

Military Operational Research: the Sensor Coverage Problem

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Military Operations Research is a field that has been growing since the Second World War, and in particular in the last decades. Within this vast area, Air Defence, the protection of the air space against an airborne threat, has become a hot topic. In order to successfully protect a given zone against an air attack, it is essential to possess an adequate air picture of this zone, that is produced by sensors (for example a radar). The area where there are no terrain obstacles between sensor and target is called the sensor coverage. This paper deals with the development of fast algorithms to point out candidate locations where one or more sensors can be placed in order to obtain the best coverage satisfying a given set of criteria.

Introduction

The protection of a given zone against an airborne threat depends on an adequate air picture of this zone. This air picture is produced by sensors (for example a radar). Basically, a radar radiates electromagnetic energy that propagates until meeting an obstacle that reflects part of the energy back to the radar. Based upon the time between emission and reception and the direction the sensor creates an air picture.

Clearly, the location of the sensor(s) influences the air picture that is obtained. For instance, whenever the given terrain is mountainous and the sensor is placed in a valley, targets flying at low altitude in adjacent valleys may not be detected, as figure 1 shows.

The coverage of the sensor can be calculated using the *Line Of Sight* (LOS) principle. A sensor has LOS with a target if the target is within the range of the sensor and there are no terrain obstacles between the sensor and the target. Note that this is dependent on the target height. This principle is illustrated in Figure 1.

The Air Force Research Group of the TNO Physics and Electronics Laboratory has developed a tool to compute the LOS sensor coverage diagrams using a digitised terrain da-

tabase as well as sensor and threat characteristics. An example of the output produced is shown in Figure 2, where the grey zone corresponds to the coverage obtained by the sensor marked by the cross.

Such sensor coverage diagrams can be used to find a “good” sensor position by trial and error, but this is a very time consuming method. Therefore, there is a need to develop fast search algorithms that point out promising locations for the placement of one or more sensors.

What is the “best” sensor coverage?

The definition of the best sensor coverage is very subjective and dependent on the sensor and its tasks, threat and terrain. The most intuitive criterion is perhaps the maximisation of the area covered by a sensor. This simple criterion can be combined with other criteria such as:

- asset coverage: a given asset (bridge, airport, power station, etc.) has to be covered;
- overlap: a given area has to be covered by several sensors.

Another important criterion is to minimise the gaps in the coverage, which are temporary losses in the LOS.

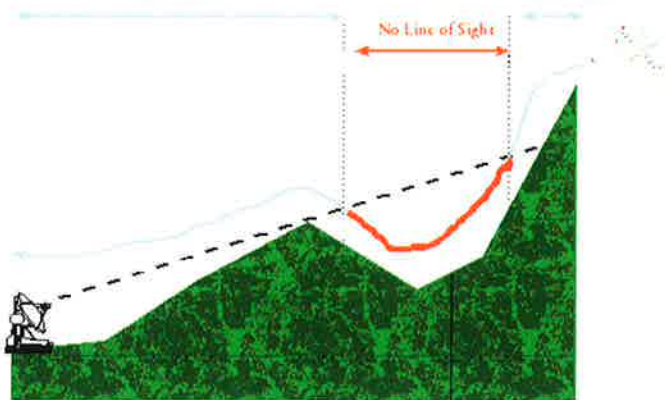


figure 1. The influence of terrain geography on the sensor coverage.

Besides these criteria, other restrictions can be taken into account, like:

- geographical constraints may prevent the sensor from being placed in cities, industry, woods, swamps, etc.
- the minimum or maximum distance from the sensor to a certain point in the terrain may be restricted.

Search methods

The construction of a sensor coverage requires a LOS evaluation (is LOS achieved yes or no?) for successive points from the place where the sensor is placed until its maximum range. Unfortunately the LOS evaluation cannot be translated into a mathematical formula (due to the use of digitised terrain). Moreover, an exact procedure to find an optimal solution implies evaluating all points in the terrain, and this is very time consuming.

The sensor coverage problem sketched has two main characteristics. On one hand, it has a large number of possible solutions (all points in the given area have to be analysed). On the other hand, the objective function (dependent on the LOS evaluation) is not mathematically tractable and has a rather non-monotonous and unpredictable behaviour: if at a given location a good coverage is achieved this does not guarantee that an adjacent location will also have a similar coverage.

Considering the mentioned characteristics, local search methods like Simulated Annealing, Tabu Search and Variable Neighbourhood Search appear to be quite suitable to tackle this problem as we show next.

Shortly, in a Simulated Annealing algorithm a new solution x is randomly drawn from $V(x_n)$, the neighbourhood of the current solution x_n . If the value of the objective function $F(x)$ is improved, then x becomes the next current solution. Otherwise, one of the two following alternatives is selected according to a probabilistic law: either x becomes the current solution with acceptance probability $p(n)$ or x_n remains the current solution with probability $1-p(n)$. Typically, the acceptance probability $p(n)$ decreases with the number of iterations (n) (i.e. it decreases with time) and

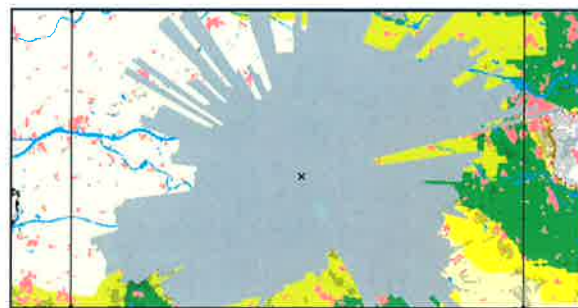


figure 2. Sensor coverage diagram.

varies according to the changes on the objective function's value.

