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Battlefield Robot Cybernation and Navigation

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Abstract

This report describes a paradigm of battlefield robot cybernation and presents, within that paradigm, a navigation technique for such robots. The navigation technique is an algorithm for route planning in an open terrain that contains areas with different characteristics, such as navigation speed or level of threat. Optimal routes for battlefield robots in such a terrain are task specific: for instance, the fastest route, the safest route, a hidden route, a combination of the three, etc. The robot route planning in this report is based on a granulation of the space-time world of the robot. The terrain map is represented by a rectangular mesh, and terrain properties are specified as average properties for each cell. The robot's position is assumed to be in the center of a cell, and its movements are restricted from one cell center to one of the eight neighbor cell centers. The algorithm for finding optimal routes in the granulated terrain uses Huygens' principle of wave propagation and provides a complete solution for the navigation problem. This report presents the navigation technique for a stationary destination and fixed terrain, but, because of its simplicity, it can be easily adapted to follow moving destination points and accommodate changing environments.

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1. Introduction

The Army has built and successfully tested robotic unmanned ground vehicles for scout missions [1]. To supplement these results, the Army is interested to determine the feasibility of simultaneous deployment of several cooperative unmanned ground vehicles. Such an extension of the operations from one robot to several cooperative robots demands a nontrivial increase of the robots' capabilities to navigate in a dynamically changing environment and to make intelligent decisions based on incomplete and contradicting information. It also requires a carefully designed structure of the robots' decision making algorithms and an appropriate model of a robot's world view. The purpose of this report is to present a working paradigm of the cybernation of a battlefield robot and a route-planning algorithm within that paradigm.

In this report, we are mainly concerned with the planning of long-range routes. For a battlefield robot, such routes are with lengths of the order of kilometers and down to about 10 meters. This means that small obstacles (potholes, explosion craters, equipment of the size of the robot, etc.) are of no concern for the route planning. Avoidance of such obstacles requires strategies that are different from long-range route planning and should be delegated to special programs. The route-planning task is specified by providing an approximate terrain map, indicating a point of destination, and asking the robot to find an optimal route based on such information. The terrain map should contain information about attainable speeds in various parts of the terrain, location and shape of large impenetrable obstacles (e.g., lakes and rivers, levels of danger, visibility and detectability information, and other information that is essential for the task). In case of a robot group, the initial information should also contain the locations and destinations of all other robots within the group.

The route-planning method should be fast, simple to implement, and easy to adapt to changing conditions when new information about the terrain, obstacles and other robots becomes available.

There are two principal types of long-range route-planning algorithms for robots: potential-field methods and navigation-function methods. The potential-field method was introduced in 1978 by Khatib and Le Meitre [2] as a method to avoid obstacles in cluttered environment. In that method, obstacles are modelled by singularities in a repulsive potential field, causing a robot to circumnavigate them. It was soon recognized, however, that a pure potential method has disadvantages (mainly, the existence of local minima) (see Koditschek [9]). Therefore, several modifications have been suggested [3-5] but they either considerably complicate the route-planning algorithms or are restricted to certain types of obstacles. An essential improvement was suggested in 1988 by Rimon and Koditschek [6-8] by introducing the idea of a navigation function that was defined as a function with only one minimum at the destination and uniform height at obstacle boundaries. These functions cannot be constructed with the aid of potential functions (except in the simplest cases), and other methods must be devised. One such method was suggested by Barraquand, Langlois, and Latombe [9] and Barraquand and Latombe [10, 11] and actually implemented by Lengyel et al. [12]. The method is based on the calculation of a wave-front expansion from a signal that is emitted from the destination point, whereby the lengths of the signal paths are calculated in terms of the so-called "Manhattan distance" in a map with rectangular blocks. The navigation route of the robot is obtained from the wave-front expansion function by additional analyses and calculations that ensure smooth paths and avoidance of obstacles [13].

The route-planning algorithm in this report is based on the construction of a function that shares with the navigation function of Rimon and Koditschek its most important property: a unique minimum at the destination that prevents the robot from becoming stuck in a local minimum. It is calculated by using Huygens' principle of wave propagation [5, 6]. The optimal route of the robot is obtained by steepest descent, and additional analyses are usually not needed. For battlefield robot route planning, this approach, which uses information about terrain conditions and allows motion in eight directions, is more useful than a wave-front expansion function that relies on Manhattan distances, ignores terrain conditions, restricts motion to four directions, and requires additional algorithms for route construction.

In Section 2, we describe the paradigm of the cybernation of battlefield robots, the world view of a robot, and the information flow within a robot's memory. Section 3 describes the granulation of the robot's world view. The calculation of the navigation function, with the help of Huygens' principle, is outlined in Section 4. Section 5 presents route-finding algorithms, and Section 6 contains examples. Section 7 is a summary of the report.

