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Knowledge-Based Resource Management for Multifunction Radar

A look at scheduling and task prioritization

In recent years, phased array antenna technology has been maturing rapidly, and this form of transduction is set to become the norm in complex and advanced radar systems. Instantaneous, adaptive beam pointing enables the combination of functions such as tracking, surveillance, and weapons guidance, which previously were performed by separate, dedicated individual radar systems. However, while being able to instantaneously and adaptively position and control the beam has clear advantages, it also brings about a new set of challenges. In particular, this form of radar is able to adapt its parameters according to the way it perceives its environment. Thus, the interpretation of radar backscatter and the subsequent decisions as to what and how radar resources are to be allocated becomes vital to unleashing the full potential of a phased array system. This dynamic and interactive interplay between the setting of radar parameters to optimize the tasks to be carried out and perception of environment highlights the role in which knowledge and intelligence will be central in multifunction radar performance. For example, the system has to share its time between all the different types of functions that it has to perform. This means that in certain operating conditions, it may not have enough resources to perform all required tasks. In this instance, a control system has to evaluate the allocation of resources to provide the best solution. The radar resource

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management problem therefore reduces to the allocation of finite resources in an optimal and intelligent way. In this article, we consider two related aspects of radar resource management, scheduling and task prioritization. Two different methods of scheduling are examined and compared and their differences and similarities highlighted. The comparison suggests that prioritization of tasks plays a dominant role in determining performance. A prioritization scheme based on fuzzy logic is subsequently contrasted and compared with a hard logic approach as a basis for task prioritization. The setting of priorities is shown to be critically dependent on prior expert knowledge.

The efficient allocation of radar resources such as time and energy has been the subject of increasing research over recent years. Since the problem is complicated and multidimensional, it is sensible to make use of whatever prior information is available to form a knowledge-based solution. Most studies have included different techniques such as artificial neural networks, decision theoretics, information theory, and mathematical programming techniques including linear, nonlinear, and dynamic. Radar resource management approaches have been divided into three areas: adaptive track updates [1], search scans [2], and scheduling. Here, we concern ourselves with scheduling and its close relation task prioritization.

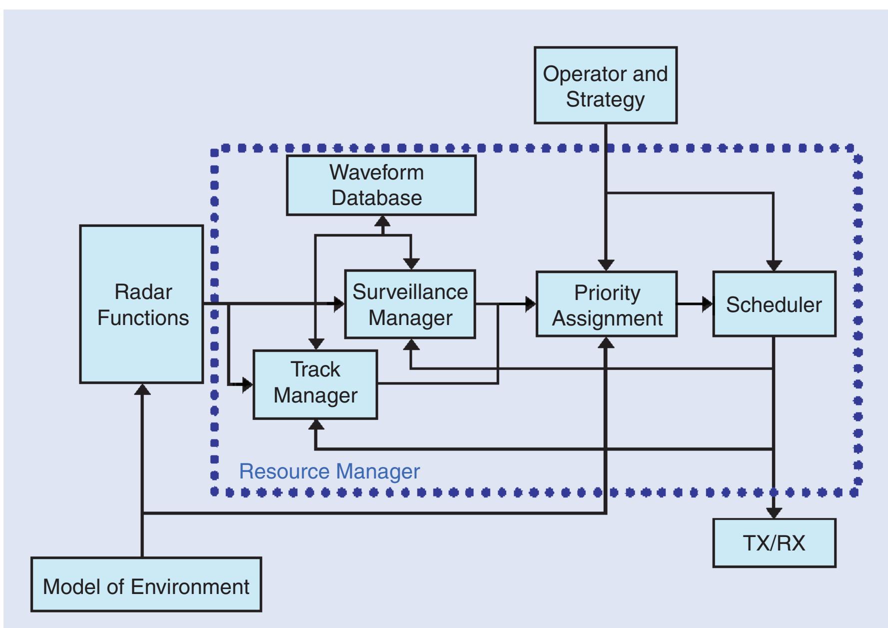
Scheduling is an important subproblem of radar resource management and has been the focus of intensive research in order to optimize the process of accomplishing a set of measurements to be performed by a multifunction radar system, e.g., [3]–[8]. These scheduling approaches are dissimilar in design and methodology, and little has been reported about the differences in their performance in resource allocation when utilized in similar operational conditions [9]. In addition, while most approaches have used fixed priority orders for ranking radar tasks, few analyses have addressed the development and the effects of adaptive methods for prioritizing radar tasks as a function of changing tactical scenarios [10]–[12]. Other notable papers that have examined scheduling and closely related topics include [16]–[21].

