- terrain reasoning AI in 3D action games

how to
- translate terrain concepts to algorithms
- use terrain reasoning for real problems
- add it to your game (AI)

when (not)
- to use it (ideas, techniques, data structures)

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researching and developing (tactical) AI
- CGF-AI, Veldhoven, the Netherlands
- experiments using ‘open’ game engines
- www.cgf-ai.com

senior scientist / architect + team leader
- Philips Electronics Research Labs
- embedded systems software

defense simulations
- naval simulations, TNO-FEL, 1995
Contents

- intro
- case: track and predict opponent
- waypoints, and their use
- case: tactical terrain assessment
- pre-game and in-game analysis
- case: team maneuvers
- look up tables
- implementing terrain reasoning
- conclusions
- questions

GDC proceedings

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Why Terrain Reasoning

3D level design theater to shape interaction every spot has a (tactical) purpose stronghold, cover, avenues,...

10,000+ polygons

AI running around in shortest paths

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Case: Track and Predict Threat

this case illustrates

- the need to represent terrain
- the use of waypoints
  - more than navigation aids
- some smart, light-weight solutions
  - prediction, corrected by path info
  - prediction, corrected by line-of-sight info
  - aiming for ‘reappear spots’ and portals
- expressed in waypoints!
Case: Track and Predict Threat 2
Case: Track and Predict Threat

Problem
- predict position of opponent that moves out-of-sight
- scan and aim smart
- suppression fire? try a rocket?

Relevance
- one-on-one deathmatch
- friendly team member AI
- hard to shake off opponents

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Case: Track and Predict Threat

- House
- Door
- Window
- Threat
- AI actor

Situation (top view)
Case: Track and Predict Threat

Where to look for the threat?
What to aim for?
Case: Track and Predict Threat

Option: assume threat static after moving out of sight (often incorrect)
Case: Track and Predict Threat

Option: assume threat continues last observed movement (incorrect after a little while)
Case: Track and Predict Threat

If the AI

- assumes threat is static; or
- assumes threat continues movement

then the AI ignores information about

- (in)accessible terrain
- portals
- shortest paths
- (valid) lines of sight
- game play data

Often already available in 3D action games

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Case: Track and Predict Threat

Waypoints\(^1\) describe
- accessible terrain
- valid movement (speeds)
- properties of their local environment
  - door, window, water, tunnel, traffic, ...

Inter-waypoint visibility approximates
- valid lines of sight

\(^1\): or similar constructs such as navigation cells, navigation meshes

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Case: Track and Predict Threat

The waypoint grid (overlay)
Case: Track and Predict Threat

The waypoint grid (AI “view”)
Case: Track and Predict Threat

Extrapolate movement along waypoints (valid paths, movement speed known).

Threat no longer “leaves” the house!
Use known line-of-sight for “negative” observations. Exclude some likely threat movements.
Case: Track and Predict Threat

The AI can use the waypoint graph to
- restrict guesses to valid movements
- estimate the threats’ movement speed
- exclude visible potential movements that were not observed

Predict a likely path, for example
- path best aligned with last observed direction
- using per waypoint traffic statistics
- towards most attractive nearby objective
- towards strongest defensive position
Case: Track and Predict Threat

Where to aim?
- where the threat likely reappears!

Good guesses
- visible spot closest to threat
- first visible spot on shortest path from threat to observer
- first visible spot on predicted path
- any nearby portal (door, window, hole, ...)

