Path Planning in an Unknown Environment on the basis of Observations of Occluded Areas

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***Abstract*—In order to get to a destination in an unknown environment, one must make efficient observations of the environment while moving toward the destination. This report begins with a classification of the conditions under which an observer's view is blocked (occlusion). Once the agent has classified the visible occlusions in its environment, it determines the next point from which to carry out observations. A method is proposed here for planning the path to a given destination by planning a path to successive observation points. In doing so, the proposed path to the destination passes through a series of observation points. A simple algorithm is used to determine the location of the next observation point. The method allows planning calculations to be performed in real time and also provides sufficient flexibility for mapping of obstacles with curved surfaces. This search scheme also separates and alternates between the tasks of moving and taking observations, which facilitates the programming of real robots to use this algorithm. Simulations of operations using this algorithm in a variety of environments are described in this report.**

I. Introduction

What does a person do when they open their eyes and find themselves in a labyrinth that they have never seen before? They begin by looking around and considering how best to escape from the labyrinth. If such a person were to encounter a completely sealed room upon looking around, they may approach one of the walls and begin testing different methods of escape. Alternately, if they see something that looks like an exit, then they are likely to move directly towards it. On the other hand, if the observer does not find an exit, but is still unable to tell if the room is completely sealed, what will they do? Since there may be spaces that are not visible from their initial location, the observer will almost certainly move from his initial location so as to get a better look at their surrounding. It is also important to consider how such an observer would realize when there is space that is hidden. In reality, we instinctively know that such spaces can be negotiated based on discontinuities in the observed environment.

This report describes the responses of an agent with no previous knowledge of a given environment. Specifically, this study focused on how the agent identifies hidden regions (occluded areas) from discontinuities in their observations and how the agent then searches those areas from which it can exit that environment, and in so doing, acquire knowledge about its surroundings. Taken together, these processes enable the agent to escape from the labyrinth.

The path planning procedures are based on information about the occluded areas and these procedures enable the agent to learn about the labyrinth. The specific procedures developed in this research begin with identifying occlusions and classifying them as one of three types: (1) An obstacle that hides another region or obstacle (forced occlusion); (2) the surface of an obstacle is at such a sharp angle with respect to the agent that the agent cannot distinguish between of the surface features (autonomous occlusion); and (3) a region or the objects in it cannot be observed because they are not within the agent's field of view (FOV occlusion). Adopting this classification facilitates clarification of the reasons responsible for the occlusion and enables the agent to determine an efficient exit path. However, importantly, the detection of occlusions is not only dependent on the relative positions of objects, but also on the characteristics of the distance sensors employed by the agent. Consequently, several assumptions need to be made regarding the characteristics of the sensors used in this research: (a) Distances of up to infinity can be detected; (b) the viewing angle is finite; and (c) observation data can be regarded as a discrete series. Assumptions (b) and (c) are the most important. Limiting the viewing angle means that objects outside the agent's FOV cannot be measured. When the observation data have the form of discrete series, there are slits between the data sets, i.e., unobserved locations. The greater the tilt of the surfaces of obstacles for any given observation, the larger these blanks will be. A path-planning algorithm is introduced that considers the classifications of the occlusions, which then identifies the most efficient observation points and is then used to move the agent between the two points. Following this path allows the agent to efficiently observe the occluded areas and, ultimately, to locate the exit.

Previous studies have demonstrated the application of typical search algorithms such as A*[2] and LRTA*[3] which have been applied to the elucidation of paths for leading agents to pre-determined destinations. A* seeks the optimum among all possible paths before undertaking its initial motion, and is thus usually employed in situations where the environment does not change and the destination itself does not move. Conversely, LRTA* seeks the optimum local path while the agent is

978–1–4244–1674–5/08/$25.00

moving, and is thus employed when it is necessary to perform fast calculations. Another algorithm RTEF[4] considers the agent's current location, the destination, and the locations and shapes of obstacles in order to optimize search efficiency. It should be noted that LRTA* and RTEF, which are designed to minimize calculation time, both allow for motion of the destination. All of these algorithms assume that the locations of the destination (whether they are moving or stationary) are already known, and these algorithms emphasize strategies for planning the motion of the agent.