Closely coupled to scheduling and fundamental to successful system performance is task prioritization. Indeed, in any system where more tasks are demanded than there is time to execute, some form of prioritization is mandatory. In real-time systems, a prioritization is said to be feasible if the resulting system is schedulable. Thus, solving the priority assignment problem means determining a feasible priority assignment for a given system. Priority is usually associated with the urgency and importance of a task and a system must prepare a sequence able to execute ready tasks that have the highest priority. Most algorithms are classified according to how priorities are assigned as a function of time. Thus, the algorithms can be classified as fixed, dynamic, or of mixed priority. A fixed-priority algorithm evaluates all priorities at the design time, maintaining them for the lifetime of the task or mission. This is the simplest form of algorithm and is typically used for assigning priorities in scheduling algorithms. Conversely, a dynamic-priority algorithm assigns priorities online, based on execution parameters of tasks, such as upcoming deadlines. Finally, mixed-priority algorithms have both static and dynamic components. This article investigates and presents methods based on fuzzy logic for prioritizing radar tasks with the aim of analyzing their effectiveness in radar scheduling.

SCHEDULING

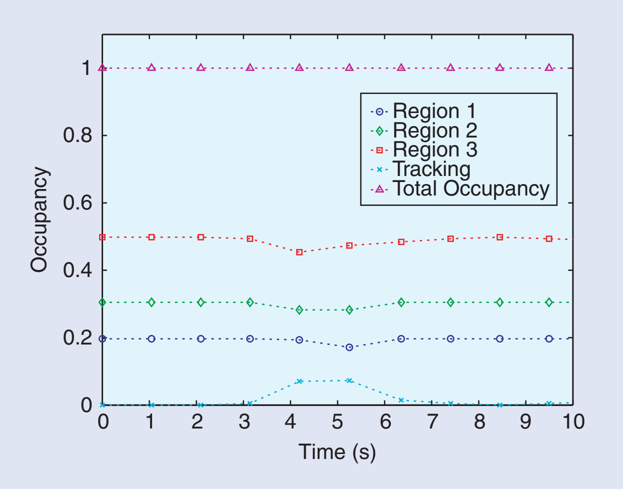
Two different scheduling algorithms proposed in [3] and [4] are first briefly described prior to comparing and contrasting their performance. First, we introduce a model for the phased array radar system to be examined. The model of the multifunction radar developed here is focused on tracking, surveillance, and task scheduling. The architecture used in the simulations is presented in Figure 1.

A radar system composed of four fixed-phased array antennas is considered, and the simulation covers the behavior of one of its faces. The boundaries of the volume of coverage of the face of the radar can be user defined. Based on this information and on the desired surveillance performance, the surveillance function calculates the number of radar beams necessary to survey that volume. A list of task requests is generated, taking into account the desired surveillance performance of the radar system. The surveillance manager is fed by the task list, maintained an inactive queue of tasks (not yet

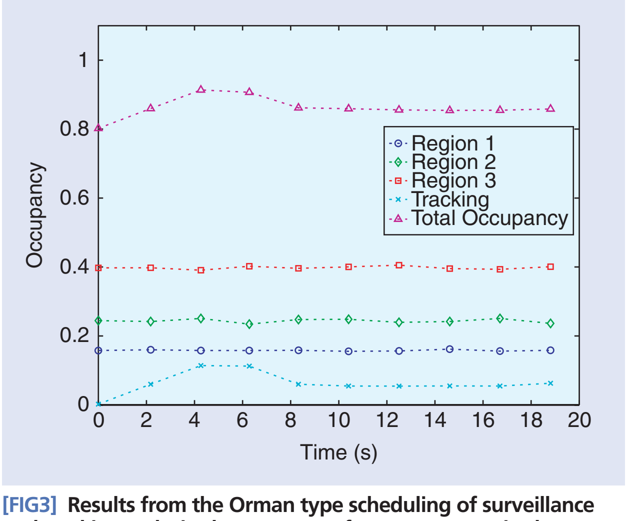


[FIG1] Radar resource manager architecture.