- easily computed using waypoint graph
Case: Track and Predict Threat 16

Threat turns to attack (1) or moves to nearest attack position (2), or continues movement (3)
Waypoints and their use

Waypoints

- more than a navigation aid
- mark terrain accessible to AI (and player)
- describe and represent surroundings
- express paths and travel time
- already in use by many AI’s
- in the order of 300 - 3000

- denser waypoint grid
  → represents terrain better

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Waypoints and their use

To support tracking and prediction

- per waypoint
  - outgoing neighbor waypoints
  - travel time to nearby waypoints
  - waypoints fully visible from here
  - (portal annotation)
  - (game play data)

and

- flood fill waypoint expansion; or
  - (short distance) path finding

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waypoints, and their use

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pre-game and in-game analysis

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look up tables

implementing terrain reasoning

conclusions

questions

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Case: Tactical Assessment 1

this case illustrates

- AI tactical understanding of terrain
- use of captured game play data to
  - vary AI behavior
  - enhance AI tactical understanding of terrain (wrt to mission, objectives, spawn spots ...)
- expressing tactical concepts as evaluation functions per location
- incorporating analysis in the game
- expressed using waypoint graph
Case: Tactical Assessment 2

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Case: Tactical Assessment 3

Problem
- identify strong sniping positions
  - efficiently
  - take into account the scenario
  - also signal absence of good positions

Relevance
- AI in territory based team games
- automated terrain annotation
- team member AI in tactical shooters
Case: Tactical Assessment

example terrain, top view

(symmetric map)

building, 1 door, 2 windows

stairs, from water

bridge w. 1m / 3ft walls

depth water

wall, 1m / 3ft

wall, 2m / 7ft

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Case: Tactical Assessment

example terrain, shots

bottom right: waypoint grid

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Case: Tactical Assessment

Approach

1. search among nearby waypoints
2. identify waypoint $w$ with highest sniping rating towards target
3. check rating $w$ is good enough
4. if so, move to waypoint $w$

and (first)

5. pre-compute sniping rating for each waypoint and direction
Case: Tactical Assessment

What makes a good sniping spot?

- inconspicuous
- overlooking distant locations
- hard to reach from target locations
- nearby cover for sniper
- overlooking key locations
- hard to surprise
- focus
- protected flank
- freedom of movement
- target locations lacking cover

Any relation with waypoints? How to compute these?

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Case: Tactical Assessment 8

Waypoints

- do represent terrain
- can express tactical “ingredients” using:
  - travel time
  - line of sight
  - line of fire
  - distance
  - part of area
  - local environment properties
  - ...

for example:
- nearby cover
- for sniper
- from targets overseen

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Case: Tactical Assessment

Idea

\[ \text{tactical value} \ (w, d) = \sum k_i \times \text{tactical ingredient}_i \ (w, d) \]

Tuning!

It’s a heuristic

\( w \) a waypoint
\( d \) a direction

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Case: Tactical Assessment 10

Same Idea, Lots of Experiments Later

tactical value (w, d) =

\[ \sum k_i \times \text{local property}_i (w) \]

\[ + \sum k_j \times \text{group membership}_j (w) \]

\[ + \text{focus} (w, d) \times \sum k_l \times \text{relationship}_l (w, d) \]

① non-directional
② directional

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Case: Tactical Assessment

Waypoint local properties
- describe environment
- non-directional

Examples
- light level
- water, low ceiling, power-up, ...
- local movement speed
Case: Tactical Assessment

local property: light level

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Case: Tactical Assessment

Waypoint group membership
- being part of larger terrain representation
- non-directional

Examples
- room, roof, alley
- base, objective area

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Waypoint relations

- (potential) “interaction” or influence between two waypoints
- directional, leveled [0..1]

Examples

- nearby cover from threat
- hard to reach from target
- overlooking key locations
- hard to surprise
Case: Tactical Assessment

Relation: nearby cover from threat
- the amount of nearby cover from threat and nearby positions

2/9 = 0.22
Case: Tactical Assessment

nearby cover
from seen threats
east of position

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Focus
- concentration of relations in certain direction (sphere sector)

Expresses
- flank protection
- view cone

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Case: Tactical Assessment

Focus

- implementation depends on
  - relation chosen (line of fire, line of sight, ...)
  - # sectors
  - emphasis on flanks and rear

\[
\frac{3 \times \text{front}}{\text{left} + \text{right} + \text{rear}}
\]

\[
3 \times N + 2 \times (\text{NE} + \text{NW}) + 0.5 \times (\text{E} + \text{W})
\]

\[
2 \times (\text{E} + \text{W}) + 1 \times (\text{SE} + \text{S} + \text{SW}) + 0.5 \times (\text{NE} + \text{NW})
\]
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focus

east

(E, NE, SE, Eup, Edown)

