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The Base Zone Protection Problem

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Abstract

The "base zone" in combat operations refers to an area that is secured against intrusion and attacks from insurgents. During any type of military operation, the number of sensor assets that are available for detecting intrusions are limited. Thus, the size of a base zone is limited by the number of available sensors, and how those sensors are deployed. Depending on the assumptions made in modeling the coverage properties and the terrain of area being covered, the size and shape of the base zone can vary widely. The base zone protection problem is the task of determining the largest area that can be protected given a limited number of sensors. The base zone protection problem is related to the problem of determining sensor coverage. In this paper, we look at the various variations of the base zone protection problem, with a range of difficulty in their solution.

1. INTRODUCTION

The green zone in Iraq is a secured area that was the center of the coalition provisional authority and currently remains the center of international presence in Iraq. If we make the reasonable hypothesis that a similar secured area will be needed in future coalition operations in the context of most asymmetric operations, we can extend the concept to that of the base zone -- an area needing protection that needs to be defended so that it is highly unlikely that an insurgent will be able to enter without detection. In other words, it is an area that is relatively well-protected in the context of any operation. It is the intention of this paper to introduce the concept of the base zone, and develop techniques for estimating the size of the base zone based on the number of available assets.

We define the base zone as an area which is secured completely by a combination of Intelligence, Surveillance and Reconnaissance (ISR) assets as well as defensive firepower. In the context of an asymmetric operation, we assume that the defensive firepower is sufficient to neutralize any intruder who is detected as having penetrated the base zone. Despite the superiority in firepower in asymmetric operations, any coalition force only has access to a finite number of ISR assets. Thus, it needs to determine the best way in which those assets can be used. It would be useful in asymmetric operations for the coalition commander to determine the maximum size or value of a base zone permitted by the set of available sensors that would be placed around the periphery to protect the zone from intrusion attacks. The base zone protection problem is the task of determining the optimum size and shape of the base zone given a set of sensors. Depending on the assumptions made regarding sensor models, sensor mobility, terrain models, the impact of terrain on sensor performance, and the definition of value, different variations of the base zone definition problem can be formulated. These variations range from the simple ones to complex formulations whose solution would be NP-complete.

Securing the base zone includes the task of detecting any potential incursions into the zone, as well as taking defensive actions against any such incursion. For the purpose of this paper, we assume that detection of incursion is sufficient to take defensive action and to protect against the incursion. This assumption is likely to be true in cases of asymmetric warfare. However, there may be a lag between the detection of an incursion and the initiation of the defensive action. If we assume that the lag is zero, then the task of maximizing the base zone reduces to that of determine the maximum (or most valuable) area that can be covered by the sensors available.

With modern day weapons, it is possible to launch grenade or mortal attacks from a remote location into the base zone. For full protection, one would need to include ISR assets which can detect such intrusions from a remote area as well, e.g., an acoustic sensor which can detect remote launch of a mortar and take steps to neutralize that attack. The approaches we have discussed in this paper can be extended to cover the case of remote sensors, but we are restricting the scope of this paper to a discussion of ISR assets that detect intruders in a physical proximity area.

Although related, the base zone definition problem is distinct from the sensor coverage planning problem, which has been extensively covered in current research literature. The sensor coverage planning problem can be characterized as follows: Given an area to be monitored and a set of sensors with various capabilities, determine the best locations for each sensor so that the area can be effectively monitored, usually defined as completely. In contrast, the base zone definition problem tries to provide a secured area given a limited number of sensors by creating a boundary around the zone. By covering the boundary, the area will be said to be covered.

The sensor coverage planning problem has been studied in different formulations in a variety of ways. The Art Gallery Problem addresses the issue of determining the number of observers necessary to cover a space, like an art gallery with many rooms such that every point in every room is seen by at least one observer. It has found several applications in many domains such as for optimal antenna placement problems in wireless communication. It can be solved optimally in 2D and is known to be NP-hard in the 3D case (O'rourke 1992). Marengoni et al. 1996 have proposed heuristics for solving the 3D case using Delaunay triangulations.

