Isovist Analyst--An ArcView Extension for Planning Visual Surveillance

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Abstract

Visual surveillance (e.g., CCTV) is now an essential part of the urban infrastructure in modern cities. One of the primary aims of visual surveillance is to ensure maximum visual coverage of an area with the least number of visual surveillance installations, which is an NP-Hard maximal coverage problem. The planning of visual surveillance is a highly sensitive and costly task that has traditionally been done with a "gut-feel" process of establishing sight lines using CAD software. This paper demonstrates the ArcView extension Isovist Analyst, which automatically identifies a minimal number of potential visual surveillance sites that ensure complete visual coverage of an area. The paper proposes a Stochastical Rank and Overlap Elimination (S-ROPE) method, which iteratively identifies the optimal visual surveillance sites. S-ROPE method is essentially based on a "greedy" search technique, which has been improved by a combination of selective sampling strategy and random initialization.

1. Introduction

The CCTV network is one of the most common modes of visual surveillance used in large office environments and open public spaces. A surge in the events of organised terrorism and other criminal activities in modern cities has given rise to an increased monitoring on CCTV networks. In 2004, an estimated £1023 million were spent on sales and rental of CCTV and the expenditure would grow 9% by 2010 (Market and Business Development Press 2005). Despite the widespread use of CCTV networks, their effectiveness has often been the focus of debate on issues ranging from being an effective deterrent for crime, ethical issues and limited use of their full potential (URL 1). While the solutions to the ethical issues surrounding CCTV networks are non-trivial, it is however definitely possible to improve the underlying technology and usability of the extensive and expensive CCTV network.

Traditionally, the design of CCTV type visual surveillance networks has been done by the architects and urban landscape designers, following an iterative manual, gut feel process using CAD software. As a result, there could be redundant or incomplete visual coverage of the open space thus affecting the value for money of the CCTV network and aesthetical aspects (Figure 1). This paper discusses the algorithms of the ArcView 3 extension, Isovist Analyst, which could be used to augment the planning process of a CCTV/visual surveillance network ensuring maximum visual coverage. Owing to its GIS-based form, it also allows the possibility of an interactive participation process during the design of the CCTV network.

2. Methodology

The assignment of optimal locations for visual surveillance sites (for brevity, hereafter referred as observers) in an arbitrary open space is similar to the well-known NP-hard computational geometry question, namely the Art Gallery Problem (AGP)[1] (Chvátal 1975) and broadly analogous to the location-allocation problem in GIS.

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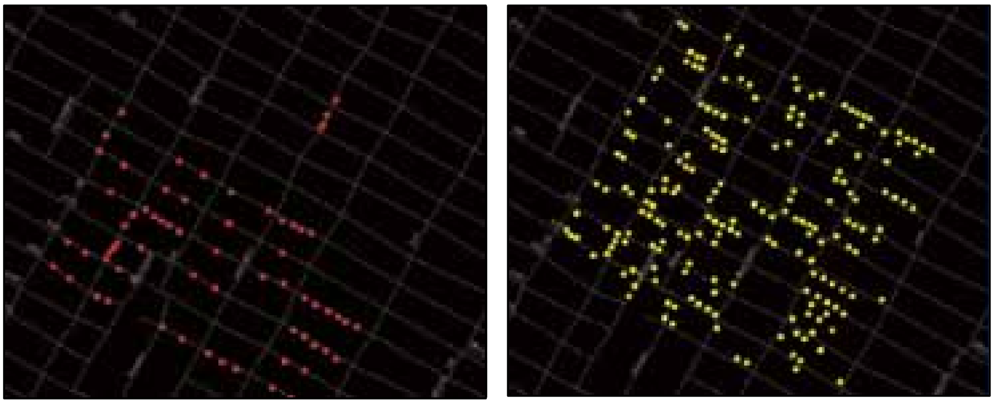
[1] The challenge in the AGP is to find the minimum number of guards required for complete visual coverage of an art gallery.