When the locations of the destination or of the obstacles are unknown, however, it is not possible to calculate an optimum path. The agent must then observe its nearby environment, and develop a strategy for conducting efficient observations. This is the situation addressed by this report.

There are some path planning procedures that emphasize strategies for observations. Such procedures actively seek out occluded areas in order to arrive at the destination. Reference [5] describes a successful attempt to get a robot to conduct a search in, and navigate through, an unknown environment toward an unknown destination. However, the path strategy that was employed was directed at simply driving the agent toward the borders between the visible area and occluded areas; the system was unable to develop an efficient plan that reflected how the obstacles were perceived.

The procedure proposed in this report creates an efficient motion plan on the basis of the type of occlusion. Reference [1] describes the planning of a path in order to efficiently observe an occluded area, using a kinetic model of the space between the occluded area and the agent. However, this algorithm assumes that the agent can move while it is making observations, something that is difficult to achieve in robots using current technology. An advantage of the proposed procedure over the previous procedures is that it calculates the most effective location for the agent based on observations before proceeding to that observation point in successive navigation processes. Therefore, there is no need for the agent to observe the environment while moving to the next location.

This report has the following structure. In order to clarify the character of the procedure suggested here, Part II introduces the assumptions made in relation to the agent. Part III describes the three classification methods used to characterize occluded areas. Part IV is a detailed description of the proposed algorithm. Part V mentions about exceptions with proposed algorithm and describes how to cope with these exceptions. Part VI shows the results from a simulation and discusses the potential applications of this method. Part VII presents our conclusions.

II. Assumptions related to Agents

Let us begin with some assumptions about the capabilities of agents. An agent has the following functions:

1) It is capable of moving in a straight line and of rotating (changing azimuth) in one place.
2) It possesses accurate instruments for measuring the distance from itself to an obstacle.
3) It can create an accurate map using its distance measurements.
4) It can accurately localize its position.

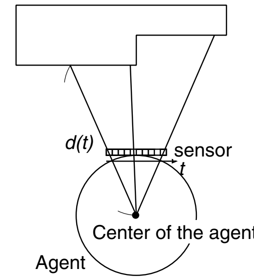


Fig. 1. Alighnment of the sensor of the agent.

The distance measurement instrument (sensor) shall meet the following specifications (Fig. 1).

1) It can only be used when the agent is stationary.
2) It is composed of cells arranged in a horizontal T pattern.
3) The row of cells lies perpendicular to the direction of motion of the agent.
4) The center of the cell array is a fixed distance from the center point of the agent toward the direction of motion of the agent.
5) The cells output the distance from the center point of the agent to the intersection of a line drawn from that center point of the agent through the cells to the surface of the obstacle. 't' is the variable expressing cell location and $d(t)$ is the distance output by each cell. The leftmost cell is the origin for $d(t)$ and $0 \leq t < T$.

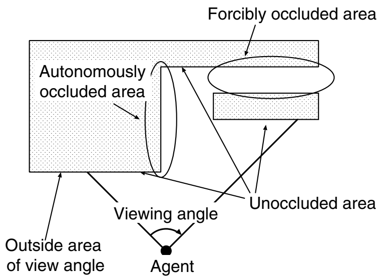
III. Occlusions

In this section, occlusions are classified into three types on the basis of relative positions of objects and the characteristics of the distance sensors. And efficient observation appropriate to each type of occlusion is introduced.

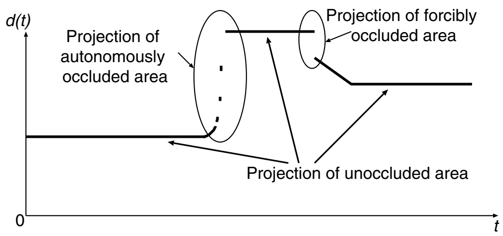
A. *Types of occlusion*

Occlusions can be classified into the following three types: Forced occlusions, FOV occlusions and autonomous occlusions.

- Forced occlusions
  Forced occlusions occur when there are two objects in front of the sensor and one of the objects is blocking the view of the other.
- FOV occlusions
  The sensors only have a limited area of view, and any surface that is not visible is handled as an occluded area. No shape information is available about objects outside the view triangle.
- Autonomous occlusion
  When a surface is at a steep angle with respect to the line of sensors, the greater the tilt of the surface, the lower the detected area of the surface. As a result, when the focal point of the sensor (the center of the agent) and the



(a) Observations of the surrounding environment.