2. Paradigm of the Cybernation of Battlefield Robots

To behave intelligently, a battlefield robot must have a description of its environment stored in its memory. The description constitutes the world view of the robot and task planning is carried out within this description. Figure 1 is a list of the essential information that is needed to define the robots world. Most of the items in the list are self-explanatory. The route planning is one of the tasks in the "list of tasks" under the heading "Future Activities to be Planned." Route planning can be exercised independently of and concurrently with other activities of the robot. For a route-planning task, the robot will be given coordinates of a destination (and other information, if needed, such as admissible levels of threat) and the instruction to compute a route. A subsequent task could be, for instance, to start navigation along the computed route at a given time or on a given signal.

The "Targets" listed in Figure 1 are distinct from the robot's destination. In the context of battlefield robots, targets are objects of interest that should be observed, reported, attacked, etc. The "labeled targets" are descriptions of objects that the robot is supposed to recognize when acquired by its sensors.

- **Self**
  - ***Coordinates***
    - Time and date
    - Location
    - Orientation
    - Velocity vector
    - Rotation vector
  - ***Technical State***
    - Fully operational
    - Mobility impairment
    - Communications impairment
    - Firepower impairment
    - Vision impairment
  - ***Tactical State***
    - Idle
    - Navigating
      - Dedicated
      - Evasive
    - Observing
    - Attacking
  - ***Future Activities to be Planned***
    - List of tasks
- **Others** (other robots)
  - ***Coordinates***
  - ***Technical State***
  - ***Tactical State***
  - ***Next task***
- **Targets**
  - ***Labeled targets and properties***
  - ***Generic targets (objects) and properties***
- **Terrain**
  - ***Navigable Areas***
    - Coordinates (x,y,h)
      - Degree of safety
      - Attainable speed
  - ***Obstacle Areas***
    - Coordinates (x,y,h)

Figure 1. Information defining a robot's world.

The information flow that produces the world-view files of a robot is outlined in Figure 2. The information is obtained from three different sources. An initial part of the information is stored in the robot's memory before the start of the mission; a second part is obtained by radio transmissions during the mission, either from the command center or from other robots; and a third part is obtained from sensors during the mission. The acquired data must be appropriately screened, modified, and fused to generate a clean current version of the world view. Also in this part of the process, optimal long-range routes are calculated according to specified tasks and included in the data basis as a property of the terrain. (The technique is described in Sections 3 and 4 of this report.) The resulting collection of data is passed to a decision-maker program that decides which actions the robot should take and what movements should be attempted. Among other things, the decision maker will also decide when and how the robot should deviate from the route that is included in the world view of the robot. To do this, the decision maker might use the same technique as was used for the long-range route by applying it on a detailed map and, if necessary, supplementing it with algorithms for short-range motion planning.

The data that are acquired from the environment are heterogeneous, and different parts of the data will require different treatments. Contradictions among the data must be resolved or indicated by a warning signal. We now shortly discuss, in turn, the characteristics of each data source.

Data that are received from the command center are likely to be least complicated. Usually, they will consist of task assignments or information about changing environment (e.g., weather changes, new obstacles, new other robots, newly identified targets, etc.). Difficulties might arise from bad communications that can cause the loss of a command or instruction. Contradicting task assignments are possible. When contradictions are detected, the data fusion program attaches a warning signal to the corresponding task assignments for the benefit of the decision maker.

Data provided by other robots will mainly consist of information that is needed for cooperative actions, such as robot coordinates, states, and assigned tasks. Information about targets and terrain that is received from other robots should be checked for consistency because such data can be contradictory. For instance, a target that is classified by robot *A* as a threat might be recognized as friendly by robot *B* who is closer to the target. Similarly, information about terrain conditions in the vicinity of a robot can be invaluable for other robots, but contradictions among different sources are possible. These contradictions should be resolved by the information fusion program and the decision maker should be provided with an updated "clean" terrain and target version.

Sensor information about targets typically will be passed through an automatic target recognition (ATR) screen that provides classification of targets according to a target alphabet. Targets that cannot be identified might be classified as generic targets (essentially, moving unidentified objects). The information fusion program should cross-check any ATR output with information from other robots and also check whether the generic targets have been recognized and classified by other robots.