November 1998, 56 cameras   January 2002, 197 cameras

Figure 1. Profusion of CCTV cameras in the Midtown area in Manhattan.
Source: www.appliedautonomy.org

While, approximate solutions[2] have been derived analytically for simple cases, an exact solution, especially for an arbitrary open space, remains to be found analytically. Various types of combinatorial algorithms, rooted in the location-allocation research achieve better results but these suffer from similar limitations to those of the analytical solutions and could require an unacceptable order of computations in some complex shapes. Therefore, for algorithmic and computational tractability, heuristics in most existing solutions assume a certain simple geometry and topology of the gallery i.e. the gallery is convex, rectilinear etc., which makes them unsuitable for real operations. For example, in practise an open space could be without a boundary and could consist of any kind of obstacles (e.g. polygonal, lines). In fact, installation of visual surveillance networks is a multi-criteria decision-making process, which involves other factors such as budget and site-related constraints (e.g. CCTV camera could only be placed at certain locations). Therefore, the aim in practical planning of CCTV networks is to maximise the visual coverage under the given constraints.

In this paper, we propose a space discretisation and greedy search based approach that is deterministic and can be adapted by the user to ensure a maximum visual coverage with few observers, under various constraints. In the proposed method, the void around the obstacles in the open space is discretised into a dense mesh of potential observers (Figure 2a), with the assumption that the mesh is sufficiently dense enough so that union of the vistas from each observer is equivalent to the visible area or open space[3]. Thus, the mesh represents both the open space and the potential observers. The aim of the observer placement now therefore, is to find the smallest set of observers from the mesh, which between themselves can see all other observers in the mesh. Because, the initialisation of the mesh does not depend upon the topology of the open space, the proposed discretisation approach could be used for any topology of the open space. The space visible from an observer v_i in the discretised open space can be expressed as a set a_i where $a_i = \{v_i, v_j, \ldots, v_n\}$; $1 \geq i, j, \ldots, n \leq N$, $v_j, \ldots, v_n$ are observers visible from v_i and N is the set of all observers in the open space. $|a_i|$ is referred as the *rank* of the observer. Figure 2b shows the space visible or the visibility polygon from the highest ranking observer amongst the dense mesh of observers in Figure 2a. Section 2.2 provides more detailed information about the

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[2] For instance, at most $\lfloor n+h/3 \rfloor$ guards are required for a simple polygon shape space with n faces and h holes (Chvátal, 1975).

[3] An open space without a boundary can be bounded by the minimum bounding rectangle.

visibility polygon computation. With the above premise, the following algorithm can now be used to reduce the dense mesh to the set of few optimal observers to provide complete visual coverage.

2.1 Stochastical Rank and Overlap Elimination (S-ROPE)

The Stochastical Rank and Overlap Elimination (S-ROPE) is essentially a greedy-search method based on an earlier simple Rank and Overlap Elimination method (Rana 2005). The simple ROPE technique starts with the selection of the highest-ranking observer and then removal of observers in *N*, visible from the high-ranking observer. This step is then repeated with the next remaining highest-ranking observer and continued so until *N* is empty. The following pseudo-code shows how ROPE can be used to derive complete visual coverage with few observers:

```
while ($N \neq \emptyset$) {
    Get $v_i \in N$ with maximum rank i.e. $|a_i|$
    Add $v_i$ to $\alpha$
    Remove $a_i$ from $N$
} loop
```

where α is the set of optimal observers.

The computational load of the ROPE technique varies between $O(1)$ and $O(|N|)$ for the two extreme cases of mutual overlaps, viz. a complete visual coverage of the open space by a single observer and no overlap between individual vistas. Figure 2c shows the output of the ROPE method revealing the location of 13 optimal observers although in fact only 9 observers are sufficient to provide complete visual coverage. This example illustrates a key weakness of the greedy search type algorithms, i.e. the outcome depends upon the choice of the solution in the first step. Thus, in certain shapes the ROPE method will produce a reduced set of observers which although guaranteeing complete visual coverage of the open space may not necessarily be the minimum number of optimal observers (see e.g. Figure 2c).