scheduled), and provides the scheduler with a smaller queue of requests that are close to their due time of execution. Likewise, the track function calculates the update times of the targets under track and feeds the track manager with a queue of tasks to be scheduled. The track manager also maintains a list of inactive track tasks that are to be sent to the scheduler when close to their due time of execution. Both surveillance and track manager select from the waveform database the parameters to be used in the transmission of the radar pulses associated with each radar job. Several aspects are to be taken into consideration in the criteria of selection, including boundaries of the regions of coverage, expected targets, target range, and target speed. Decisions relating to how resources are to be allocated according to the relative importance of the tasks and how to assess this relative importance are made by the block called *Priority Assignment*. The scheduler is fed by queues of track, plot confirmation, and surveillance task requests and creates a set of measurement tasks to be carried out by the radar based on task priorities and time constraints. A feedback loop between the output of the scheduler and the radar functions enables the next update times related to those tasks to be calculated. The overall preferences related to mission requirements and resource management decisions based on evaluation of the tactical scenario are accounted for in the block named *Operator and Strategy*. This module operates as a human-machine interface, allowing intervention to enable corrections in the behavior of the system.



[FIG2] Results from the Butler type scheduling of surveillance and tracking tasks in three sectors of coverage. Required surveillance occupancy = 80%.



[FIG3] Results from the Orman type scheduling of surveillance and tracking tasks in three sectors of coverage. Required surveillance occupancy = 80%.

Two different schedulers were developed and are compared for the same operational conditions. They are based on the online scheduling algorithms presented by Orman et al. [4] and Butler [3]. The scheduler suggested by Orman et al. is centered on a coupled-task specification of the radar jobs. A coupled task is a job consisting of two different operations separated in time by a specified interval; for example, the transmission and reception times of a defined waveform type. Thus, each coupled task can be represented by the processing time of the first operation, the processing time of the second operation, and the separation time between them. The job is considered to be a set of tasks that must be executed to achieve the radar function performance requirements (e.g., a pulse burst). The scheduler organizes a queue of tasks to be executed in any order provided that two tasks do not occupy the radar at the same time. The main idea of the coupled-task scheduler is to use the idle time existing within a radar job to interleave other radar jobs and achieve improved usage of the radar time.

An alternative approach was postulated by Stafford [14] and subsequently modified by Butler [3] that is based on the concept of time balance and was implemented in the experimental multifunction electronic scanned array radar (MESAR) system. MESAR is an experimental active phased-array radar system developed by QinetiQ and AMS Ltd. The first version of this radar was delivered in the early 1990s, and advances have been introduced more or less continuously since then.

The Butler (or MESAR) algorithm uses a time-balance scheme to control the scheduling process of the requested tasks. There is a time balance related to every radar job, indicating to the scheduler how much time is owed by the radar to that job. A zero time balance meant that the job is due to be executed at the exact time. A negative time balance meant that the new job is not to be executed at this time, and a positive time balance means that the job is late, thus the radar owes time to that job. A job consists of several tasks and is usually associated with surveillance of a region of coverage or the keeping of a target under track. A task is a group of activities that are noncoherently integrated to give detection. A task can be divided into looks, consisting of one or more activities. This algorithm schedules the looks of a task in sequence and the tasks are selected according to the desired priority order. All radar functions are assumed to have fluid deadlines. When a task of higher priority than that currently being scheduled is requested, the process is interrupted, and that task is scheduled. An interesting characteristic of this algorithm is that no idle time is left on the radar time line. When the desired surveillance occupancy is less than 100% and the radar load associated with other functions is less than one, then surveillance tasks are scheduled earlier and the surveillance occupancy is increased to the stage where the total radar time line is completely used. Similarly, when the tracking load is increasing due to a great number of detected targets, the surveillance jobs are progressively delayed and the detection performance degrades. This could lead to a situation in which no surveillance is performed and only tracking tasks are executed.