The treatment of the coverage problem has been well studied and varies from theoretical analysis (Megerian et. al. 2002) to pragmatic usage models (Meguerdichian et. al. 2001). While several variations of the coverage problem examining aspects such as connectivity maintenance, mobility management, and query optimizations can be found in various papers (Liu et. al 2003, Huang et. al. 2003, Gupta etl. al. 2003, Poduri et. al. 2004), there has been little work on incorporating terrain considerations. Wilson et. al. 2007 look at the real world problems of the difficulties of incorporating terrain and atmospheric environmental factors in acoustic and seismic sensors. The work by Dhillon and Chakrabarty 2003 attempted to model some of the location dependence by approximating the sensor field to a Manhattan grid. Dhillon and Chakrabarty approximated the sensor field by a grid and used an asymmetric probability matrix to model the terrain, and proposed two heuristics to address the problem – both using a greedy approach with one maximizing average coverage with each sensor and the other placing sensors at the point on the grid with least amount of coverage. Brown et. al. 2008 have tried to develop the impact of terrain on the coverage area of a sensor and simulated its impact on sensor coverage. Kumar et al. 2007 also examine the problem of determining a belt of coverage using sensors to protect a border (e.g., U.S/Mexico border) or an enclosed area using random placement of sensors.

Since the sensor coverage planning problem provides the inverse solution to that of base zone, i.e., determining the number of sensors required to cover an area, iterative usage of the sensor coverage planning problem can be used to solve the base zone definition problem. However, such solutions may not always be the most efficient ones to use.

In this paper, we provide several variations of the base zone protection problem and approaches to solve them. We also provide by a section discussing the adaptation of the sensor coverage planning algorithms to address the base zone definition problem. The variations of the problems we consider range from simple ones which can be solved analytically to the ones which can be shown to be NP-complete, and the only possible approach is to design efficient heuristics for the problems.

The first variation we consider is that of uniform sensors which have a constant coverage radius in any direction. We show that the optimal solution for monitoring a uniform terrain in this formulation is that of a circle with a radius dependent upon the number of available sensors. We then consider a variation where the value of securing different points of the terrain is different. We show that an analytical solution can obtained for cases where the value function is a smooth convex function of the distance from the base camp. We further obtain the properties of the optimal shape that contains the base zone with a differing value function. We examine the case of mobile sensors, and obtain the relationship between the size of the base zone and the speed of motion of the ISR assets. Mobility allows the size of the base zone to be expanded.

Since real-world applications cannot be expected to have value functions that are smooth and analyzable, we examine some heuristics that will allow the base-zone problem to be solved in practical application scenarios. Finally, we present our conclusions and directions for future work.

2. UNIFORM TERRAIN

The first variation of the base zone protection problem provides a simple formulation that is easy to solve. It assumes that covering the perimeter of the base zone is sufficient to prevent intrusions, and that any preventive actions are immediate. Furthermore, for this first formulation the terrain being modeled is uniform with the implication that the coverage area of each sensor is independent of its location amdthe sensors are all identical. Suppose there are K sensors, and each sensor can monitor a circular area of radius s. The goal is to find the largest area in a planar surface which can be covered completely by K such sensors. The boundary must enclose an origin point (0,0) defined as the center of the base zone. We assume that the origin point contains the processing center for sensor information, and that all sensors are able to communicate with the origin point. In practice, this means that the maximum distance of each sensor from the origin is bounded by the range of its communication.

Under this definition the problem can be seen as the task of determining the closed shape with the largest area, where the perimeter of the shape is covered completely by all the sensors together. Therefore, the base zone definition problem in this case devolves to that of finding the shape with largest area given a fixed perimeter. Such a shape in a plane is a circle.

If the zone to be covered is much larger than *s*, than a good approximation to the maximum size of the perimeter would be *2Ks.* (If the zone to be covered were not significantly larger, the mathematics is still easy, but the formulas look more complicated as the arc of the coverage zone and the boundary conditions would need to be included in the calculations.)