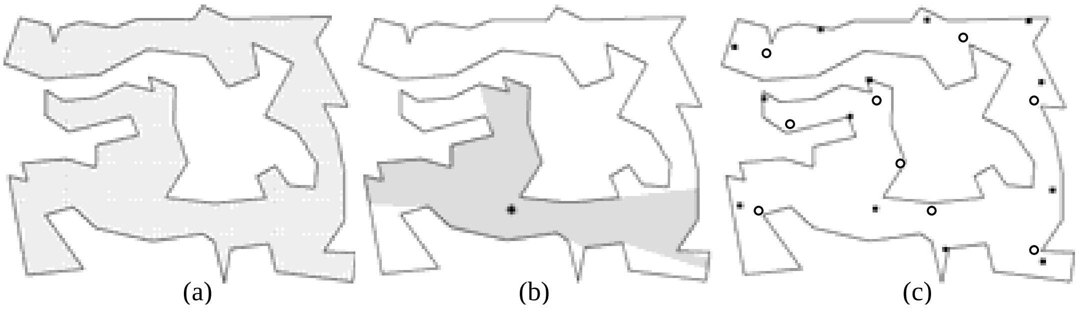
(a) (b) (c)

Figure 2. A polygonal open space. (a) Dense mesh of more than 20,000 potential observers, (b) The largest visibility polygon and its origin, and (c) 13 ROPE-based observers (filled squares) and 9 correct optimal observers (hollow circles).

A simple technique to improve the ROPE is to follow a stochastic approach letting a random (or even each observer for an exhaustive case) potential observer to be the first solution, resulting into *N* sets of optimal observers from which the smallest set, will be the optimal set of observers. The S-ROPE pseudo-code for the exhaustive S-ROPE implementation is as follows:

```
for each $v_i \in N$
    Add $v_i$ to $\alpha_i$
    Remove $a_i$ from N
    while $(N \neq \varnothing)$ {
        Get $v_i \in N$ with maximum rank i.e. $|a_i|$
        Add $v_i$ to $\alpha_i$
        Remove $a_i$ from N
    } loop
} loop
```

where α_i is a set of optimal observers.

Consequently, the range of the computational load increases to between $O(1)$ and $O(|N|^2)$. The computational load can be reduced by a pre-selection of the potential observers that are used to test for optimal observers. Observers located along a “centreline”, formally referred as the “medial axis”, of the open space are such an ideal subset of all potential observers in the dense mesh because although few in numbers, a union of the vistas from their unique locations will guarantee a complete visual coverage. The medial axis is considered the “skeleton” of the open space and defined as the loci of centres of bi-tangent circles (Figure 3). A computationally simple approach to identify the medial axis is to perform the Distance Transform (DT), which involves calculating the distance from each observer to the nearest boundary of an obstacle (including boundary wall). An observer along the medial axis will be equidistant to at least two boundaries. The ray tracing technique discussed in the following section can be used to compute both the visibility from an observer and DT.

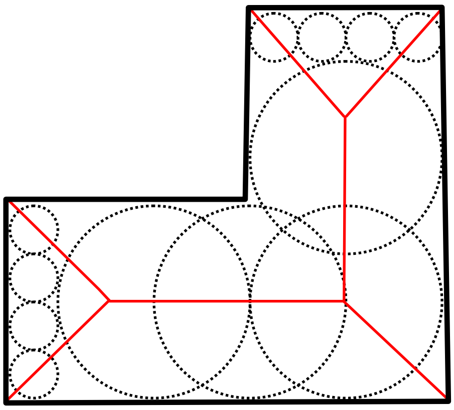

Figure 3. A polygon with some bi-tangent circles and its medial axis (red line).

The step to pre-select certain observers as potential optimal observers could also be applicable in situations in which the number/location of the observers is limited to certain areas of the open space due to budgetary or other constraints. Thus, the entire mesh becomes the target but only a few pre-selected observers could be the optimal observers. For example, CCTV cameras are generally placed in areas easily (and cheaply) accessible for maintenance (e.g. above platforms in train stations, on street lampposts) although these may not necessarily be the best locations for complete visual coverage. In some cases, in fact the lack of complete visual coverage is intentional because it is important to monitor only a few important sites in the open space (e.g. a sensitive installation). In this case, it will be suitable to limit the mesh to these areas. A GIS type information-rich working environment is ideal for such a task that requires graphical interaction and incorporation of multiple criteria.

