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ABSTRACT

Practical Results from a Mathematical Analysis of Guard Patrols

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The guard force at a nuclear facility performs many functions; among them is the patrol of protected areas. During a patrol, the initial detection of an intrusion may occur; however, using guard patrols as a primary detection mechanism is not generally viewed as a highly efficient detection method when compared to electronic means. Many factors such as visibility, alertness, and the space-time coincidence of guard and adversary presence all have an effect on the probability of detection. Mathematical analysis of the guard patrol detection problem is related to that of classical search theory originally developed for naval search operations. The results of this analysis tend to support the current practice of using guard forces to assess and respond to previously detected intrusions and not as the primary detection mechanism.

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Practical Results from a Mathematical Analysis of Guard Patrols

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In addition to responding to threats of intrusion or other potential safeguards incidents, guards at nuclear facilities provide patrols of protected areas and protected area boundaries. Surveillance in this manner may provide the initial detection of an intrusion or discover evidence of an intrusion. However, using guard patrols as the primary detection means is not generally viewed as highly efficient when compared to electronic means. Many factors, such as visibility, alertness, and the space-time coincidence of guard and adversary all have a bearing on whether the detection of an adversary by a guard will occur. Mathematical treatment of the guard patrol detection problem is related to that of classical search theory as developed by the military in naval search operations. In related work on police patrol allocation, the deterrent effect of patrol activities on crimes such as burglaries is known to exist but it is rarely quantified. The deterrent potential of guard patrols at nuclear facilities should be effective against certain adversaries but probably not against dedicated and armed terrorists.

The problem we treat here is that of analyzing the visual search for an adversary intrusion by guard patrols. The guards patrol an area A which may be the perimeter or protected area boundary. Each guard spends all his time while on patrol continuously searching and performs no other function. The entire area A can be searched by moving along the patrol path length C. We now present several important assumptions concerning the randomness of the patrol and the physical requirements necessary to make a detection possible. We assume that the search patrol is random in time and location and further that the adversary's attempted intrusion upon the plant is a random event in both space and time. Guards normally patrol in a random fashion in order to maintain an element of surprise and to avoid a predictable patrol pattern. In order for a detection to occur we assume that certain basic physical requirements are met; that is, there is at least sufficient lighting and visibility for the guard, at each point along the patrol path C, to see an intruder if he is present nearby in the patrol area A. Given that the physical requirements are met, there is only a conditional probability of detection which is dependent on guard alertness, perception, variations in the physical requirements, and other factors. Under these assumptions then, the probability that a patrol detects an intrusion is dependent upon the space-time coincidence of the guard and an adversary action. This condition can be relaxed to mean that if an adversary is present and visible during a time t the guard will detect him with some probability dependent upon

the time T needed by the guard to search the area of the intrusion. Before proceeding further we define several variables and parameters used in the analysis to follow.

A = area to be searched by guard patrols

C = patrol path length in feet; along C the basic physical requirements are met

V = average velocity of each guard on patrol

N = total number of guards responsible for patrolling the area A

$T = \frac{C}{VN}$ = average time to search the area A

t = average time during which a guard can observe an adversary attempting an intrusion

b = conditional probability density of a detection; depends on guard alertness and perception and variations in lighting and visibility

$\gamma = b/T$ = instantaneous probability (of detection) density function; a measure of the adversary's vulnerability

$P(t)$ = probability of detection during time t

$Q(t) = 1-P(t)$ = probability of no detection during time t

The factor $\gamma = b/T$ is a measure of the adversary's vulnerability to being detected by the guard patrol. Moreover, γ does not vary to any appreciable extent over short periods of time on the order of from 1 to 10 minutes. This means that the lighting, visibility, guard alertness and perception are all constant over any given short interval of the total search time. The probability of detection in a short time, dt, is then equal to γdt. For larger values of t relative to T we reason as follows. Let $Q(t+dt)$ be the probability of no detection in time t+dt. Then we have

$$Q(t+dt) = Q(t)\ (1-\gamma dt). \qquad (1)$$

The second term on the right of (1) is the probability of no detection in time dt. Rearranging terms and passing to the limit as $dt \to 0$ we obtain

$$Q'(t) = -\gamma Q(t). \qquad (2)$$

Since there is no detection when no time is spent searching then $Q(o)=1$ and we obtain for the solution of (2)

$$Q(t) = e^{-\gamma t}$$

from which it follows that the probability of detection in time t,

P(t), is given by

$$P(t) = 1-e^{-\gamma t}, \qquad (3)$$

or in terms of the components of γ

$$P(t) = 1-e^{-btVN/C} \qquad (4)$$

The assumption on the time invariance of γ for short intervals of time is not an unreasonable one. Furthermore, the average time t during which a guard can observe an adversary attempting an intrusion is probably also small, on the order of 2 to 3 minutes as has been reported in the law enforcement literature (1, 2) for police patrol to detect burglaries. Hence equations (3) and (4) provide a reasonable approximation for the probability of detection P(t) for most cases of interest. The exponential form for P(t) originated with B.O. Koopman (3) in regard to air searches for submarines and other seagoing vessels. The functional form for P(t) is also appropriate for other search problems and is discussed by L.G. Williams in (4). Elliott in (2) also uses the exponential form in analyzing police patrols to detect burglaries, an application close to the present one. Note that for small γt the probability of detection is γt and this may be recovered from equation (3) by expanding and neglecting higher order terms.