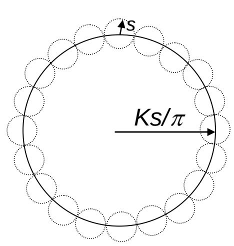

Fig. 1. The base zone for uniform terrain and uniform sensors.

Looking at Figure 1, we can conclude that the base zone in a uniform terrain given K sensors covering a radius of *s* each is a circle of radius Ks/π, augmented by the semi-circles of additional coverage beyond this range. The total area of the base zone is $K^2s^2/\pi + K\pi s^2/2$.

However the boundary does have a point of vulnerability. If an intruder were to traverse the boundary at any of the *K* points where two sensors meet and travel along a ray, there is only one point of sensing that can detect this intrusion and furthermore this point is on the extreme range of the two sensors. Thus, the solution above is valid only if the lag between detection and defensive action is zero.

There are advantages to placing sensors closer than just meeting at a point on the circumference. One advantage is that this creates an annulus of coverage rather than a minimum coverage of a single point. This can be useful for the problem mentioned above or secondarily by providing redundancy it allows some degree of non-exact placement of the sensors. The annulus provides for a finite lag to exist between detection and defensive action, such lag being the time it takes for an intruder to cross the span of the annulus.

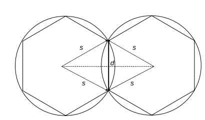

Fig. 2. Overlap among sensor coverage areas to create an annulus.

One possible way to create such an overlap is to inscribe a regular hexagon within the circle. Adjacent sensors overlap so that the adjacent inscribed hexagons are abutting as shown in Figure 2. In order to create an annulus of depth d, two adjacent sensors need to be moved closer together, creating an isosceles triangle with base length of *d* and equal sides being of length *s*. The separation between the centers of two adjacent sensors in this case equals $2\sqrt{s^2-(\frac{d}{2})^2}$. Thus, the perimeter of the circular base zone is $2K\sqrt{s^2-(\frac{d}{2})^2}$ and the maximum radius of the circular base zone is going to be:

$$\frac{K}{\pi}\sqrt{s^2-(\frac{d}{2})^2}.$$

In both of the cases above, it might be acceptable to have a small probability ε of undetected intrusion. If we assume that the probability of intrusion is same as the fraction of the perimeter that is not covered, then the perimeter of the base zone without any overlap would be

$$\frac{2K\sqrt{s^2-(\frac{d}{2})^2}}{(1-\varepsilon)}$$

and the corresponding base zone will be a radius of size

$$\frac{K}{(1-\varepsilon)\pi}\sqrt{s^2-(\frac{d}{2})^2}$$

For the case of no overlap, the corresponding perimeter is $2Ks/(1-\varepsilon)$ *And* the corresponding radius would be $Ks/\pi(1-\varepsilon)$.

3. NON UNIFORM TERRAIN – SIMILAR SENSORS

In the next variation of the base zone protection problem, certain parts a region are more likely to encounter human intruders than others because of the accessibility of the terrain. Even when the sensor performance, i.e., detection range, it not affected by the terrain, the best placement of the sensors must take into account the likely routes where a security compromise can occur. To this end, the security value of any point on the ground will be proportional to its accessibility. Furthermore, one should expect the security value to decrease as the distance from the base increases.

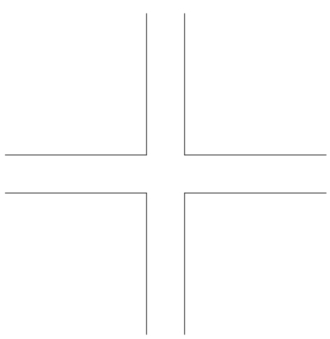

Fig 3. Terrain with different monitoring values

An example of such an environment is shown in Figure 3. The terrain consists of four roads that intersect at the origin point. It is more important to monitor the access points of the road rather than monitoring the access points that are not along the road. If there are only four sensors available, then they ought to be used for monitoring the access points rather than monitoring other locations. Assuming that the sensor coverage area can span the width of the entire road, the sensor ought to be located at the maximum range of their communication limit to maximize the base zone.