Admittedly, the S-ROPE technique does not always guarantee the minimum number of observers however, it has two important qualities, which still makes it an ideal technique to derive a complete visual coverage e.g.

- S-ROPE does not depend upon the geometry and topology of the open space.
- S-ROPE reduces the otherwise non-trivial spatial problem into one of trivial set union and inequality tests.

2.2 Ray Tracing for visibility polygon and distance transform

The visibility and DT are computed by shooting rays (radials), in a clockwise or counter-clockwise order from each observer over 360^o and collecting the first point of intersection with the obstacles. The visibility polygon formed by joining the intersection points can be used in a point-in-polygon query for performing the overlap elimination during the greedy search. A plot of the shortest radial length of the observers corresponds to the DT (Figure 4a). A 2.5D plot shows that the medial axis lies along the curvature discontinuities (ridges) of the DT plot (Figure 4b) and highlights the "centreline" nature of the medial axis. The ridge-like aspect of the medial axis is used as criteria for the identification of potential optimal observers on the DT plot. In the current version of Isovist Analyst, an observer is considered to be on the medial axis ridge, if its DT value is the highest along one of the four cardinal directions (i.e. N-S, E-W, NE-SW, NW-SE) in a user-defined area of interest (Figure 4c). There are however more advanced ways of identifying a ridge based on curvature variations (Rana 2006) and these will be added in a future release.

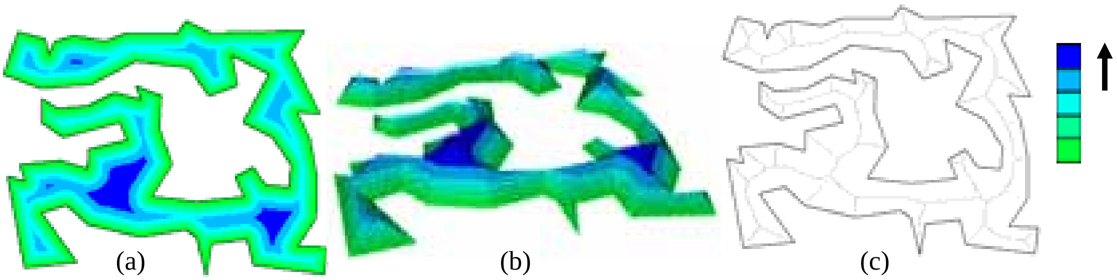

Figure 4. Distance transform of a polygonal open space. (a) Plot of shortest radial length of each observer, (b) Ridges and channels on the distance transform plot, and (c) 2422 potential optimal observers located on the ridges of the DT plot.

An approach for reducing the computation load in Ray Tracing involves performing intersection tests with only the "visible edges" of obstacles. Techniques for fast front-to-back ordering of edges around an observer such as z-buffering and Binary Space Partition (BSP) tree can be used to find out the edges visible from the observer. The visibility polygon computation in Isovist Analyst is based on a C++ BSP tree software library developed by Yiorgos Chrysanthou[4]. A detailed discussion on BSP tree is outside the context of this paper. Thus, for further information on how BSP tree can be used to do ray tracing, please refer to an example by Sung and Shirley (1992).

