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THE THEORY OF SEARCH - AN APPLICATION IN THE ARCHIPELAGIC SEA

TEORIJA TRAGANJA - PRIMJENA U ARHIPELAŠKIM MORIMA

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Prethodno priopćenje

Sažetak

U ovom radu prikazane su osnovne postavke teorije traganja. Također, razmatrani su problemi koji se odnose na praktičnu primjenu spoznaja teorije u arhipelaškim morima. U radu se također predlaže i rješenje složenih praktičnih problema pomorskog traganja u arhipelaškim morima, zasnovano na temeljnim postavkama teorije traganja i računalnog modeliranja stvarnih uvjeta u pojedinom slučaju.

Summary

The basic concepts of the theory of search are presented in this paper. Issues related to the practical application of the theory of search in archipelagic seas are also discussed. A proposal for a solution of the complex practical problems of maritime search in archipelagic seas, based on the fundamental search theory concepts and computer modeling of real conditions in every particular case, are given too.

Introduction
Uvod

Searching is an activity performed by each person many times a day. Generally, it is a part of many complex tasks and as such, it is undertaken for a wide variety of purposes in an equally wide variety of situations. Except when it is a time-consuming and expensive task, it is rarely considered as separate activity.

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At sea, beside common meanings, search operation is understood as an activity of search and rescue units following a marine accident with least probability that somebody could survive. As opposite to common experience, search operations following marine accident are clearly defined in time and space. In time, they include all efforts executed from the moment the accident take place until it is officially closed as unsuccessful or until all survivors are found. In space, search operations are always executed in well-defined area, delineated, as a rule, by searching capabilities of used search units.

If compared with other search and rescue activities, maritime operations are characterized by high costs, a numerous personnel required and extremely short time to be organized and executed. Unfortunately, because of numerous physical and technical limitations, unsuccessful search operations are not exceptions. The most important limiting factors are environmental factors, available personnel, safety and capabilities of search units and available time. Therefore, the proper uses of available resources are of the utmost importance. Consequently, in order to be successful, maritime search operation must be well planned, organized and executed.

The well organized and executed maritime search operation can be defined as an operation that for the given personnel and available means return the highest probability of success. Conceptually, this probability is a compound outcome of numerous uncertainties caused by the nature of maritime accident, the most important being:

- when, where and even whether an accident actually occurred,
- the direction and speed of survivor's movement since last known location and since accident occurred,
- the size and other characteristics of search object, and

- environmental factor affecting object motion, search unit's detection performance and survivor's behavior.

In order to cope with these and other uncertainties the mathematical discipline known as probability theory has been used to develop a theory of search with particular emphasize on maritime search and rescue operations.

The Search Theory - Basic Concepts
Teorija traganja - temeljni koncepti

The basic concept of the search theory is the probability of the containment (POC). It can be defined as the measure of the likelihood that search object is located within boundaries of some area. Obviously, it is always possible to achieve 100% POC simply by making search area large enough, but this approach will more than often result in an extremely large area, practically impossible to search. The area that has 100% POC value is sometimes called possibility area. If an initial area is divided in smaller areas, being equal in size or not, these sub-areas will, in reality, have different POC values. As a rule, those sub-areas are of rectangular shape.

The next important concept is the probability of detection (POD). Essentially, it is defined as likelihood (or conditional probability) that a sensor used for searching will detect the search object if it happens to be in the area searched. The most used sensors are human eye, ear or an electronic device. In practical applications the term "probability of detection" is used with different meaning, *i.e.* as measure how well some area has been searched after more than one pass through or over the search area. Following this line of reasoning, the cumulative probability of detection (POD_C) can be expressed as:

$$POD_c = 1 - \prod_{i=1}^{n} (1 - POD_i) \qquad [1]$$

where n is a number of search passes and POD_i is a detection probability of i^{th} search. If an additional search with the given POD value is concluded with no success, then the previous POC value has to be rectified according to the following expression:

$$POC_{n+1} = POC_n^* (1 - POD) \qquad [2]$$

Two previously defined concepts together define the probability of success (POS). It is the probability that search object will be found in the given area and with the given sensor, and since two events are absolutely independent, it can be expressed as:

$$POS = POC * POD \qquad [3]$$

Consequently, the optimal search operation can be defined as operation with the highest POS value. The same line of reasoning used for the cumulative POD can be used for the cumulative POS.