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Case: Tactical Assessment 20

Combining all waypoint properties

- **sniping value** \((w, d)\) =
  \[
  \sum k_i \times \text{local property}_i (w) + \sum k_j \times \text{group membership}_j (w) + \text{focus} (w, d) \times \sum k_l \times \text{relationship}_l (w, d)
  \]

- 17 ingredients, 26 directions, 480 waypoints, 10 seconds PIII/500, et voila...
  24KByte of sniping ratings (16bit)

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Case: Tactical Assessment

sniping east, using geometry + physics

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Case: Tactical Assessment

Results and Process

- waypoint directional sniping quality
  - using “geometry” + actor/weapon physics
- most (key) sniping spots identified
Case: Tactical Assessment

Computed results not perfect
- formulas / weights not always correct
  - easily changed
- waypoints not always representative
  - put in a few more waypoints
- environment dynamics
  - discussed later in this presentation
and
- game play ignored!
  - easily turned into an advantage

Also: visualization errors!

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Case: Tactical Assessment

Add reinforcement learning
- analyze sniping behavior / waypoint

- per waypoint (+ direction), reward
  - time spent sniping
    - static, sniper weapon, zoom, shots
  - damage issued while sniping

- per location (+ direction), punish
  - damage received while sniping
Case: Tactical Assessment

positive
sniping
experience,
after
40 rounds,
non-directional

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Case: Tactical Assessment

sniping
east,
using
gometry
+ physics
+ learning

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Case: Tactical Assessment

With reinforcement learning

- better sniping ratings
- adaptive AI sniping behavior!!!
  - AI varies position based on performance

Diagram:
- Level design
- Terrain analysis
- Game round
- Analyse activity + rerank locations
- Sniping activity
- Sniping ratings
- Sniper spot analysis (~20 s)
- Sniping activity tracking [0.0 s]
- Reinforcement learning [0.1 s]
Case: Tactical Assessment 28

We can do even better!

- use game play data in terrain analysis
- look at (hostile) traffic across terrain
- look for “kill zones”, “early contact zones”
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traffic data (all teams) after 40 rounds

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Case: Tactical Assessment

sniping east, using geometry + physics + learning + tactical game play analysis

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Case: Tactical Assessment

Results

- Sniper spot analysis (~20 s)
- Sniping activity tracking [0.0s]
- Reinforcement learning [0.1s]
- Analyze activity + rerank locations

Flowchart:

1. Level design
2. Terrain analysis
3. Game round
4. Sniper activity
5. Traffic + kills...
6. Sniping ratings
7. Pathways + travel time
Case: Tactical Assessment

Results

- good sniping ratings
  - all locations, no manual ‘flagging’ required
- adaptive AI
  - responds to in-game success and failure
- tactical AI
  - after game play analysis, sniping ratings become scenario specific
- few in-game resources required
  - 26KB, most of the work is done off-line
Case: Tactical Assessment

Many (similar) Applications

- ambush locations
- strongholds
  - per area per waypoint
- positioning sentry-guns
- base defense
  - use objective in evaluation functions
- generic ‘offensive’ / ‘defensive’ rating
  - see also team maneuvers
- assessing strength of threat position
- ...

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Case: Team Maneuver 1

this case illustrates

- emergent behavior, taking into account terrain
- tactical team path planning
  - tactical A*
  - look up tables
- using waypoints
Case: Team Maneuver 2

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Case: Team Maneuver 3

Problem

- have squad move up / move back
  - tactically
  - as a group
  - using terrain to their advantage
  - in, before and after combat

Relevance

- team AI
- tactical shooters
Case: Team Maneuver 4

how to attack the threats as a team?