This is in contrast to the Orman type of scheduler, where the highest priority is given to the tracking function and all the tracking tasks are scheduled as near as possible to their due times of execution with the aim of minimizing the number of late tasks. The surveillance performance is determined by either the radar operator or the mission requirements.

The significance of using the modified version of the MESAR scheduling algorithm is that some tasks can be scheduled with greater delays.

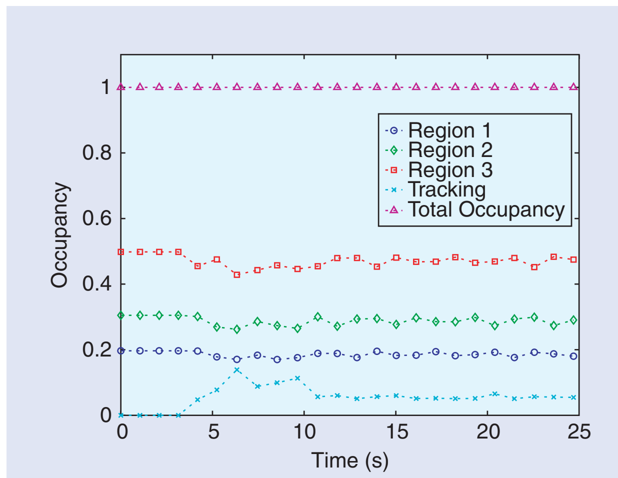
The approaches are compared by analyzing their resulting resource allocation when the multifunction radar faces different operational scenarios in respect of the amount of resources required to meet the performance requirements. Many simulations have been performed to validate the algorithms and investigate performance. Two cases are considered here, underload, where not all radar resources are required to carry out the mission, and overload, where there are insufficient resources. These highlight the essential differences and similarities of the two approaches. Consider first the case of an underload situation. Figure 2 shows that the Butler algorithm is able to use all available radar resources by scheduling low-priority tasks earlier than their desired execution time. This behavior is not observed when examining the results from the algorithm proposed by Orman, as shown in Figure 3. This is explained by the fact that once the performance requirements are met, additional resources are not used to improve surveillance performance and the radar has idle periods during its operation. Thus it may be concluded that, in this case, the radar performance will be superior when the Butler scheme is employed.

In contrast, the results presented in Figures 4 and 5 show that both schedulers produce similar resource allocation results when operating in overload situations. Here, there are not enough resources to execute all requested radar tasks. Even so, the Orman approach fails to make use of all of the radar time line and sometimes the occupancy is a little less than 100%. In general, however, it may be concluded that there is little to choose between the two in terms of overall performance under stressing conditions.

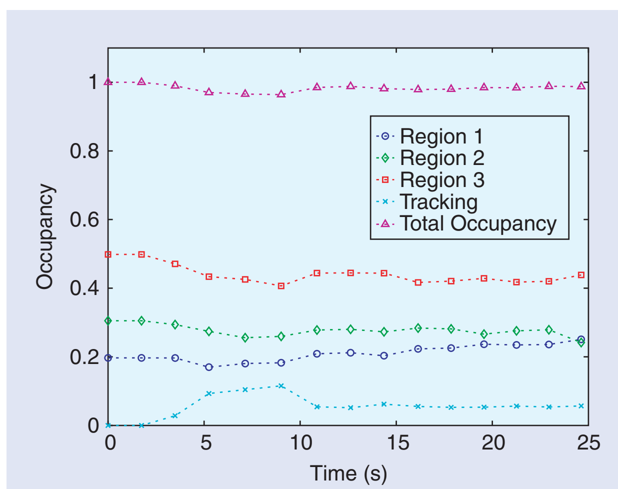
As the multifunction radar is likely to be specified as having to be able to operate in overload situations, it will be critical that a well-designed scheduler must enable highest priority tasks to be carried out. This brings into question the assignment of priorities. It is now shown that the use of adaptive prioritization methods for radar tasks is an efficient way to manage resource allocation. In particular, the application of fuzzy logic algorithms developed in [13] to prioritize target tracking and sectors of surveillance are considered and compared with fixed prioritization approaches. These algorithms are based on expert knowledge and imitate the human decision making in similar situations.