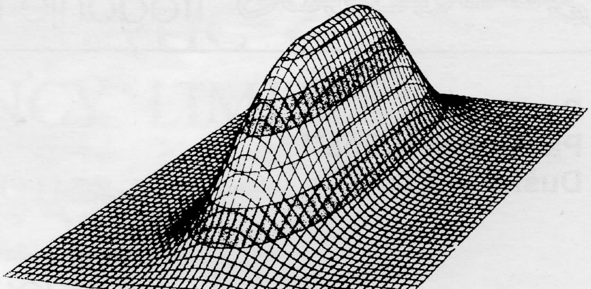

Figure 1. The probability density function for the line datum

Slika 1. Funkcija gustoće vjerojatnosti za linijski podatak

In order to be of practical value, the theory of search has to include uncertainties regarding location of the search object. The basic term is datum. It is defined as reference location from which search operation will be started as location with the highest probability density value. At the beginning of the search theory development, only a point datum is considered. If circular normal distribution is assumed, then as usually, the POC value for any circular area around a point datum is defined as:

$$POD = 1 - e^{-\frac{R^2}{2}} \qquad [4]$$

where R is radius of the circle expressed in standard deviations. If the previous equation is solved for R with POC value equal to 50% then the resulting circle with a radius equal to $\approx 1.18\sigma$ corresponds to the total probable error of position (E), a well known navigational term. According to recent proposals, a well known point datum could be, depending on circumstances, replaced with line datum ("moving" circular distribution, Figure 1), area datum (uniform rectangular probability density distribution) or with generalized datum (generalized probability density distribution).

The last important concept of the search theory is detection models. Different detection models are usually represented by their corresponding lateral range curves. The x coordinate of the curve is the distance between search object and sensor moving along the

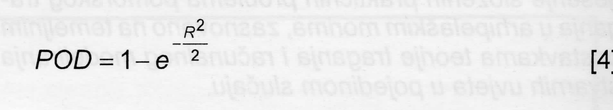

Figure 2. An example of map presentation of the line datum

Slika 2. Primjer zemljovidne prezentacije pravca

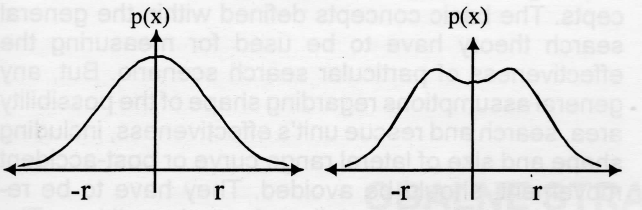

Figure 3. Examples of lateral range curves
Slika 3. Primjeri krivulja lateralnog dometa

straight line at the closest point of approach. The curve is defined as a probability that a sensor, moving along the straight line and passing at the closest point of approach at distance *x,* will detect an object. The area under the lateral range curve, between points where cumulative probability of successful detection in one search pass equals probability of unsuccessful detection, defines the sweep width and it is the measure of the effectiveness for the particular sensor. Thus, it is useful for the comparison of the two sensors with different lateral range curves. In the past, several hypothetical models were defined. Among them, the inverse cube model of the lateral range curve has been used as the closest to real conditions. It is a very crude model because of numerous simplifications, stating that the instantaneous probability that the search object will be detected is inversely proportional to the cube of the range from the sensor to the object.

The basic concept described in previous paragraphs and known as "Simplified Search Planning Method", has not been essentially changed for the past fifty years. Recently, various improvements of the basic search theory have been proposed, mainly aiming at improving the search unit's effectiveness. The most noticeable improvement has been proposed in [1] where authors have proposed the concept of the optimal search pattern. This proposal is based on the assumption that any programmed search must produce the POD value highest than the POD value of random search. Otherwise, any planning will be meaningless. As shown in [1], the POD value for the random search is defined as:

$$POD_r = 1 - e^{-\frac{WL}{A}} \qquad [5]$$

where *W* is sweep width, *L* length of trackline in the search area and *A* is the search area size. The exponent in the previous expression is termed *the coverage factor.* It can be easily proved that even the simplest parallel sweep search based on the simplest definite range sensor model will have the POD value higher than the random search for any coverage factor higher than 0,2. The optimum search, according to the proposal, is found by applying numerical calculation to determine track space that produces the maximum POS value for the given search effort. The method requires complex numerical computations and it could be practically used only for parallel sweep search.

Maritime Search Operations in Archipelagic Seas
Pomorske operacije traganja u arhipelaškim morima

Considerations, in form as presented in the previous section, are applicable only for search operations whose real conditions match the mentioned theoretical assumptions. Probably, the closest match between theoretical assumptions and real conditions is, in case of maritime search operations, at ocean areas using visual observer(s) from a search airplane. In other cases, real conditions and limitations could be different than assumed in theory so that the resulting conclusions could be of no value or even misleading. This is particularly true for maritime search operations in archipelagic seas.

The archipelagic sea, from the search planner viewpoint, could be defined as a sea area occupying a segment of high sea without islands and navigational obstacles and a segment of a coastal sea with numerous islands. This definition evolves from the fact that responsibility for search and rescue operations always lies on the responsible authority of the coastal state whose area of responsibility, beside territorial waters, always covers a part of international waters.