The probability of detection obtained by substituting into equations (3) or (4) is too low to be relied upon for the primary detection method at a nuclear facility. For example, with T as small as 5 minutes, the conditional probability factor b=0.9, and with t a generous 3 minutes we obtain P = 0.42. From equation (4) it follows that to increase the probability of detection one can:

- increase b by providing better and uniform lighting, better visibility, improving guard motivation to raise alertness
- increase N, the number of guards on patrol
- improve or modify barrier construction to increase t
- reduce C the length of the patrol path
- increase V, but only to a limit as at some point the searcher is "too rushed" to consistently detect a target

The cost of implementing some of the improvements described above may be high and the resulting improvement in detection probability could be disappointing. An improvement over the previous example with b going from 0.9 to 1.0 and with t=T=4 minutes only yields a detection probability P = 0.63. In practice, however, the actual detection probability may be extremely low as can be seen from the example of J.F. Elliott in (2). Here data regarding police patrol to detect burglary was obtained from the Syracuse Police Department in upstate New York. About 400 miles of public streets were patrolled by 23 patrol units in an eight hour shift. This

gives an optimistic value for T of 4 hours. It was assumed that the time that a police officer may view a burglar (and recognize that a crime may be underway) is t = 2 minutes. With the conditional probability factor b=1.0, equation (4) gives P=0.0083. If we were to choose t=3 minutes instead of 2, we would find from (4) that P=0.0124. From Elliott's data there were about 2500 burglary type crimes committed per year at locations accessible to patrol. In 1966, the Syracuse Police patrol detected 31 such crimes. This gives a probability of detection $P = {}^{31}/_{2500} = 0.0124$. The point here is not the potentially good agreement between theory and actuality for one isolated case, but the theoretical and actual low probability of detection.

A few remarks remain to be made about the parameters imbedded in the conditional probability factor b. There are a number of human factors concerning the searcher that affect the probability of detection for visual searches and various experiments have been devised to isolate and study the effects of some of these factors. Of these factors, we are most concerned here with the motivation of patrol guards, the visual contrast sensitivity of each guard, their overall general health, and the length of time spent on search patrol. Individuals that are highly motivated are apt to be more alert and thorough in their searching efforts. Obviously, individuals in good health will also perform consistently better than those burdened by one or more health problems. The visual contrast sensitivity is the ability of an individual to sense changes in the level of contrast between an object and its background. Visual target detection is highly dependent on the contrast sensitivity of the searcher and in (5) the authors recommend selecting security observation personnel on the basis of visual contrast sensitivity.

It is evident that the performance of human searchers decreases as the length of the watch increases. This does not conflict with our assumption made earlier that γ does not vary with time since we are now discussing somewhat longer intervals of time. Teichner in (6) obtains results which show that the detection probability for a simple monitoring task drops off rapidly (but linearly) during the first 30 minutes of the watch. This is not totally surprising since we are all aware of the attention span of school students being on the order of 45 to 60 minutes. Teichner found that the probability of detection went from initial values of 0.9 to 1.0 down to values of 0.4 to 0.55 at the end of 30 minutes. While these results were for a simple monitoring task, similar behaviour for the search considered here would not be unexpected and the implications for actual guard patrols are obvious.

The other set of parameters embedded in the conditional probability factor b are more related to the target and background than the searcher. The first of these is the target-background luminance contrast factor C_{TB}. This has been defined in (5) as follows:

$$C_{TB} = (L_T - L_B)/L_B$$

where L_T = target luminance and
L_B = background luminance.

The target-background contrast factor and the contrast sensitivity at the searcher are important factors in visual detection. Meguire et al. in (5) conclude that the probability of detection may be increased by increasing C_{TB}. One possible way to do this is to use highly reflective background materials such as chalk dust and concrete.

Another important factor in human visual search is the size of the target. As one would expect, the size of the target image on the retina of the observer is inversely proportional to the square of the distance between the observer and target. Therefore, observers should remain in search paths close to potential intrusion areas for the intruder to present a sizeable target. Additionally, searchers could utilize optical aids similar to the use of night vision devices which are utilized at several nuclear facilities at this time. Facility lighting systems may be designed to create large-area shadows from potential intruders for patrols during dark hours.

In general, the contrast sensitivity of an individual is enhanced as the background luminance increases. This is not surprising and simply means that the search area must be adequately illuminated. In addition to an adequate illumination level, the illumination of the search area should be uniform. Uniformity in the background luminance allows the searcher to increase his search rate and reduces the effort of transient changes in retinal adaption level. This last effect is recognized as the uncomfortable adjustment from glaring headlights to darkness that we all experience when driving at night.

Other factors such as background glare from light sources or reflections, target-background color contrast, and target movement all have an effect on the efficiency of visual searches. A substantial list of references is contained in (5) on these subjects.

Conclusion

The use of guard patrols at nuclear facilities to detect potential intruders does not appear to have a high enough detection probability for use as the primary intrusion detection system. Moreover, a number of factors concerning the search area, the intruder, and the searcher can vary (within certain basic minimal requirements) and lead to uncertainty concerning the detection capabilities. These considerations therefore tend to support the current practice of using guards to assess and respond to previously detected intrusions or threats of intrusions and not as the primary detection mechanism. Guard patrols may be used to

augment the primary detection system or to replace portions of it during a system failure. Recognition of the important factors in random visual searches should lead to improved detection capabilities whenever guards are used for patrol service. It is also prudent to capitalize on the deterrent effect of guard patrols through the use of security lighting systems, facility design, and the appearance the guards make to the potential intruder. It is also most important to weigh carefully any attempts to increase guard effectiveness in terms of probability of detection which may conflict with their response capability to actual or suspected intrusions.

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