INTELLIGENT PRIORITIZATION USING FUZZY LOGIC

The attribution of priority to regions and targets of interest is central to the eventual performance of the array radar system and to subsequent mission success. There are a variety of methods that may be employed, from simple fixed allocations based on operational experience to more elaborate schemes that attempt to balance competing components that constitute the overall determination of priority. For example, the priority for tracking targets may be evaluated using the decision tree presented in Figure 5. This could be carried out according to information provided by a tracking algorithm, by other sensors, or by other operational modes of the multifunction radar such as high resolution.



[FIG4] Results from the Butler type scheduling of surveillance and tracking tasks in three sectors of coverage. Required surveillance occupancy = 100%.



[FIG5] Results from the Orman type scheduling of surveillance and tracking tasks in three sectors of coverage. Required surveillance occupancy = 100%.

[TABLE 1] FUZZY VALUES RELATED TO THE MAIN VARIABLES USED IN THE PRIORITY ASSIGNMENT.

FUZZY VARIABLE	FUZZY VALUES
TRACK QUALITY	HIGH AND LOW
HOSTILE	NONHOSTILE, UNKNOWN AND HOSTILE
WEAPON SYSTEMS	LOW, MEDIUM AND HIGH CAPABILITY
THREAT	VERY LOW, LOW, MEDIUM, HIGH AND VERY HIGH
POSITION	CLOSE, MEDIUM AND FAR
PRIORITY	VERY LOW, LOW, MEDIUM LOW, MEDIUM, MEDIUM HIGH, HIGH, AND VERY HIGH

Five different variables provide information used to set the priority level. These are threat, hostility, quality of tracking and relative position of the target, and weapon system capabilities of the platform. These are termed *linguistic variables*. The reasons for selecting these variables are explained in the following.

Track quality refers to the accuracy of the predicted position of the target with respect to the desired accuracy for this prediction. For example, if the error of the predicted position is small, the track quality is said to be high; however, large errors or missed detections lead to poor quality, and the priority of the target may be increased in order to improve the prediction of its position.

[THE EFFICIENT ALLOCATION OF RADAR RESOURCES SUCH AS TIME AND ENERGY HAS BEEN THE SUBJECT OF INCREASING RESEARCH OVER RECENT YEARS.]

Hostile is a fuzzy variable related to four concepts: range to the target, absolute velocity, target identity, and the manner in which the target is approaching the radar platform. Thus, the priority for tracking this target should clearly vary according to the way the target is approaching the radar platform, its absolute velocity, its range, and its identity. These four concepts are also associated with linguistic variables, which are disposed as nodes of the decision tree and combined to provide the final value for the hostility of a target. Range is the fuzzified value of the range of the target. In general, the closer the target, the higher its priority. Velocity is the fuzzified value of the absolute velocity of the target. Target identity is the probability of a target being enemy; thus, the higher this probability, the higher the degree of hostility of the target. Finally, approach is related to the fuzzified value of the range-rate-to-velocity ratio of a target relative to radar platform; high values for range-rate-to-velocity imply a fast approach, leading to high priorities. The variable *weapon systems* represents the importance of a target in respect of the weapon systems of the radar platform. In order to assess this importance, three concepts are combined: the identity of the target, the operational range of the weapon systems, and the ratio between the range rate and the absolute velocity of the target. The range-rate-to-velocity represents the way in which the target is approaching the radar platform and also corresponds to a fuzzy variable approach. The Weapons System linguistic variable accounts for the operational range at which the weapon systems can be effectively applied. Targets at long ranges cannot usually be engaged by the weapon system of the radar platform, and therefore their priority is reduced. However, this importance is gradually increased as the targets move to positions that are closer to the radar platform; short ranges lead to high target importance in respect of weapon systems capabilities. When combining the three concepts, different degrees of importance may be achieved by a target. For example, it is expected that enemy targets approaching the radar platform fast have greater priority than enemy targets moving away when they are detected far away from the radar platform.