Consequently, the overall maritime traffic in such search and rescue region could be divided in two distinctive groups. The first group is made mostly of large ocean-going ships passing by or heading to the main local ports. The second, more numerous, group consists of smaller coastal traders, fishing vessels and pleasure boats. While the first group takes routes far from the shore and navigational obstacles, the second group sails predominantly in coastal waters, sheltered by adjacent islands or in areas close to the outer island edge. The number of accidents, involving ocean-going ships, generally takes only a fraction of the total number of accidents in areas under consideration. At the same time, these ships are much more frequently involved as search and rescue units, particularly if the datum point is not in a coastal area.

The maritime search operations in such area of responsibility are characterized by two different search strategies: one applicable for search operations in the area between the mainland and outer island edge and one to be used in case of accident outside the island region. Both strategies follow the same theoretical concept, as shown in [2], but differ significantly in the execution.

The real conditions prevailing in the case of search operations away from coastal waters coincides, in greater part, with assumptions on which the general search theory (simplified or improved) is based. Therefore, the search strategy applied in such a case follows the generally accepted rules.

If the search datum is between mainland and outer island edge, the prevailing conditions could differ significantly from those used by the general search theory. The most notable difference is the irregular shape of the possibility area, *i.e.* the area whose POC value equals to 100%. Within that area there are numerous irregular "white areas" (*i.e.* islands), whose POC value equals to zero. Accordingly, it is not possible to make any simplification regarding probability density distribution.

Beside shape irregularities, there are other factors that can prevent a search planner from the direct application of search theory conclusions. One of the most important factors is a highly unpredictable influence of weather and sea conditions, *i.e.* horizontal and vertical visibility, winds and currents. In coastal areas horizontal and vertical visibility could differ significantly within small region or even at the same place, but in different directions. Because of that, any assumption regarding lateral detection range of used sensor must have a wide safety margin. In other words, there is no proof that the applied sweep width will result in the intended POD value for the given search effort. This can, depending on real conditions, result in wasting available search efforts or terminating search operation (or transferring search units from an area), before the acceptable POD value is reached.

Another important factor that highly influences the overall effectiveness of a search operation in archipelagic seas is the low predictability of survivor's post-accident movement. As opposite to ocean areas where drift, caused by sea or wind current and leeway, has, in relatively short period, a constant speed and direction, in coastal or inter-island areas the variability of drift direction and speed, in time and space, is generally much higher. It follows that any assumption without a numerical model, based on real-time measurement, could result in wrong or even misleading conclusions.

Another factor that must be taken into account is the high variability in number, features and availability of search and rescue units. In most cases, in coastal or inter-island areas, technically different units from various distant depots can be used. A different number of units and/or their different features forces search planner to prepare different scenario for each combination of the used units. Obviously, the number of so generated scenarios is clearly not manageable under ordinary circumstances.

The irregularity of planned search pattern generally decreases the overall POS value for an area. While in ocean areas those irregularities are relatively small and thus can be ignored, in coastal or inter-island areas, particularly in case of airplane search in areas where islands top-heights are more than 200 m, they cannot be disregarded. Consequently, in such areas the calculated POS value, after one complete search pattern, must be decreased for an arbitrary value depending on the type of the search unit.

Furthermore, for each case the technically same unit, but from different depots can show different effectiveness. For example, the lateral range curves of search airplanes of the same type, but arriving from two distant depots, thus arriving at different time, can be different. This example reveals a significant shortcoming for practical application of the general search theory. It does not take into account the time needed for a particular search activity nor it accounts the change of POC, POD or POS values in time.

In order to overcome the limitations, pointed out in previous paragraphs, for search operations in archipelagic seas it is necessary to modify basic concepts. The basic concepts defined within the general search theory have to be used for measuring the effectiveness of particular search scenario. But, any general assumptions regarding shape of the possibility area, search and rescue unit's effectiveness, including shape and size of lateral range curve or post-accident movement, should be avoided. They have to be replaced by computer modeling of actual conditions. The computer model should permit the following:

-arbitrary definition of possibility area, including insertion of "white areas",

- arbitrary assignment of POC values for particular sub-areas,
- selection between several parametric lateral range curve models for each search unit,
- capability of time/area definition of search pattern for each search unit,
- capability of calculating the effect of search pattern irregularities,
- capability of calculating a number of scenarios for a different number of engaged search units.

The proposed computer model should, as output, give the number of graphical presentations (using different color schemes or 3D model), one for each search scenario. These presentations should be used by search planner as the basis for decision-making on the search plan to be used. Obviously, this model, as proposed, will require a prolonged period of fine-tuning before it can be used as the standard tool for search planning.

Conclusion
Zaključak

The theory of search offers several highly useful concepts. However, some of them can be used in search operations only if real conditions agree with assumptions on which the theory is based. Unfortunately, search operations in archipelagic seas with numerous islands in coastal areas do not agree with these assumptions in many important factors. Therefore, it has to be used with caution. The viable solution of the aforesaid problems could be computer software based on the fundamental concepts of the search theory in combination with the computer modeling of real conditions in particular case.

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