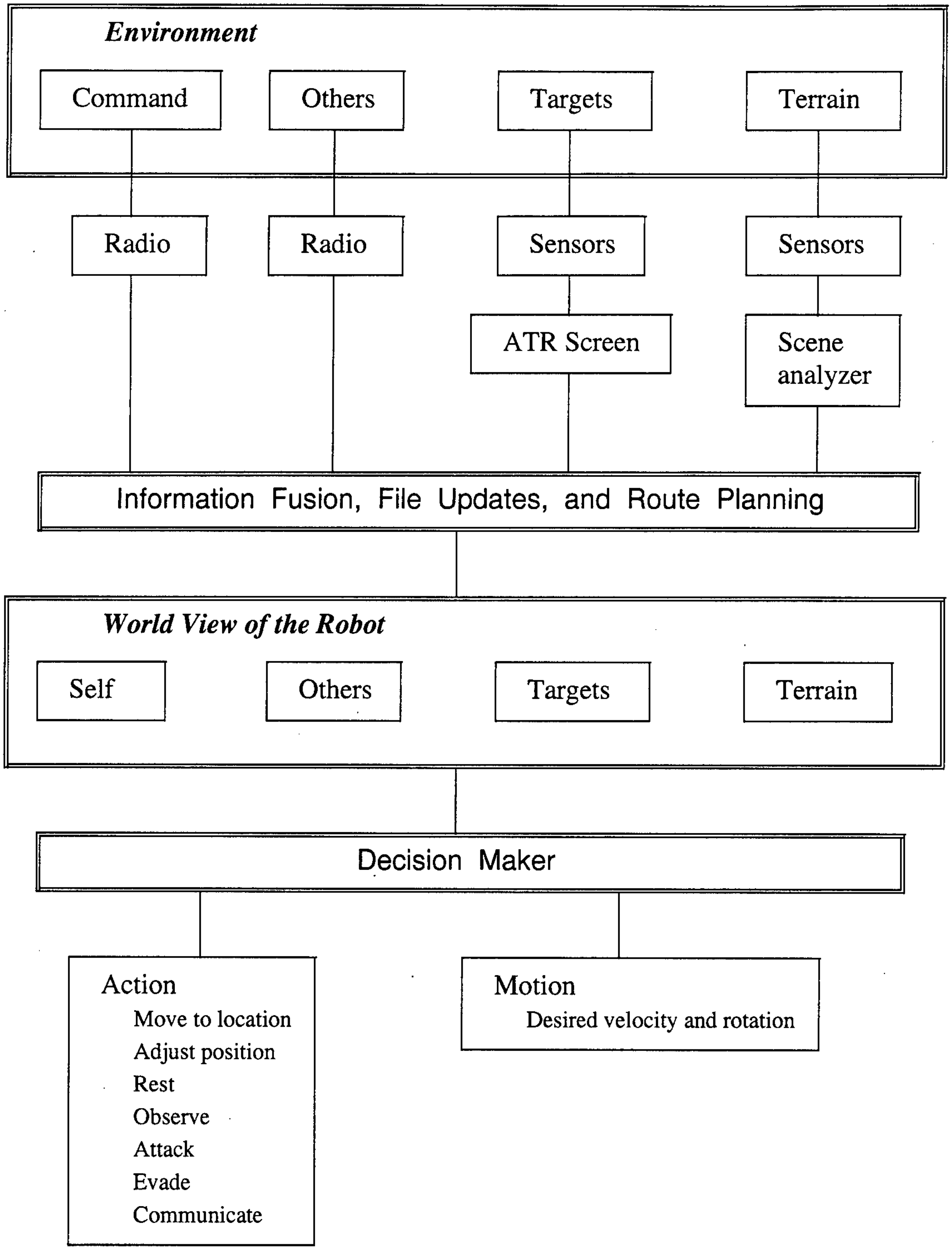

Figure 2. Schematic of robot cybernation.

Sensor information about changing terrain conditions is important for all robots that operate in the same area. This information should also be checked against other sources and contradictions resolved to provide a unique terrain map for the decision maker. The communication of the final terrain map to the other robots should be done by the decision-maker program.

3. Granulation of Terrain and Time

A simple and flexible method to store a working copy of the terrain map in the robot's memory is to granulate the map by subdividing it in rectangular cells and to store the cell array with quality indexes attached to each cell. The approximation that is caused by granulation is of little consequence for long-range route planning. Also, the cell size can be changed as necessary. Interpolation techniques, in association with grid-changing, are well developed for multigrid solutions of partial differential equations. A typical cell size of a terrain map for battlefield robots has an order of magnitude between 2 m and 50 m, depending on the task because such a size is adequate to determine an approximate route in a battlefield environment. Terrain characteristics and obstacles that require much finer grids for adequate representation might be treated more efficiently by near-field robot motion planning techniques. An exception is the navigation through a maze (a house) that can be handled with the technique presented here and a fine grid. Also, the same technique with cell sizes larger than 50 m can be used for route planning for helicopters and airplanes in hostile territory and around weather patterns.

The terrain quality index that is attached to each terrain cell is a vector, characterizing average properties of the terrain covered by the cell. These properties are the speed that can be typically achieved by a robot crossing the cell, the level of danger, visibility information, and other properties that are important for the assigned tasks. In cells that represent impenetrable obstacles, the navigation speed is specified as a very small number or zero.