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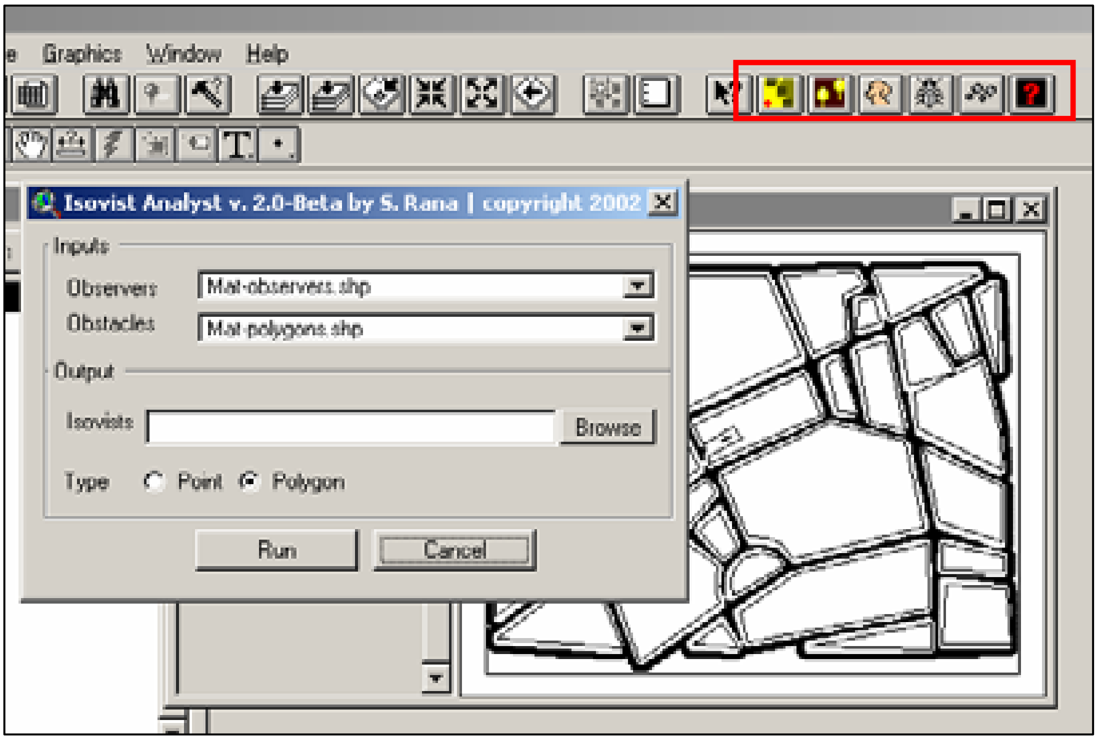
[4] http://www2.cs.ucy.ac.cy/~yiorgos/

2.3 Isovist Analyst extension for ArcView

Isovist Analyst is the first GIS extension for ArcView 3, which computes visibility polygon[5] and several other visibility measures. The unique aspects of Isovist Analyst are as follows:

- It allows the use of arbitrary topology and geometry of open spaces e.g. nonconvex, and line segments.
- It allows an arbitrary placement of observers, which can be controlled by the user using the standard ArcView mapping tools. Thus, a user is able to generate hypothetical vistas quickly and easily.

The primary inputs to the extension are point (observers), and line and/or polygon (e.g. floor plan, street maps) shapefiles. It is assumed that an observer (e.g. CCTV) is able to view all around its location i.e., it has 360° view, and can view until infinity. Isovist Analyst is broadly composed of two parts. The Graphic User Interface (Figure 5) with in ArcView for data entry alongwith the various greedy search algorithms written in AVENUE and the visibility polygon computation program. The visibility polygon is computed using a C++ stand-alone executable, written in collaboration with Yiorgos Chrysanthou.



Isovist Analyst v. 2.0-Beta by S. Rana | copyright 2002

Inputs

Observers: Mat-observers.shp

Obstacles: Mat-polygons.shp

Output

Isovists:

Type ○ Point ● Polygon

Figure 5. The Graphic User Interface of the Isovist Analyst Extension showing the data input dialog box and various control buttons indicated with a box with red edges.

3. Two Case Studies

In order to highlight the variety of CCTV networks planning situations, two types of case studies are presented here, one involving a street network and another of an indoor arbitrary shaped polygonal space shown in Figure 2a.