In a generalized version of the problem, we can associate a value $V(r,\theta)$ with each point (r,θ) which is the value derived from having the specific point protected. The Value function V for a point would depend on its location such as being on an accessible route for an attack, distance from the known installations of the enemy forces, position (there is more value in monitoring points towards enemy forces), and the impact to an attack occurring at that point. We make the pragmatic assumption that the value function V is continuous and does not increase as one moves away from the origin, i.e. the value of $\partial V/\partial r$ is non-positive. The problem of defining the base zone now becomes that of finding the area over which the surface integral of the value function is maximized with the constraint the that the total perimeter of the area is bounded. If we look at an incremental area covered around the point (r,θ) with a wedge of δr and $\delta\theta$, this area can be approximated as a rectangle of area $r\ \delta\theta$ and δr. The total value function across the rectangle is $r\ V(r,\theta)$ and the total enclosed by any closed curve $l=l(\theta)$ can be obtained by integrating the value across the curve, which results in the total enclosed value as $\int_{\theta=0}^{\theta=2\pi}\int_{r=0}^{r=l(\theta)} rV(r,\theta)drd\theta$

Given the constraints of K sensors, each capable of monitoring a circular area of radius s, and the central processing lying at the origin, the problem is to find a closed line $r = l(\theta)$ such that $\int_{\theta=0}^{\theta=2\pi}\int_{r=0}^{r=l(\theta)} rV(r,\theta)drd\theta$ is maximized subject to the constraint that $\int_{\theta=0}^{\theta=2\pi}(r^2+(dr/d\theta)^2)^{1/2}d\theta \le 2Ks$. In words we are looking to maximize $rV(r,\theta)$ that are on closed contours less than or equal to $2Ks$.

We can prove the following two properties about the shape of the optimal base zone.

Theorem 1: If V is never negative then there is an optimal base-zone that has a convex shape.

A convex shape is a shape such that any straight line connecting two points on its perimeter always lies completely within the shape. To prove this theorem, let us consider a counter-example, i.e. consider an optimal base-zone which has a shape where there are two points such that the line connecting them does not lie completely within the shape. Without loss of generality, let us assume that the line and two points lie completely in the right half of the Cartesian plane. In that case, there are some portions of the perimeter of the base zone that lie to the left of the line. Now, one can reflect the perimeter along the line while maintaining the same perimeter of the shape. See Figure 4(a) and 4(b) for an illustration. This results in a shape that is closer to a convex shape which has the same perimeter as of the original shape, but covers a larger area, and thus a larger value (which is always non-negative). But that results in a better base-zone such that the specific line remains completely within the shape. If any such line still remains (as it does here), the process can be repeated. The resulting shape has the same perimeter as the original shape, but any line connecting any points in the perimeter lies completely within the shape. If the resulting value increases, then there is a contradiction with the assumption that the original shape was optimal. If it is the same value, we have a optimal base-zone that is convex. Thus, there is at least one optimal base-zone which is convex.

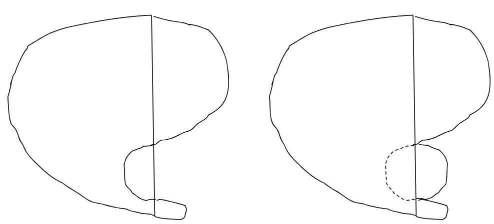

Fig 4. Removing Concavity

Theorem 2: If the value function is $V(r,\theta)$, and V is twice differentiable at all points at least two times, then the optimal base zone is defined by the equation $rV(r,\theta) = c$, where c is a constant selected such that total perimeter of the shape will be less than or equal to $2Ks$.