The robot's position is assumed to be in the center of a cell. The planned trajectory is a sequence (list) of cells that the robot should visit along its way toward the destination. Hence, for the route-planning algorithm, the time is not continuous, but is a sequence of time steps of such lengths that are necessary for the robot to proceed from one cell center to the next. Because the speed of the robot is different in different parts of the terrain, the time steps have different durations.

The details of an actual path of the robot will in general deviate from the planned route. For instance, if the route crosses a wooded area, then the robot will execute many turns to circumnavigate trees. In such cases, the planned route merely provides the robot with a general bearing, and it is assumed that the presence of cluttered obstacles has been taken care of by specifying a low navigation speed in the respective area.

4. Calculation of Huygens' Relief

The route-finding algorithms in this report are based on a navigation function that specifies, for each point of the terrain, the shortest travel time from that point to the destination. We call this function a Huygens' relief. Because we are dealing with granulated terrain maps, the Huygens' reliefs are functions that are only defined at the centers of each cell, that is, at the virtual positions of robots.

The values of a Huygens' relief are obtained by calculating, for each cell, the arrival time of a signal from the destination point, whereby the speed of the signal in each cell is assumed to be equal to the navigation speed. For the computation of the signal arrival time, we use Huygens' principle of wave propagation as follows. The arrival time at the destination cell is set equal to zero. For other cells, the arrival time in a center cell is calculated by treating all of its eight neighbor cells as sources and computing the signal arrival times from these sources. Then the arrival time in the center cell is set equal to the smallest value among these arrival times. The algorithm is applied to each cell in sequence and provides the correct signal arrival time in each cell center after a sufficient number of sweeps over all cells.

The number of sweeps in a reasonable terrain with n^2 cells should be about n, but that number can be reduced to two to four sweeps without sacrificing the simplicity of the algorithm by a proper arrangement of the sequence of sweeps. (A theoretical upper limit is, of course, of the order of n^2 because one can construct mazes where each iteration produces the final arrival time for only one cell.)

To start the calculation of Huygens' relief, the signal arrival time at the destination cell is set equal to zero, and all other cells are assigned a large number as arrival time. Next, the arrival time for each cell is calculated by the following formalism. Let $x_{i,j}$ and $y_{i,j}$ be the coordinates of cell centers, $s_{i,j}$ be the speed in cell (i,j), and $t_{i,j}$ be the corresponding arrival time. The arrival time for a signal that arrives in cell (i,j) from a neighbor cell (k,l) is

$$t_{i,j}^{k,l} = t_{k,l} + 0.5\,(\,1/s_{k,l} + 1/s_{i,j}\,)\,(\,(x_{k,l} - x_{i,j})^2 + (y_{k,l} - y_{i,j})^2\,)^{1/2}\ . \qquad (1)$$

The updated arrival time $t_{i,j}$ in the cell (i,j) is set equal to the minimum of the values $t_{i,j}^{k,l}$ over the index sets $i-1 \le k \le i+1$ and $j-1 \le l \le j+1$.

In a field without obstacles, the exact arrival times are obtained in one sweep along any ray from the source. To design a strategy for a fast computation of an initial approximation to the Huygens' relief, one can use this fact and first calculate the arrival times along a meridian through the source and continue with calculations along latitudes in East and West directions, respectively, that start from the meridian. In a field with simple obstacles, this produces the final arrival times in one sweep. To accommodate complex obstacles, the initial field might be updated by alternatively sweeping in different directions. In actual examples using a grid with 200 × 200 cells, convergence was usually achieved in less than 4, and at most 12 sweeps.

If the terrain contains nonstationary obstacles, then Huygens' relief must be updated after each terrain change. These updates can be done economically by observing that the relief is changed by a new or removed obstacle only in the shadow of the obstacle. Corresponding update calculations can, therefore, be confined to an approximate shadow area. On the other hand, if the new or removed feature is not an obstacle but rather a road with higher speed than its surroundings, then the changes in Huygens' relief are not limited to the shadow of the feature, and update calculations outside the shadow area might be needed.

5. Route Planning With Huygens' Relief

For each virtual position of a robot (each cell center) Huygens' relief specifies the value of the shortest travel time to the destination, but it does not identify the routes that correspond to that travel time. Such routes can be found in a Huygens' relief by local algorithms, that is, by algorithms that use only information from the present position cell and its neighbor cells. Let the routes that require the least time of travel be called optimal routes. For any given position of the robot, the local route-finding algorithm determines the neighbor cell that should next be occupied to travel along an optimal route. The algorithm is then applied to the next cell, etc., until the destination is reached. This route-planning process provides a very useful flexibility for the navigation in open terrain; because routes need not be fixed in their entirety ahead of time, unexpected changes in local conditions can easily be accommodated by a corresponding choice of the next planned position. We note that Huygens' relief also identifies those cells from which the destination cannot be reached at all; therefore, the local route finding algorithms provide, with the help of Huygens' relief, a complete solution to the navigation problem.