Threat is the linguist variable that represents the degree of threat of a target according to its trajectory and identity. Trajectory combines four fuzzy variables related to height, maneuver, absolute velocity, and range-rate with respect to the trajectory on which the target is moving. In general, maneuvers, low altitudes, high range-rates and high absolute velocities lead to assessing a target as having a high degree of threat. However, even friendly targets may have a degree of threat if they are moving towards the radar platform in situations which may lead to collisions, for example.

Finally, *position* is the linguistic variable whose value is given by the combination of the fuzzified values of the range and azimuth of a target. In most cases, short ranges imply high priority for target tracking as the target may be situated in high precision tracking areas. Azimuth is a fuzzy variable that accounts for the existing coherence between the azimuth of a target at its early stages of the tracking and the expected detection azimuth of threatening or enemy targets. In military applications, this represents the coherence between the position at which the target is detected and the previous knowledge about the environment in which the radar is operating in respect of the distribution of enemy forces.

Fuzzy values are attributed to each variable. Some examples of the fuzzy values are presented in Table 1. After evaluation of these variables according to a set of fuzzy rules, the importance (priority) of the target is determined. While the membership of each fuzzy set may take any suitable shape, it is common to restrict the membership functions to triangular, trapezoidal, or bell shaped functions to reduce the computational burden required to determine the degree of membership associated with a particular value of input variable [15]. Here, only triangular and trapezoidal membership functions are used for the fuzzy sets associated with the input variables.

A similar methodology is applied to the surveillance function base upon the decision tree presented in Figure 6. In this case, the priority of surveillance sectors may be assessed through the original priorities attributed to the regions with respect to the expected tactical scenarios and the information gathered during the evolution of the actual environments. This includes aspects such as rate of detection of new targets, number of threatening targets, and rate of detection of new threatening targets. A set of fuzzy rules enables the evaluation of the priority of the different sectors considered for surveillance.

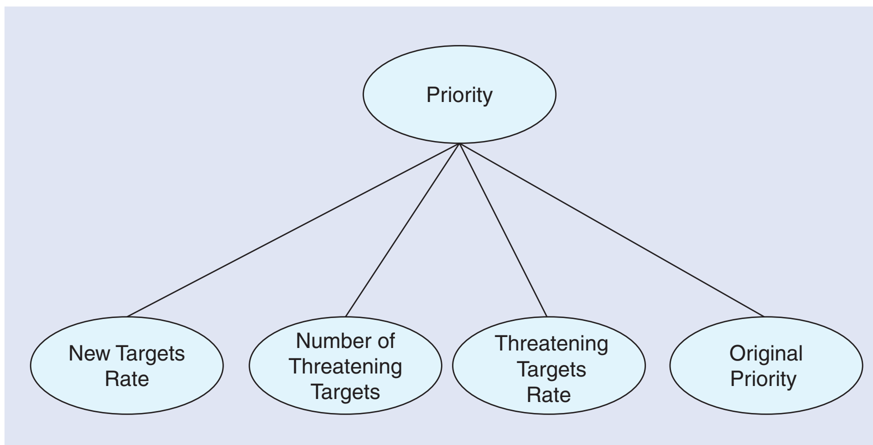
Apart from the track quality, all the variables are fuzzified in early stages of the priority evaluation. These fuzzifications explain the fact that the universes of discourse, or domains, of all variables whose membership functions are presented here vary between zero and one. The output of the system is the evaluated priority of the target under study, which is represented by the fuzzy variable priority.

The fuzzy representation of the input and output parameters is considered complete when the membership functions, the domain of each variable, and the number of fuzzy sets (values) are computed [15]. Thus, the determination of the fuzzy if-then inference rules is the next step in the design of the fuzzy logic-based prioritization system. The number of fuzzy rules required to assess the value associated with a knot in the decision tree of Figure 7 is equal to the product of the number of fuzzy values that compose the fuzzy variables linked to that knot. Table 2 shows the number of if-then rules used to evaluate the main fuzzy variables assumed here.