Proof: According to the Calculus of Variations (see Fox, 1950, p65), the extremal points of a function

$I=\int_{t_1}^{t_2} G(x,y,x',y')dt$ subject to the condition that

$J=\int_{t_1}^{t_2} \varphi(x,y,x',y')dt$ where x and y are functions of t

and x' is the derivative of x with respect to t is given by the solutions to the following two equations, where λ is a constant.

$$\frac{\partial G}{\partial x}-\frac{d}{dt}(\frac{\partial G}{\partial x'})-\lambda\{\frac{\partial \varphi}{\partial x}-\frac{d}{dt}(\frac{\partial \varphi}{\partial x'})\}=0$$

$$\frac{\partial G}{\partial y}-\frac{d}{dt}(\frac{\partial G}{\partial y'})-\lambda\{\frac{\partial \varphi}{\partial y}-\frac{d}{dt}(\frac{\partial \varphi}{\partial y'})\}=0$$

Let us make the following substitutions:

$$x = r(\theta),$$
$$y = \theta,$$
$$\varphi(r, \theta, r', \theta') = r(\theta)$$

$$G(r, \theta, r', \theta') = \int_{r=0}^{r=r(\theta)} rV(r,\theta)dr$$

Since G and φ do not depend on the derivatives of r or θ, their derivatives with respect to r' is zero. Using this relationship, we get the simplified conditions that

$$\frac{\partial G}{\partial r}-\lambda\{\frac{\partial \varphi}{\partial r}\}=0$$
$$\frac{\partial G}{\partial \theta}-\lambda\{\frac{\partial \varphi}{\partial \theta}\}=0$$

Since $\varphi = r(\theta)$, both these equations are equivalent.

Plugging the values into the equation, we get that

$$\frac{\partial}{\partial r}\int_{r=0}^{r=r(\theta)} rV(r,\theta)dr-\lambda\{\frac{\partial r}{\partial r}\}=0$$

or

$$rV(r,\theta)-\lambda=0$$

or $rV(r,\theta)=\lambda$

Substituting the value of c as a constant instead of λ gives us the desired result.

As an example, let us consider the value function defined by

$$V(r,\theta)=\frac{1}{r^2(1+\varepsilon\cos(\theta))}$$

This value function can be seen as one which decays inversely according to the square of the distance from the base camp, and is highest along $\theta=\pi$ and high along $\theta=\pi/2$ and $\theta=3\pi/2$, which is a vertical line passing through the origin. This value function could be a representation of the importance of monitoring a zone which is has a single entry road or also traversed by a straight line depending on the value of ε

The base zone will be defined by an expression of the nature:

$$c=\frac{1}{r(1+\varepsilon\cos(\theta))}$$

If we now express the constant c as product of two other constants, a and $(1-\varepsilon^2)$, we get the expression that

$$r = \frac{a(1-\varepsilon^2)}{(1+\varepsilon\cos(\theta))},$$

which is the equation of an ellipse in polar coordinates. Thus, with the above value expression, the base zone will be an ellipse with one focus at the origin and the eccentricity as defined by the parameter ε. Thus, if a base zone is traversed by one major road, the best way to deploy a limited number of sensors is by arranging them in an elliptical manner around the periphery of the road.

If the value function V is can be expressed as the product of two independent functions of r and θ, then the determination of the base zone can be made readily. Let us assume that

$$V(r,\theta) = \frac{1}{r} f(r).g(\theta),$$

then the shape of the base-zone is defined by the relationship

$$r(\theta) = f^{-1}(C/g(\theta)),$$

where C is a constant selected so that the perimeter of the shape is less than or equal to *2Ks*.

4. MOBILE SENSORS

As an extension of the case of uniform terrain with similar sensors described in Section I, consider the case of mobile sensors. In the case of mobile sensors, each sensor has the ability to move about its central point to a limited extent. Due to the ability of the sensors to move about, the sensors can be spread out to cover a larger distance and define a bigger base zone.

Consider the case where all the sensors are arranged in a circular manner as discussed in Section II, and are moving around the circle at a uniform rate. By exploiting the fact that each point will be covered by each sensor at some point in time as they rotate in the circle, the size of the base zone can be extended.