One can distinguish the following types of route-planning goals:

(1) find an optimal route,
(2) find all optimal routes that satisfy some additional conditions, or
(3) find any route that satisfies some specified condition.

The algorithms for finding these routes are based on Eq. (1) and are very similar.

For a given robot position, the next cell along an optimal route is any of those neighbor cells that is a source for the Huygens' relief (i.e., a cell from which the signal arrival time to the robot's position equals the value of Huygens' relief). Since signal arrival times are calculated with Eq. (1) source cells can be found by a recalculation of $t_{i,j}^{k,l}$ for all those neighbor cells (k,l) that have a lower arrival time than the position cell (i,j). If the recalculated signal arrival time is equal to the value of Huygens' relief at the position cell, then the cell (k,l) is a source for the cell (i,j). (We note in passing that another method to identify source cells that avoids recalculations is to label the source cells during the initial calculation of Huygens' relief.) The number of different bearings that can be chosen to start a travel along an optimal route equals the number of source cells.

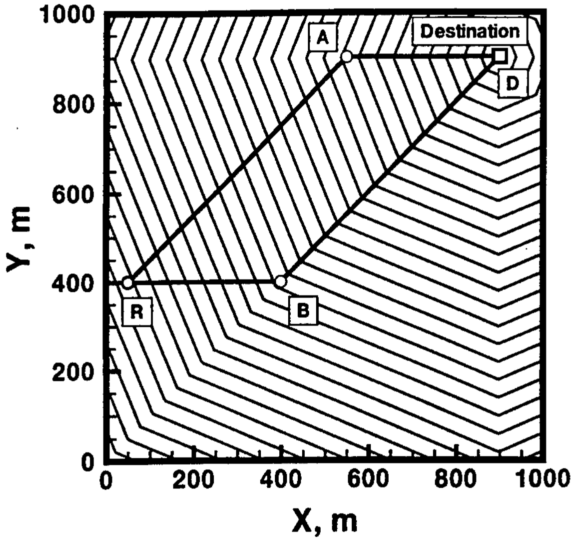

Figure 3. Optimal routes in uniform field.

A case with more than one optimal route is presented in Figure 3. It shows a contour map of Huygens' relief for a terrain with uniform navigation speed. The destination is indicated by a square in the NE corner of the map, and the contour lines are octagons around the destination. (They are octagons instead of circles because the signal propagation and travel direction are restricted to the directions toward the eight neighbors of any cell.) Optimal routes for a robot positioned at *R* are the routes *RAD*, *RBD*, and any other route within the parallelogram *RBDA*. Each cell within the parallelogram has two source cells: its *E* and *NE* neighbors. Therefore, a robot travelling from *R* to *D* has, at every station along its way, a choice between two optimal directions. If one always chooses the left-hand source cell as the next position, then the result is the route *RAD*. Always choosing the right-hand source cell produces the route *RBD*. By judicious choice of the next position between the two source cells, one can trace all possible optimal routes. The described source-cell algorithm thus produces all optimal routes. Any one of them constitutes a solution of goal (1). Solutions for goals (2) or (3) are obtained by selecting, among the provided optimal routes, those which satisfy the additional conditions. In the worst case, this might require a simple enumeration, but, depending on the additional conditions, more efficient solutions will usually be available.

As an example for the choice of a specific optimal route we consider the additional condition that the route should approximate a shortest distance route in Euclidean geometry. If the terrain were not granulated, then the shortest distance route could be obtained by moving into the direction of steepest descent in Huygens' relief. We approximate this by choosing, alternatively, the left-hand and the right-hand source cell, respectively, for the next position. The result is illustrated in Figure 4, where the calculated optimal routes are shown for a number of starting positions. The routes do not exactly follow the shortest distance route, but they are steepest descent routes in the

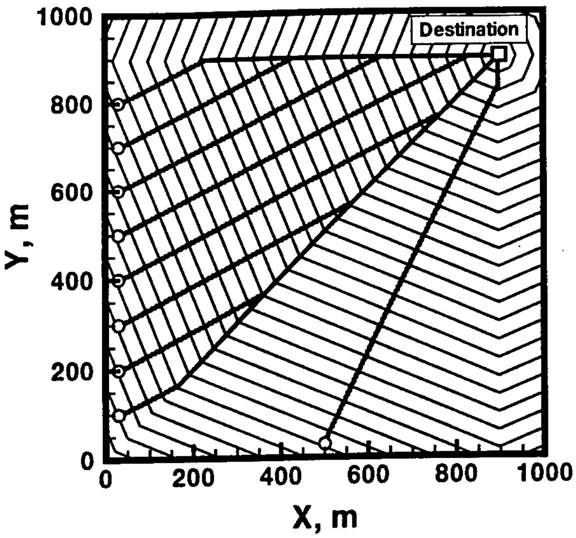

Figure 4. Steepest descent routes.

granulated Huygens' relief. Since the routes are determined from local information (the coordinates of the destination are not used by the route-planning algorithm) these results are the best approximations to the shortest routes that can be obtained from a granulated terrain representation.