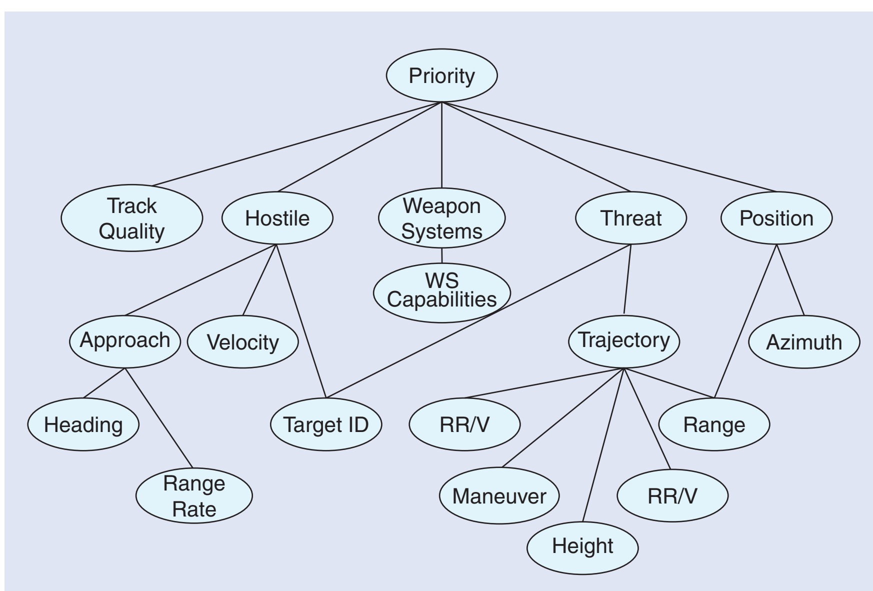
The inferential rules of the fuzzy system were written on the basis of intuitive and expert considerations and then tuned by simulation tests. The actual number of rules used in the inference system, in some cases, may be smaller than the required number. This is explained by the fact that particular combinations of fuzzy variables are very unlikely to be observed in real systems. The reduced number of rules does not represent a drawback as max-min associations are used by the fuzzy inference system. These associations ensure that the truth of an assertion is not affected by the number of contributing rules but by the degree of truth of the dominant term. This characteristic enables the system to include additional rules in the knowledge base without concerns about the contribution of other rules. The evaluation of the fuzzy rules must follow the sequence proposed on the decision tree. Thus, the system inputs are fuzzified and successively used to assess other fuzzy variables in cascade to the point where the final priority is obtained. It is not especially straightforward to evaluate how the resulting target priority is modified as a function of the main fuzzy variables by only examining the fuzzy rules. Therefore, graphic representations are a valuable tool to assess the inferential rules. These representations may be obtained by fixing all the variables but two involved in the evaluation of the priority. An example of these surfaces is presented in Figure 9. The configuration presented in Figure 9 assumes that the values of three variables (track quality, position, and weapon capabilities) are maintained at 0.5, and both threat and hostile are varied over their respective domains. This configuration may represent a situation in which the target is located at medium range and has medium importance in respect of the weapon systems of the radar platform.

[TABLE 2] FUZZY VALUES RELATED TO THE MAIN VARIABLES USED IN THE PRIORITY ASSIGNMENT.