(b) Typical measurement results.

Fig. 2. Three types of occlusion.

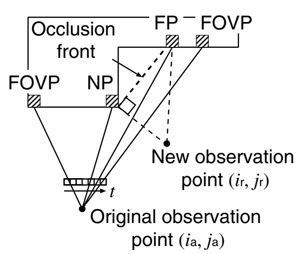


Fig. 3. Registration of occlusion borders.

surface lie on the identical line, the surface is completely disappear from the sensor. This kind of disappearance with respect to the sensors can be considered a kind of occlusion that is due to the character of the surface itself.

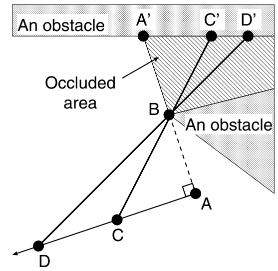
These classified occlusions appear to the sensors as discontinuities of distances toward obstacles. Fig. 2 depicts the three classifications and the measurement results.

B. Occlusion borders

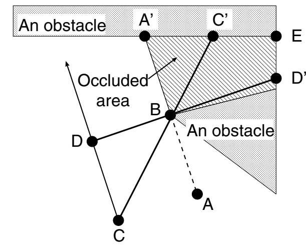
When the distance $d(t)$ to an obstacle satisfies the following inequality

$$|d(t) - d(t+1)| > \varepsilon, \quad (1)$$

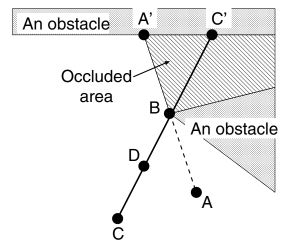
the agent detects an occluded area between the point on the surface of obstacle which gives $d(t)$ and the point which gives $d(t+1)$. These two points are also defined as the occlusion borders, with the closer and more distant of the two points referred to as the "near point" (NP) and "far point" (FP), respectively (Fig. 3). The straight line joining the NP to the FP is referred to as the "occlusion front". The points which gives $d(0)$ and $d(T-1)$ are designated as occlusion borders, classified as border points of FOV occlusions. These points are referred to as "FOV point"(FOVP).



(a) Moving perpendicularly to the occlusion front.



(b) Moving parallel to the occlusion front.



(c) Moving toward the Near Point.

Fig. 4. New observation point for forced occlusion.

C. Observation of occlusions

The agent intends to observe the occluded area not by the observation of the occlusion front but by the observation of the occlusion border. The agent specifies points for observing the occlusion border, moves to one of them, and begins observing. The following section presents some of the considerations related to improving the efficiency of observations.

- Forced occlusion
  When the area of interest is forcibly occluded, the further the agent moves in a direction perpendicular to the angle of the occlusion front, the greater the extent of the occluded area it can observe. The observable area from the new observation point C in Fig. 4(a) is triangle BC'A'. Or, if the agent observes the occluded area from point D, on line ACD, which is perpendicular to the occlusion front and further from the front than point C, then the newly observable area is △BD'A', which is larger than △BC'A'. Alternatively, moving closer to the occluded area in the direction parallel to the occlusion front also increases the view of the occluded area. In Fig. 4(b), if the agent conducts observations from point D, now on the line CD parallel to the occlusion front, the observable area is quadrangle BD'EA', which is larger than △BC'A'. If the agent travels along a line radiating from the NP, however, the observable portion of the occluded area never changes (Fig. 4.(c)). The lower the angle between the line connecting the observation point and the NP (line BD in Fig. 4) and the occlusion front (line BA'), the greater the extent of observable area. In Fig. 4(a), the observable area from the observation point D is larger than that from point C. Correspondingly, ∠DBA' is lower than ∠CBA'. The same relationships occur in Fig. 4(b).