In most applications, the terrain will not be uniform, and there will be only one optimal route. However, because the crossing of areas with uniform navigation speed is a frequent subtask of battlefield robot route planning, an algorithm that alternatively chooses the left-hand and right-hand source cells should be used as a standard. Other interesting cases are situations where the route planning involves choices among several routes with comparable but not equal travel times. To compute the travel time for a route that starts with a neighbor cell, which is not a source, we again use Eq. (1) and compute the signal arrival time from that cell. In general, such alternate routes should start with a cell that has a smaller travel time than the present position cell. Proceeding along routes with increasing travel times can result in eventual backtracking.

6. Examples

We illustrate the use of Huygens' relief to route planning in an example of a simple terrain. Figure 5 shows the granulated terrain map. The different shades indicate different navigation speeds in the respective area, starting with light shade for high speed. In this example, there are four speed levels that can be thought of as corresponding to roads, open fields, wooded areas, and impenetrable areas (e.g., lakes or swamps, respectively). The corresponding navigation speeds were assumed to be 20 m/s, 1 m/s, 0.1 m/s, and 0.01 m/s. The last value, 0.01 m/s, represents impenetrable areas and has no physical meaning, and it was simply chosen sufficiently low in comparison to the other values so that a circumnavigation of the area was ensured. The destination is indicated by a square near the center of the map, and the initial locations of five robots are indicated by circles. The task for the robots is to find optimal (smallest travel time) routes to the destination.

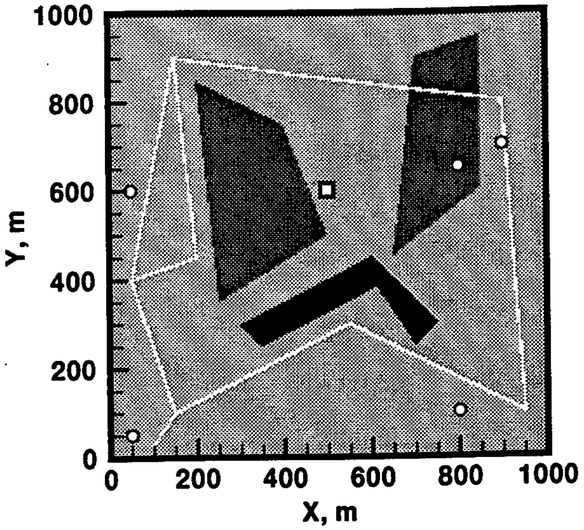

Figure 5. Example of a simple terrain.

The optimal routes are shown in Figure 6. As expected, the robots make use of available roads and move approximately straight toward the destination in open fields. The robot who was originally located in a wooded area first finds a shortest path out of the wood and then proceeds towards the destination.

The same solution as in Figure 6 is shown in Figure 7, overlayed on a contour map of Huygens' relief. The contour lines show, among other things, that the robot who initially was located in a wooded area could leave the woods in three different directions, along routes with practically the same travel time. The contour lines also indicate several other areas from which one has a choice among radically different approximately optimal routes. One such location is, for instance, the area with $x \approx 550$ m and y between zero and 300 m. In practical applications, the existence of nearby alternative routes can be very important. Mathematically, the locations of areas with nearby alternative routes are ridges and saddle points of a Huygens' relief, and they can be identified by a simple mathematical analysis of the function.

The next example illustrates navigation through a maze, such as a house. Figure 8 shows the outline of a maze. The position of the destination is indicated by a square, and initial positions of robots are indicated by circles. For the planning of routes through a maze, the size of the robot must be taken into account because the robot must be able to negotiate narrow passages between impenetrable obstacles. This is different from long-range route planning, where the relevant

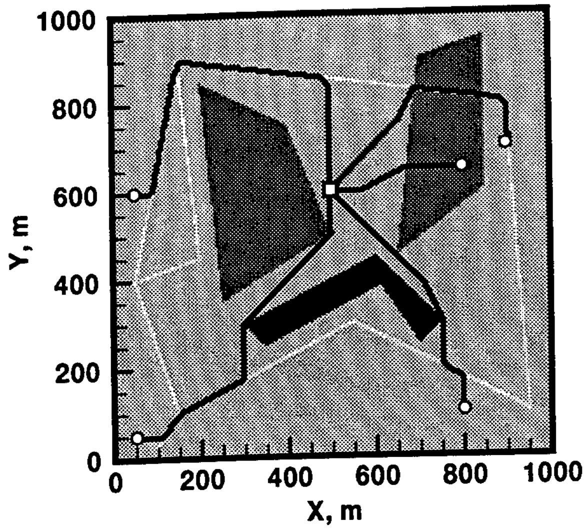

Figure 6. Optimal routes in a simple terrain.