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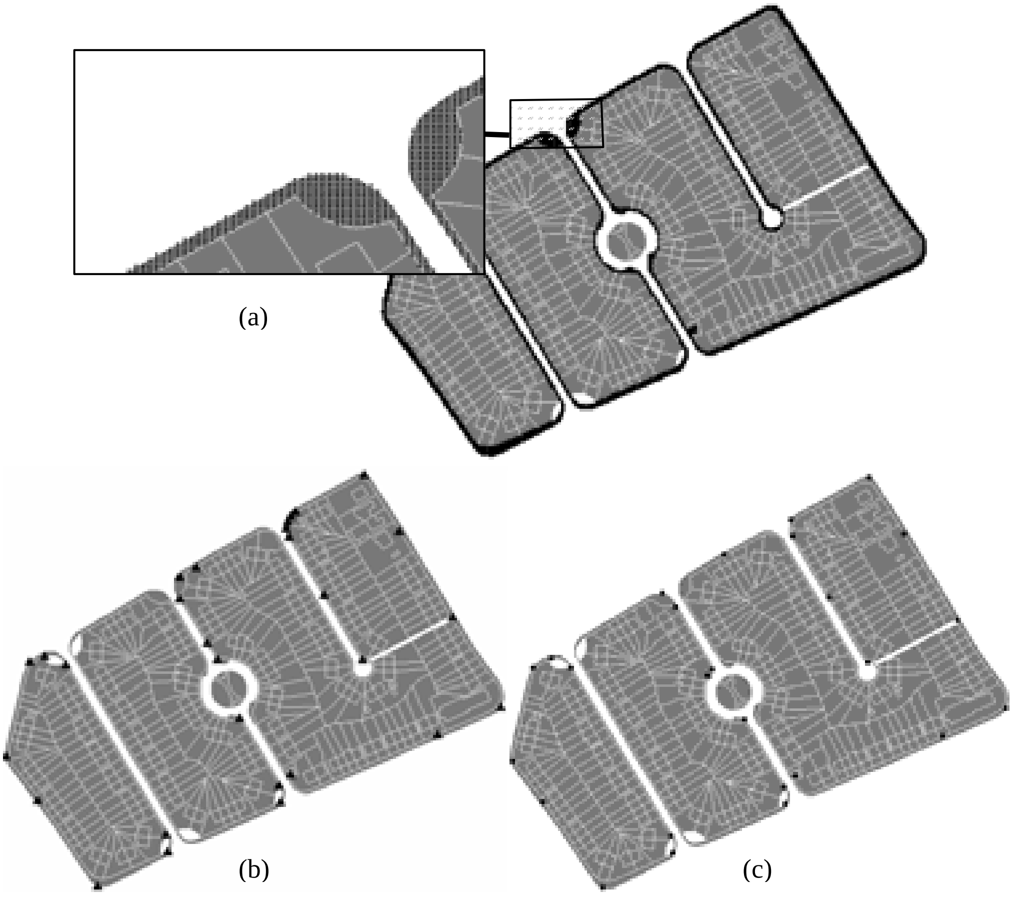
[5] The name Isovist Analyst is inspired from the term isovist, which is a term used for the visibility polygon in urban visibility analysis literature.

Figure 6a shows the street network around building blocks and the pre-selected locations of around 4000 potential optimal observers on the road pavements. Figure 6b shows the 29 optimal observers identified by the ROPE algorithm. Figure 6c shows the output from the S-ROPE algorithm, where after 101 iterations with an arbitrary initial optimal observer, the number of optimal observers is reduced to 26.

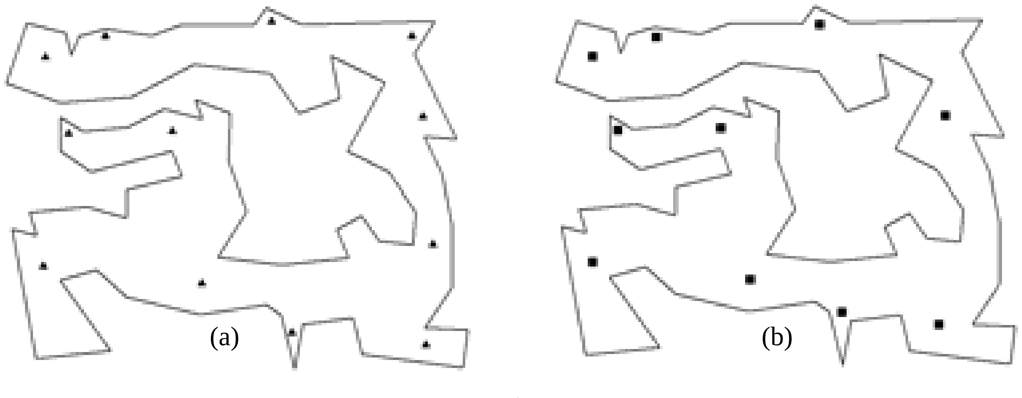

(a)

(b)

(c)

Figure 6. (a) Mesh of 3980 potential observers on the pavement of a street network, (b) 29 ROPE-based optimal observers, and (c) 26 S-ROPE based optimal observers.