Meanwhile, in Fig. 4(c), points C and D are on the same line radiating from the NP, the dimensions of the observable area are constant and ∠DBA' = ∠CBA'. Thus, it would appear to be a good planning strategy to place the new observation point near the FP (point A'), where ∠ DBA' will be relatively small and the observable area may be large. However, this increases travel distance for only a questionable gain in observations, since it is not known how large the occluded area really is, as it depends on the shape of the objects. Thus, a better new observation point lies on a line from the NP radiating perpendicular to the occlusion front. Ideally, it should also be far from the NP in order to minimize the influence of the FOV-occluded area. The further away it is, however, the greater the potential for other obstacles to interfere with the agent, which would increase the travel distance. Therefore, the new observation point is selected close to the NP and on a radial line from the NP perpendicular to the occlusion front.

- Autonomous occlusion
  When the area is autonomously occluded, more of it can be observed if the agent moves perpendicular to the direction of the surface, or if it approaches the occlusion front. Therefore, the same method is used for observing autonomous occlusions as for forcibly occluded areas.
- FOV occlusion
  When the area is outside the view triangle, it can be observed by moving away from it, or by rotating toward it. It usually costs less to rotate than to move, so rotating is the most efficient way to widen the agent's field of observation and is the usual action.

In view of the above considerations, the observation points are planned as follows.

- Forced occlusion or autonomous occlusion
  The observation point is on a line from the NP radiating perpendicular to the occlusion front and is some arbitrary distance $\varepsilon_{\rm d}$ from the NP. The observation point for NP and FP is identical (Fig. 3).
- FOV occlusion
  The agent is not moved, but is simply rotated, in order to conduct more observations. The next direction of observation is the vector from the current agent location to the FOV point.

The direction of observation is the vector from the observation point to the each occlusion borders, in all cases.

IV. Algorithm

This section describes the algorithm which searches the environment efficiently based on classification of occlusion.

A. Flow

The search proceeds as following:

- Step1: Identify occlusion borders in the process of observing the shapes of the surroundings with sensors, while simultaneously creating a map.
  - Step1-1: If the goal is identified during the sensing, stop sensing and move straight toward the goal.
  - Step1-2: When a new occlusion border is identified during the sensing, record it.
- Step2: When the sensing is complete, select the next occlusion border to observe. If no unobserved occlusion border is recorded, finish the searching.
- Step3: Go on to the next observation point and return to Step 1.

TABLE I
THE OCCLUSION TABLE.

	Near	Far	Fov
Location	$(i_{\rm n}, j_{\rm n})$	$(i_{\rm f}, j_{\rm f})$	$(i_{\rm b}, j_{\rm b})$
Original observation point (current agent position)	$(i_{\rm a}, j_{\rm a})$		
Location of NP	$(i_{\rm n}, j_{\rm n})$		void
New observation location	$(i_{\rm r}, j_{\rm r})$		$(i_{\rm a}, j_{\rm a})$
Direction of observation	$\theta_{\rm n}$	$\theta_{\rm f}$	$\theta_{\rm a}$
Type of occlusion border	"Near"	"Far"	"FOV"

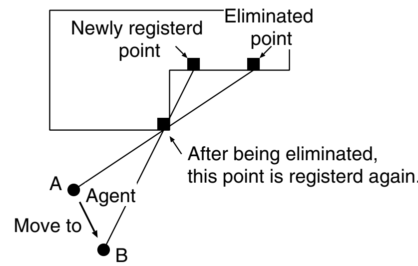


Fig. 5. Reentry of occlusion border.

B. Registration of occlusion borders

In accordance with the above findings, when an occlusion border has been detected, the information about occlusion borders is recorded on an occlusion table (TABLE I). If the borders have already been registered, however, they are not re-registered. Each occlusion border is observed from the observation point; when the beams from a sensor touches a location that had been registered as an occlusion border, that 'border' location is then erased from the database. However, when no contiguous surface is found, then the border location is re-registered in the database (Fig. 5).