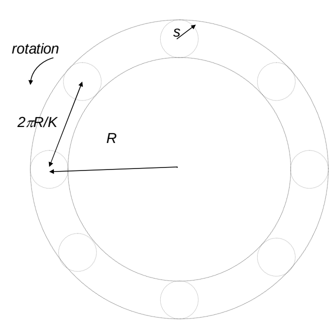

Fig. 5. Sensors in uniform rotational motion.

Suppose that the sensors are moving with a velocity of v_s along a circle of radius R. Each point is covered directly by a sensor when the sensor is within a distance of s from that point, which is $s/\pi R$ fraction of the total time in one period of rotation $T=2\pi R/v_s$. With K sensors, each point is covered for $Ks/\pi R$ fraction of time per period of rotation. If the sensors are equally spaced along the circumference of their circular path, then the maximum contiguous time period when a point is not covered by any sensors is given by $(2\pi R-Ks)/v_s$. Since any intruder has to cover a distance of 2s in that block of contiguous time to avoid detection, the intruder will need to have a velocity toward the center of at least $v_s Ks/(\pi R-Ks)$ if the intruder's angular velocity is zero.

If follows from the previous analysis that if we wanted to maintain a base zone with unit probability of detection against intruders with the maximum velocity of v_i, and we have K sensors with coverage radius of s moving along the perimeter of a circular base zone with a *sensor velocity of* v_s, then the maximum size of the base zone will be given by a circular area of radius $Ks/\pi\ (1+v_s/v_i)$.

If the intruders are relatively slow in their movement, then the radius can be made significantly larger. On the other hand, if the intruders can move faster than the sensors, then the size of the base zone reduces to a circle with static sensors. Figure 6 shows the relative increase in the size of the base zone that can be attained as a function of the relative speeds between the intruders and the sensor.

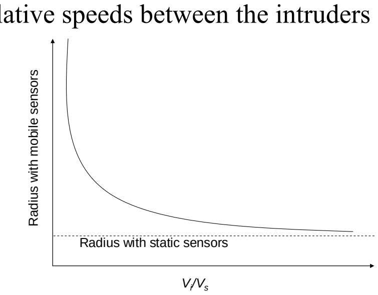

Fig. 6. Base Zone Radius

The analysis is valid for motion of sensors which are other than that of rotating around the perimeter of the base zone. As an example, the sensors may move in an oscillatory motion around the perimeter. Each sensor maintains their distance among each other, but reverse direction after traveling a fixed distance in either side. Almost any kind of motion in which the sensors move around the perimeter with a fixed distance among their positions would result in a similar characteristic for the base zone.

If we consider the case of non-uniform terrain, then a similar analysis of mobile sensors can be used to determine the expansion in the perimeter of the optimal base zone. The different sensors would need to move along the perimeter of the optimal base-zone as defined by Theorem 2.

5. APPLICATION IN PRACTICE

The results of the analysis provided in previous sections can be applied in practical sensor planning tools. One can take an area where the base zone needs to be established, establish a value function reflecting the terrain characteristics, examine the finite set of sensor assets that are available, and try to determine the size of the base zone that maximizes the value of the protected area. However, the value functions that one obtains in practice are not likely to have the smooth behavior (continuity and differentiability) that are required to have the theorems in section 3 to hold true.

In order to deal with real-life value functions, we would need to develop heuristics that draw upon the observations that are valid about the different value functions. Three such heuristics are provided below. Each heuristic assumes that the value function is largest at the center or origin which must be protected, and then tries to cover the area that maximizes the value enclosed.

Greedy Heuristic: We start from the origin, and grow the shape in the direction of the highest value of V, with the expansion ending when the convex hull of the area equals the bound on the perimeter of the base-zone.

Circular Heuristic: A circle covers the maximum area among any shape. The logic behind the circular heuristic is that the shape that maximizes the area covered by the set of sensors will provide the optimal base zone. The limitation of the circular heuristic is the fact that it does not take into account the differences in the values of different points.

Greedy Ratio: Motivated by the theoretical solution, a Greedy Ratio heuristic was created. The greedy ratio mimics the greedy heuristic but instead of using V in comparisons it uses V/r^{α} for a fixed α.