Figure 7a shows the 12 optimal observers based on the ROPE technique, identified amongst the medial axis observers in the arbitrary polygonal shape. Please note that this is one less optiomal observer than identified based on the entire mesh.


(a)

(b)

Figure 7. Optimal observers chosen because of their location on the medial axis. (a) 12 optimal observers based on ROPE-based search, and (b) 10 optimal observers based on S-ROPE. Note: Only 9 observers are sufficient to provide complete visual coverage.

Figure 7b shows the 10 optimal observers based on the S-ROPE technique, identified amongst the medial axis observers in the arbitrary polygonal shape with 101 iterations. This is a significant improvement from the ROPE-technique based results as it is close to the minimum 9 observers actually sufficient to provide visual coverage (see Figure 2c).

4. Conclusions

Despite being a controversial issue, the rise in the public anti-social behaviour has led to routine visual surveillance by CCTV networks in modern society. Installation of visual surveillance technology such as CCTV networks is expensive and generally follows an iterative, manual and gut-feel process. Therefore, techniques to identify the minimal number and locations of such installations (like an observer) with the maximum visual coverage of open spaces are highly desirable. However, this is a NP-hard problem because a solution to the problem would involve exhausting all possible locations of such observers, rendering it non-heuristic. In this work, we have addressed the issue by discretising the open space with a dense mesh of potential observers so that the upper limit to the number of optimal observers is always known. The large number of potential observers is reduced to the set of optimal observers by a combination of greedy-search and selective Stochastical sampling strategies involving medial axis of the polygon and preferred location of the optimal observers. The proposed S-ROPE (Stochastical Rank and Overlap Elimination) algorithm provides a near-optimal solution to the problem by iteratively selecting the most visibly dominant observer with minimum overlapping vistas. Although, the output of the S-ROPE may not be the minimum number of observers to cover an open space, it could serve a quick and simple way to ensure complete visual coverage. Isovist Analyst also serves a tool for a collaborative and iterative process of planning the surveillance network.

Two case studies of different kinds of open spaces, viz. building blocks in a street network and an arbitrary polygonal space, are presented to highlight the application environments and constraints that may appear while designing a real CCTV surveillance network. The current work lacks a treatment of the practises and standards involved in surveillance planning in the industry and planning organisations. The implementation of S-ROPE technique in Isovist Analyst could be improved by practical considerations such as camera viewing distance, preferred location, and analysis of 3D open spaces. In fact, an enterprise-wide or citywide GIS-based visual surveillance system could be an ideal platform to incorporate a multi-criteria decision making process that can be used for real-time surveillance as well as planning future networks.

Acknowledgments

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References

Chvátal, V., 1975. A Combinatorial Theorem in Plane Geometry. *Journal of Combinatorial Theory 18,* 39-41.

Market and Business Development Press, 2005. *UK CCTV Market Development Report*, Manchester.

Rana, S., 2005. Use of GIS for Planning Visual Surveillance Installations, In: Proceedings *ESRI Homeland Security Summit*, Denver, CO, Online at http://gis.esri.com/library/userconf/hss05/docs/pap1001.pdf

Rana, S., 2006. Use of plan curvature variations for the identification of ridges and channels on DEM, In: A. Riedl, W. Kainz, G. A. Elmes (eds.), *Progress in Spatial Data Handling*, Springer-Verlag, In Press.

Sung, K., and Shirley, P., 1992. Ray Tracing with the BSP Tree. In: D. Kirk (ed.), *Graphics Gems III*, Academic Press, San Diego, CA , 271-274.

URL 1. *http://www.crimereduction.gov.uk/cctvminisite19.htm*

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