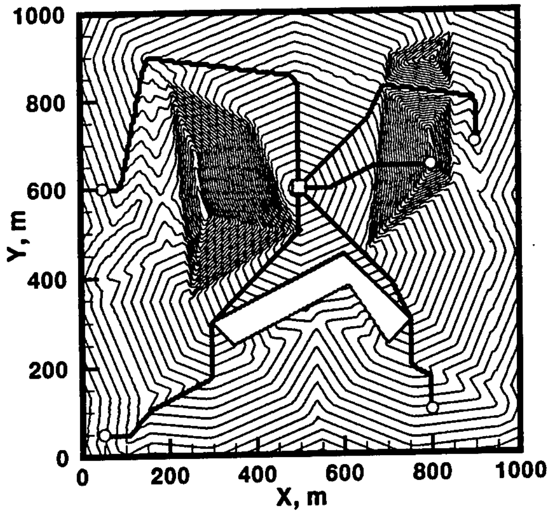

Figure 7. Optimal routes in Huygens' relief.

characteristic of an open terrain is the navigation speed, and the size of the robot is not very important. In a maze, the robot's size can be taken care of by augmenting the sizes of impenetrable objects by a half-diameter of the robot. The obstacles that are obtained by this addition are called C-obstacles [13]. In a granulated terrain map, C-obstacles can be efficiently constructed by an algorithm that replaces the value of the navigation speed index in every cell by the maximum of index values in those neighbor cells that are located within an area that approximately equals the area of the robot. This algorithm produces a terrain map where all obstacles are modified to

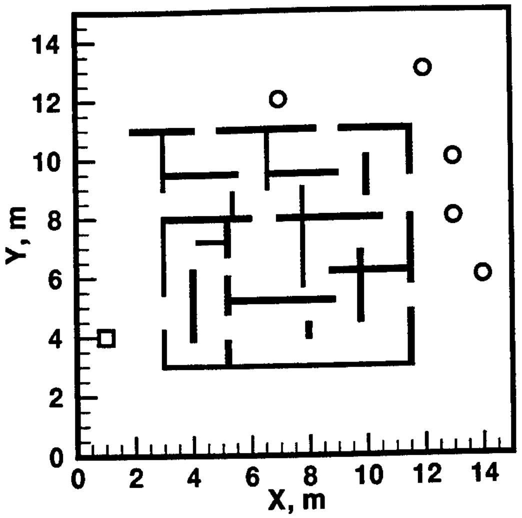

Figure 8. Maze and initial positions.

C–obstacles (and all areas with higher speed indexes than their surroundings modified to "C-areas"). The computation of the Huygens' relief for finite-size robots is based on such modified terrain maps with C-obstacles of appropriate size.

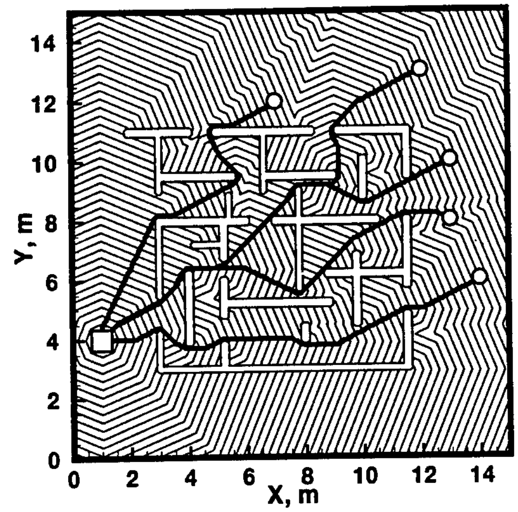

Figure 9. Routes of small robots through a maze.

Figure 9 shows the maze of Figure 8 with contour lines of Huygens' relief and corresponding robot routes. In this example, the granulation cell size was 75 mm, and the diameters of all robots were 0.2 m. Because all passages in the maze have openings that are larger than 0.2 m, the routes shown in Figure 9 are practically the same as for robots with zero diameters. The Huygens' relief in Figure 9 is that of the original maze without modifications for a finite dimension of the robots. One observes that by following approximately the direction of steepest descent, the robots can take advantage of the various passages through the maze.