C. Movement of the agent

There are some criteria to decide a next observation point among new observation points registered in occlusion table. Here, we adopt a criterion that chooses the nearest observation point from the current agent's location as the next observation point. The agent is always moved from the current location to the next observation point $(i_{\rm r}, j_{\rm r})$ by returning to the original observation point $(i_{\rm a}, j_{\rm a})$ and then proceeding to $(i_{\rm r}, j_{\rm r})$. It returns to $(i_{\rm a}, j_{\rm a})$ by the same path that it used when coming from $(i_{\rm a}, j_{\rm a})$. Thus, a plot of agent movements becomes a tree graph, where the branches are the detours taken by the agent to observe occluded areas. The next observation points

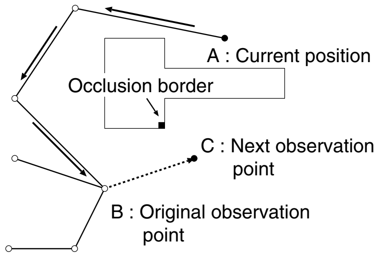


Fig. 6. Movement of the agent.

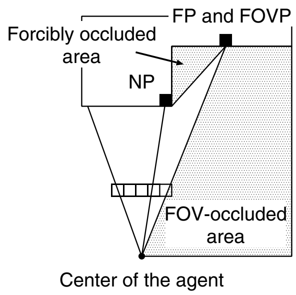


Fig. 7. Duplication of occlusion borders.

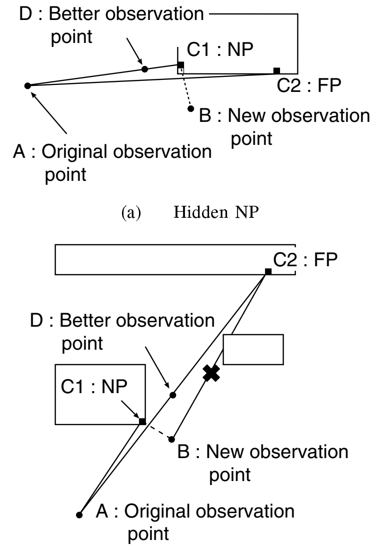


Fig. 8. Hidden occlusion borders.

are recorded in the graphic database with the previous point to which they were linked and the paths employed to move through the environment being stored. As shown in Fig. 6, the process for registering movements and destinations is as follows:

- Step1: The agent retraces its previous path back to $(i_\mathrm{a}, j_\mathrm{a})$.
- Step2: Once the agent reaches $(i_\mathrm{a}, j_\mathrm{a})$, it proceeds to the next observation point $(i_\mathrm{r}, j_\mathrm{r})$.
- Step3: If $(i_\mathrm{r}, j_\mathrm{r})$ has not been registered in the tree graph previously, it is registered with its link to $(i_\mathrm{a}, j_\mathrm{a})$.

V. Exceptions

The algorithm described in the previous section can be used to observe occluded areas, but there are several cases that need to be treated as exceptions. This section describes such exceptions and discusses how they can be resolved.

A. *Duplication of occlusion borders*

Sometimes, the border is in a forcibly occluded area and also in a FOV-occluded area. Or, sometimes it belongs both to a forcibly occluded area and an autonomously occluded area. These cases occur when two occluded areas closely neighbor a border (Fig. 7). In this situation, it becomes a question of which of the new observation points should be registered on the occlusion table. There are 24 possible patterns, but all of the patterns confer a higher priority to forced and autonomous occlusions than to FOV-occlusions. When both of the occlusions adjacent to the border are forcible (or autonomous), the occlusion that was observed more recently can be given priority.

B. *Hidden occlusion borders*

Sometimes, it is not possible to conduct observations of the border of interest from a new observation point. This can occur under one of situations; observations of a near point and observations of a far point. To resolve this issue, the agent must be moved to a better observation point in a process that can be defined as one of the following scenarios:

- Near Points
  A better observation point lies at some arbitrary distance of ε_d from the NP on the straight line connecting the original observation point $(i_\mathrm{a}, j_\mathrm{a})$ with the NP $(i_\mathrm{n}, j_\mathrm{n})$. In Fig. 8(a), although, the NP (point C1) cannot be observed from the new observation point B, it can be observed from the better observation point D.
- Far Points
  In observations toward the FP, a better observation point lies on the straight line connecting the original observation point $(i_\mathrm{a}, j_\mathrm{a})$ with the FP $(i_\mathrm{f}, j_\mathrm{f})$, at some arbitrary distance of ε_d from the NP. In Fig. 8(b), although, the FP (point C2) cannot be observed from the new observation point B, it can be observed from the better observation point D.