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Case: Team Maneuver 5

Approach

- initially, sequentially for each member
  - evaluate nearby waypoints (within $r$) for position improvement
  - claim best position $p$
  - move up to position $p$
- repeat on member initiative

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Case: Team Maneuver

For each waypoint evaluate
- travel time to / from threat, power-up, ...
- nearby cover and flank protection
- tactical rating of position
  - generic tactical rating (similar to sniping)
- min projected distance to team member
  - (spread as seen by threat)
- keep out of friendly line-of-fire (dotproduct)
- maintain visual contact with enemy
- distance to grenades...

...
Case: Team Maneuver

how to attack the threats as a team?

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Case: Team Maneuver

evaluate for each waypoint:
- distance to threat
- spread
- nearby cover
- not claimed
- etc.

and claim best position...
Case: Team Maneuver 9

member1 claims position and will move up

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Case: Team Maneuver

member2 evaluates and picks best position given existing and claimed positions

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Case: Team Maneuver

same for member3

however, in the search radius, the best spot might not be that good (LOF blocked)...

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Case: Team Maneuver

upon arrival, member 3 indeed sees a blocked line-of-fire.

he quickly executes the same procedure from his new spot...

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Case: Team Maneuver

now member3 moves up again to a good position...

in an obstacle rich environment, you'll get flanking for free...

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Case: Team Maneuver

Results

- terrain specific team maneuver
  - plan new position every time actor wants to move (reload, enemy lost, time out)
  - pretty robust for terrain, team/threat sizes
    - in combat, team size and threat count vary
  - easily parameterized (also from a script)
    - offense, defense, cautious, power-play, objective location, ...

- might also work at higher level...

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Case: Team Maneuver

Warning

- do use tactical rating of location!
  - without it, AI too reactive (not pro-active)
    (can be drawn away from stronghold)
  - check ‘best evaluated’ position for
    position improvement

- inter-member collision avoidance
  - plan, flock, prioritize... debug
Case: Team Maneuver

Tactical Path Finding

- satisfy more objectives than ‘short’
  - safe (from enemy fire)
  - stealth (from enemy observation)
  - cautious (don’t get caught in weak position)
  - maneuver (offer positions to regroup)

- custom A*
  - heuristics for the cost function
  - heuristics for performance

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Case: Team Maneuver

find a safe path to objective, given threat and his line of fire

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Case: Team Maneuver 18

a valid solution

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Case: Team Maneuver

Approach

- add A* ‘being in the line of fire’ costs

Improvements

- assume spots nearby threat also hostile
  - more robust solution

- use a non-linear function ($x^n$, $n > 1$) of exposure time, to prevent long exposure in open areas
Case: Team Maneuver 20

Results

- tactical maneuvering feasible,
- but CPU intensive

Intermediate results improve performance

- waypoints can ‘host’ these results
  - easily used for other reasoning as well

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Case: Team Maneuver 21

Look Up Tables (Intermediate Results)

- per waypoint (and direction)
  - outgoing neighbors
  - (un)protected sectors
    - near and far threats
  - tactical value
  - visible waypoints
  - cover from waypoints
  - travel time to/from neighbor
  - (cached) paths

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Implementation 1

Implementation Issues

- resource consumption
  - memory and CPU load
- dynamic environment
  - dynamics may invalidate preprocessed data
- reinforcement learning
  - balancing player and AI input
Implementation 2

CPU and Memory Load

- infeasible to do all reasoning on-the-fly
  - too many spots and relations to check
  - many AI actors

- thus pre-computed data required
  - CPU problem turned into memory problem?
  - look for intermediate data that
    - consumes little memory
    - saves lots of CPU
    - is frequently used / on critical path
Lookup vs Compute

Path finding / Travel Time
- (tuned) A*: 1,700 paths/s
- lookup: 3,300,000 paths/s

Line-of-Sight/Cover (up to 4 ray traces)
- BSP checks: 25,000 l.o.s./s
- lookup: 4,000,000 l.o.s./s