Tabu Search is another search strategy that moves from the current solution x_n to the best possible solution x in $V(x_n)$ or in a sub-neighbourhood $V'(x_n) \subseteq V(x_n)$ in the case that $V(x_n)$ is too large to be explored efficiently. If the neighbourhood structure is symmetric, i.e. if x_n belongs to the neighbourhood $V(x)$ of x whenever $x \in V(x_n)$, there is a danger of cycling when we explore $V(x)$ in the next iterations. This cycling situation is avoided by storing a certain number L of the last solutions encountered in a list $(x_{n-1}, \dots, x_{n-L})$ called *tabu list*. If x is in the list, the move from x_n to x is forbidden.

Contrary to the approaches mentioned, Variable Neighbourhood Search does not follow a search trajectory but explores increasingly distant neighbourhoods of the current solution, and only jumps from the current solution to a new one if an improvement has been made.

Clearly the above methods can be applied individually to the sensor coverage problem. However, each of these three methods has a specific characteristic suitable for our problem. For instance, since there does not appear to be a relation between "good" locations, the Simulated Annealing approach seems quite suitable for this problem. Moreover, geographical restrictions like avoiding lakes, cities and swamps, can easily be taken into account in a (fixed) tabu type of list. Likewise, if locations were already evaluated, they should become tabu. Finally, similar to the Variable Neighbourhood Search approach, it also seems logical to consider a local search with starting points at different locations. Moreover, in the case of the sensor coverage problem (large number of possible starting locations), this subset of starting locations should be taken in the whole search area and formed by "promising" locations.

"Promising" locations appear to be high places. However, this reasoning should not be applied directly as Figure 3 shows. The sensor positioned at the highest place (sensor C) has a smaller coverage than the sensor positioned at B. However, sensors placed at the other high positions A and D yield larger coverages than the one produced by a sensor at B.

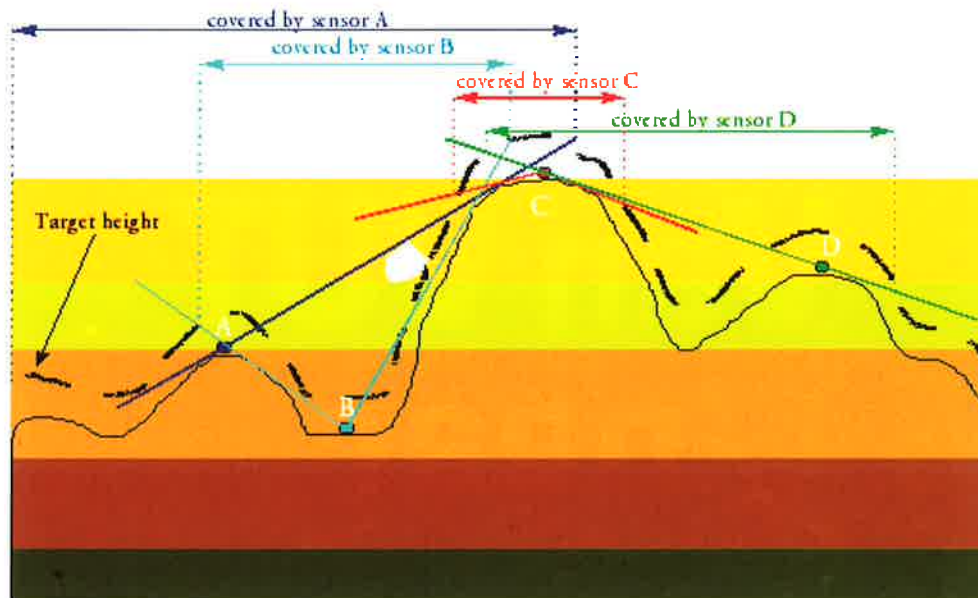


figure 3. The effect of selecting high positions to place sensors.

Combining the above characteristics, we developed a tailor-made heuristic algorithm for the optimisation of sensor locations. This algorithm starts with defining the tabu points. A subset of initial promising locations in the total search space is found (high places), and the coverage at these locations is calculated.

For each initial location, the algorithm performs a Simulated Annealing phase to find the best locations of the neighbourhood. Note that every new solution obtained during this Simulated Annealing phase is added to a tabu list, and therefore these solutions will not be revisited.

The algorithm stops when all starting locations in the initial set have been analysed. The stopping criterion for the neighbourhood search (Simulated Annealing phase) consists of terminating the search if the total maximum number of iterations has been reached or when no improvement is achieved after a maximum given number of iterations.

The algorithm described above can be used to find good locations according to different criteria. Moreover, additional restrictions are also easily embedded.

In the version implemented at TNO-FEL, the user has the opportunity to accept or reject the solution given by the algorithm. When a solution is rejected, the algorithm provides the second best solution, etc. This feature is useful whenever other (subjective) criteria also play an important role in the planning of sensor locations.

The heuristic algorithm was tested for the maximum coverage criterion. For this criterion the results for three types of terrain (flat, mountainous and woody) were very encouraging. In most cases a solution near to the optimal (obtained via exhaustive search) was found in a very short amount of time.

Concluding remarks

The heuristics developed appear to be very effective and

can quickly find a good "solution". Moreover, using these heuristics it is possible to compare in short time different solutions and choose the most suitable to the particular planning or analysis.

It is important to remark how an apparently difficult military planning problem can be efficiently tackled using an Operational Research approach.

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¹ This research was the subject of Jeroen Koopmans' master thesis at TNO-FEL. The TNO Physics and Electronics Laboratory (TNO-FEL) is, together with TNO Prins Maurits Laboratory (TNO-PML) and TNO Human Factors Research Institute (TNO-TM), a member of TNO Defence Research (TNO-DO). TNO stands for the Netherlands Organization for Applied Scientific Research.

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