C. *Infinite loops*

After observing an occlusion border from a new observation point, sometimes the previously established border maintains its status as the occlusion border. However, these borders will lose its status, if such border changes the status NP to FP, or FP to NP. In Fig. 9, the point C2 is border by observation from point A and also observation from new observation point B. However, the point C2 is changes the status FP to NP. Eventually, the point C2 lose its status as occlusion border by observation from the next new observation point C3. However, sometimes, the planning strategy directs the agent to return

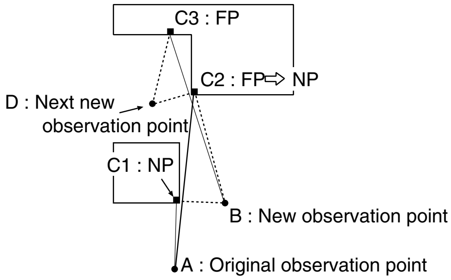


Fig. 9. Complex, but not stuck, occlusion border.

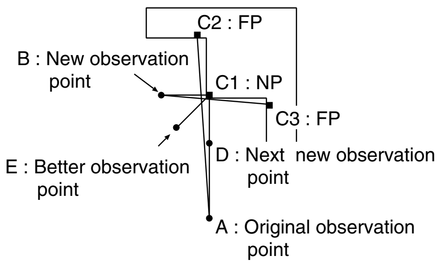
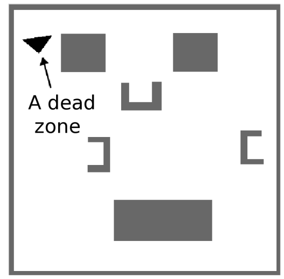


Fig. 10. Stuck occlusion border.

from the new observation point to original observation point in attempts to get "new" observations. The agent then becomes "stuck" and travels repeatedly between the two points. And, then the border point maintains its status as NP (or FP). When the controller detects this "stuck" condition, the agent is directed to observe the NP from a different, pre-specified angle. In Fig. 10, the point C1 is NP and the point B is set as new observation point by observation from point A. However, the point C1 is still NP by observation from the point B. And the new observation point returns to the point B by observation from the point D which is set as new observation point by observation from the point B.

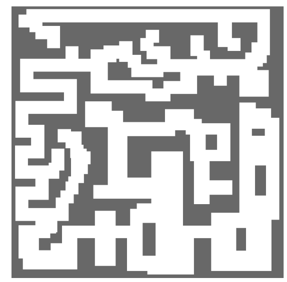
VI. Simulation and Solvability

Frequently, while an agent can reach the destination by the search procedures outlined above, the algorithms described in this paper can leave dead zones, i.e., unobserved portions of the space. If the destination lies in one of the dead zones, the agent cannot reach it, and if an obstacle is in a dead zone, its existence will not be noted and the output map will not be complete. Fig. 11 shows three maps created by an agent after searches. Fig. 11(b) and (c) incorporate complicated structures, but the agent was able to create complete maps. Despite the simple structure of the object in Fig. 11(a), however, the agent was unable to produce a complete map and there was thus a dead zone in this test region. Nevertheless, if the areas observed by the agent are recorded on a map, it is possible to detect dead zones once the search has been completed. It does not require very many calculations to record what kinds of regions in the map were observed by the agent. Once all of the occlusion borders have been observed, returning to observe the areas that were missed will ultimately enable the agent to reach its destination or at least, to create a complete map.



(a) Open space, obstacles and a dead zone.

(b) Obstacles with curved surfaces.



(c) Maze.

Fig. 11. New observation point for forced occlusion.

VII. Conclusion

This report proposes a path-planning algorithm designed to promote efficient observations of an unknown environment. This algorithm considers different situations where objects (occlusions) are detected by distance sensors. It uses a simple model to express general objects and actions, the observations taken by the agent and the actions it performed in order to take them. Therefore, as long as the environment meets certain conditions, the agent is capable of coping with obstacles even when they have curved surfaces. It also has the capability to perform detailed structural analysis of unusual patterns, according to the classification of occlusions presented here, making it a robust algorithm. Path planning is not limited to 2-dimensional motion, but can be easily extended to 3 dimensions. Its capabilities to "see" objects and to reproduce the actions taken by the agent seem to promise construction potential for this algorithm in the future.

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