When the value function is a smooth shape that obeys the constraints described in section 3, a theoretical heuristic should provide the best possible base-zone. We found that that it does not work well for not well behaved functions. If the function decreases much more slowly in a few directions, a heuristic based on the theoretical concepts will result in an elongated area. The Greedy ratio algorithm because it has a bias for closer points results in a more rotund area.

The performance of the three different heuristics in the cases where the theoretical assumptions are not satisfied can be useful in obtaining an efficient technique to determine the optimal base-zone and are consequently important when the properties are not satisfied.

Let us consider a base zone protection problem which consists of a base-camp with a single road running out of it. Let us assume that the value of protecting the base-camp is very large, while the value of protecting areas along the road is V, while the value of protecting the areas elsewhere is smaller. Figure 7 shows the layout of the area that needs to be protected.

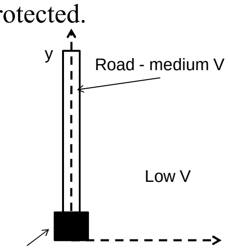

Fig. 7. Base Camp with a single access Road

The result of running each of the three heuristics on this shape is shown in Figure 8. The circular heuristic moves the circle upward until it reaches the area where the base-camp is just touching the circle. The greedy heuristic produces an oval shaped base-zone that is elongated along the road. The shape is oval in order to maintain the convexity of the resulting figure. The greedy ratio heuristic also produces an oval or tear-drop shape that is slightly better than the greedy in performance.

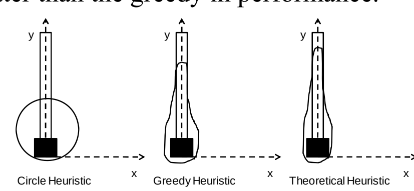

Fig. 8. Base-camps with different heuristics

It is also instructive to observe the behavior of the three heuristics where the value of V on the road is increased. The results of that heuristic are shown in Figure 9. The starting values are 3 for the required area, 2 for the road and 1 for the area surrounding the road.

The x-axis shows the value of V which was used on the road, while the y-axis shows the area of the base-camp that was covered. At small values of the V function on the road, the circle heuristic performed better than the other two heuristics, as its additional area of the zone more than compensated for the higher V values included in the other two heuristics, while at higher values of V, the greedy heuristics performed much better than the circle (fixed-shape) heuristic. The greedy ratio heuristic had the characteristics of the circle heuristic at small values of V, while having those of the greedy heuristic at larger values of V. Thus, the greedy ratio heuristic provided a good model that worked at various different values of V.

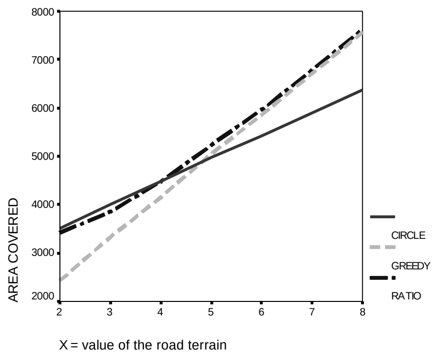

Fig. 9. Comparison of the different heuristics.

6. CONCLUSION AND FUTURE WORK

In this paper, we have presented several variations of the base zone protection problem, looking at approaches to determine the maximum size of a protected region with a limited number of proximity sensors. We have provided analytically tractable solutions for some simple cases, and proposed heuristics to address the problem in the case of more realistic scenario where values are arbitrarily defined.

Our current formulation makes the assumption that detection implies protection and there is no lag between detection and a defensive action. In future work, we intend to incorporate the concept of a finite lag between detection and defensive action and study the impact of such lag on the size of the base zone. Another future extension that we want to investigate is the relax the assumption regarding proximity sensors, and solve the base zone protection problem to protect against remote threats such as mortar attacks using non-proximity sensors. We also want to evolve the simulation tool we have into a tool that can be used for base-zone planning problems in real-world environments.

7. ACKNOWLEDGEMENTS

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