1 Quakel³ PIII/500Mhz, 1K waypoints
Implementation 3

Memory Consumption

- terrain reasoning uses more waypoints than navigation
  - to represent terrain properly
- memory consumption dominated by
  - $ N \times N $ paths + travel time
  - $ N \times N $ lines-of-sight / fire
  - $ N $ about 1,000 for larger Half-Life levels

but terrain is growing
Implementation 4

Memory Consumption
- > 1,500 waypoints, matrices get large
- path storage
  - hierarchical path finding
  - cache computed paths (AI actor inertia)
- flatten visibility data
  - visible/viewer waypoints p. waypoint

matrix

flat

directional for multiple distances

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Implementation 5

Memory Consumption and Performance

- AI has “planning horizon”
  - most reasoning during combat
  - most combat decisions are short-term typically 1 to 2 s, depending on game

- gain performance by storing
  - nearby waypoints (< planning horizon)
  - all nodes seen by those nearby waypoints

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Implementation 6

Dynamic Environment
- doors, vehicles, smoke, lighting, destructible terrain, ...
  invalidate pre-computed results

but
- humans aren’t perfect either
- if exceptions are few, they often can be accommodated
  - often, patching pre-computed tables is more efficient than not using these tables

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Implementation

Reinforcement Learning

- value human game play more than AI
  - player is more creative
  - typically more AI than humans present
  - AI may hone into its flaws otherwise

- visualization
  - terrain reasoning is heuristics
  - set-up feedback facilities early on
  - preferably in game engine (overlays)

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Conclusions 1

3D level design
theater to shape interaction
every spot has a (tactical) purpose
stronghold, base, avenues,...

richer reaction and interaction
more realism
more variation

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Conclusions 2

Terrain (tactical) concepts such as

- terrain analysis
- situational awareness
- team maneuvers, ...
- threat assessment
- team positioning (regroup, defend, ...)

- can be expressed as evaluation functions per location
- as heuristics, but with...
  - clear relation to original concept

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Conclusions 3

Analysis 10% : Experiment 40% : Tune 50%

- simple ideas: no rocket science
  - (thus?) little literature available 😞
- experiment a lot
  - see what (emergently) solves your problem
  - see what you can get rid off
- tune! tune! tune!
  - too much terrain and more to come
  - measure and visualize first, then modify
  - design data structures after AI (query) patterns
- yep, this will take you time

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References + Suggested Reading

  - http://www.sisostds.org/cgf-bl9th

- Dave Pottinger, "Terrain Analysis in Realtime Strategy Games" in GDC 2000

- William van der Sterren, “AI for Tactical Grenade Handling”, 2000

Questions?

- Waypoint distribution?
- Waypoint placement?
- Do the algorithms run in real-time?
Questions?

Q Do the waypoints need to be distributed as a uniform grid?

A Most algorithms presented assume a more or less uniform distribution of waypoints across the terrain (see ‘focus’). However, the algorithm is largely robust to deviations from the uniform distribution. It makes sense to cover outdoor feature-less terrain with fewer waypoints, while increasing the waypoint density near obstacles.
Questions?

Q Are the waypoints automatically placed?

A The waypoints are placed semi-automatically. The process is not fully automatic (as, for example, Quake III Arena), but requires a player to visit all locations in the game. Waypoints are spawned automatically when the player visits location not visited before.

Note that the algorithms are independent of the way waypoints are positioned.
Questions?

Q Do the algorithms run in real-time?

A Except for the sniping spot analysis, all algorithms run fine ‘real-time’ in the game (most of them were developed to run on a Celeron300, with 16+ AI NPC’s in the game).

The A* tactical path finding in general is the most expensive algorithm to run.
Credits

- reviewers (proceedings, presentation)
  - Jan Paul van Waveren
  - Doug Reece
  - Tobias Heimann
  - Markus Klinge

- screen shots from Quake II
  - by Id Software
  - content from mod Action Quake2
    - action.telefragged.com
    - www.botepidemic.com/aid/cgf/features.shtml

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