If the sizes of the robots are increased, then some openings in the maze cannot be used, and the routes change correspondingly. This is illustrated in Figure 10, which shows in the same maze optimal routes for robots with 0.4-m and 0.6-m diameters, respectively. If the robot diameters are larger than 0.7 m, then the maze becomes impenetrable for such robots and is circumnavigated from all initial positions.

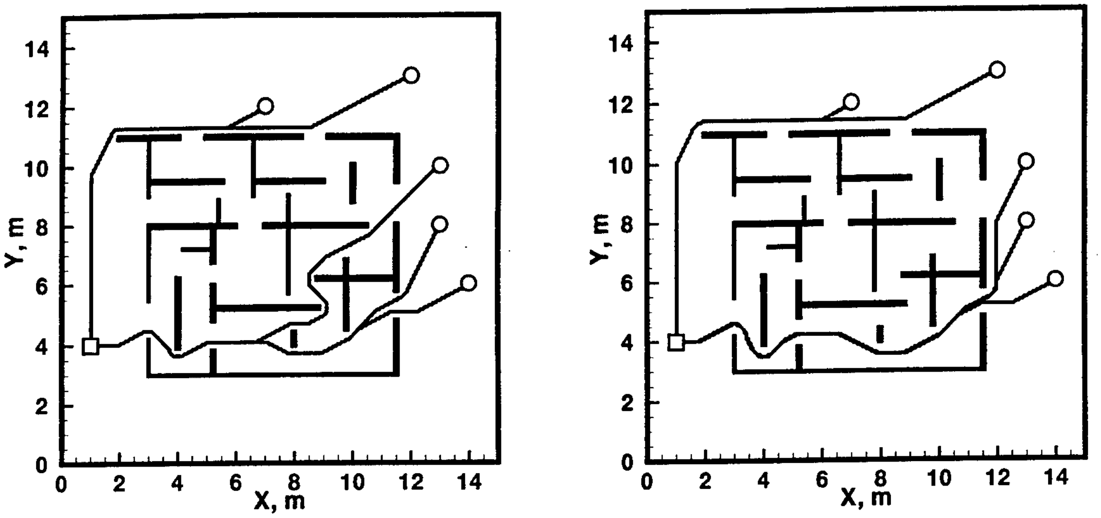

Figure 10. Routes of robots with finite diameters through a maze.

7. Summary and Conclusions

We have discussed a concept of the cybernation of battlefield robots and presented a detailed description of route-finding algorithms based on Huygens' principle of wave propagation. The algorithms are developed for a granulated representation of the terrain and provide optimal routes for navigation in open terrain. Examples of route finding in this report are restricted to stationary destination points and static terrain. The route-finding algorithms are, however, so simple, that an application to moving destination points and dynamic terrain should be easily implementable.

A problem that has to be considered when the algorithms are implemented in actual robots in open terrain is the economic storage of terrain information. The route-finding technique is designed to work with granulated terrain maps. In the pilot programs presented here, the terrain was represented by a map with fixed cell sizes. Such a terrain representation is adequate if the navigation space is restricted, for instance, to a laboratory space for experimental work or to a building of moderate size (in terms of the size of the robot). For navigation in open fields, the terrain representation should be made more flexible, allowing to switch from detailed to coarse maps and back. A simple but wasteful approach to this problem is to store the terrain information in a huge map with very fine granulation and obtain the necessary coarser maps by interpolation. Such an approach might not be practical, however, because the storage facilities within a robot are limited and extraction of data from a massive storage can be time consuming. A more practical approach would be to store all information about the terrain in a concise form that is independent of a granulation and construct granulated maps with the desired coarseness as the need arises. A problem that must be solved for this approach is the design of a concise form for the description of a general map.

Some problems that were not addressed in this report are the navigation in partially specified terrain where the robot establishes a terrain map with the help of its sensors during navigation, the cooperative navigation of several robots, and the navigation under additional constraints. These problems are in principle solvable within the framework of navigation in Huygens' relief and are subject of ongoing work at ARL.

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This report describes a paradigm of battlefield robot cybernation and presents, within that paradigm, a navigation technique for such robots. The navigation technique is an algorithm for route planning in an open terrain that contains areas with different characteristics, such as navigation speed or level of threat. Optimal routes for battlefield robots in such a terrain are task specific: for instance, the fastest route, the safest route, a hidden route, a combination of the three, etc. The robot route planning in this report is based on a granulation of the space-time world of the robot. The terrain map is represented by a rectangular mesh, and terrain properties are specified as average properties for each cell. The robot's position is assumed to be in the center of a cell, and its movements are restricted from one cell center to one of the eight neighbor cell centers. The algorithm for finding optimal routes in the granulated terrain uses Huygens' principle of wave propagation and provides a complete solution for the navigation problem. This report presents the navigation technique for a stationary destination and fixed terrain, but, because of its simplicity, it can be easily adapted to follow moving destination points and accommodate changing environments.

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