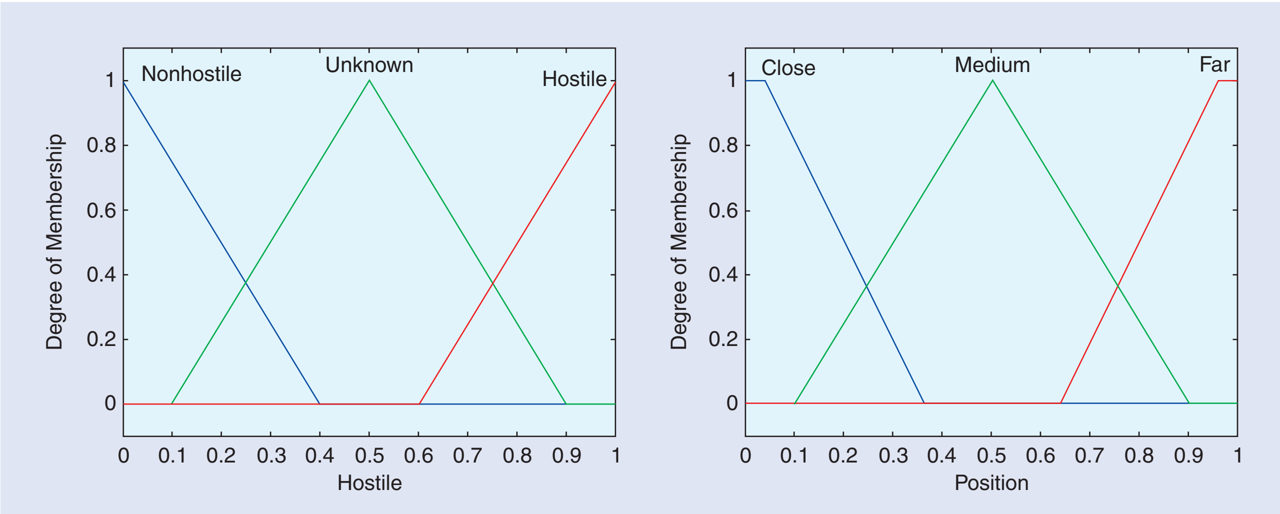
FUZZY VARIABLE	NUMBER OF FUZZY RULES
PRIORITY	270
HOSTILE	108
WEAPON SYSTEMS	16
THREAT	36
POSITION	6



[FIG6] Decision tree for sectors of surveillance priority assessment.

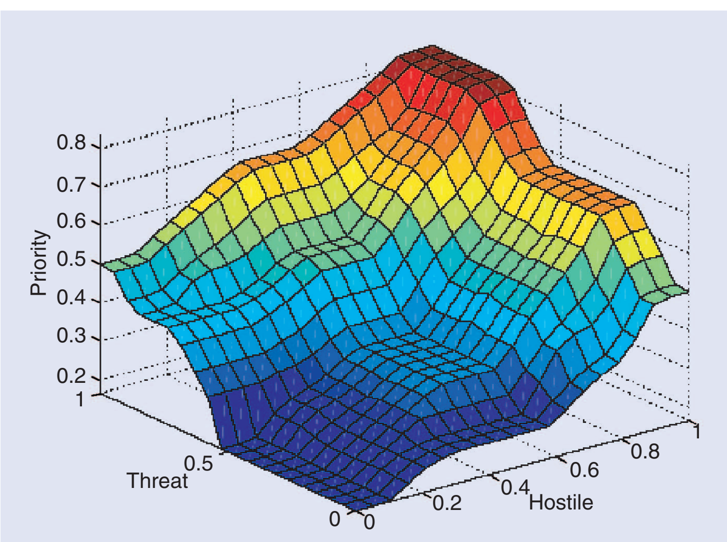


[FIG7] Decision tree for targets priority assessment.



[FIG8] Fuzzy membership functions related to the fuzzy variables representing the degree of hostility and the position of a target.

It is observed that, as might be expected, the priority increases as a consequence of increases in the degrees of threat and hostility of a target. Conversely, low degrees of hostility and threat maintain the resulting priorities at low levels. Two other areas may also be identified on this surface. The first is related to the degree of hostility varying 0.5–1 (medium to very high) and the degree of threat varying 0–0.5 (very low to medium). The resulting priority increases as a result of rises in the degree of threat or hostility. However, the sensitivity to rises in degree of hostility is greater than the sensitivity to the degree of threat. This behavior is explained by examining situations in which targets with medium and high probability of being the enemy are moving away from the radar platform, in this case, the higher the differences in the way the target is moving away from the radar. Thus, the high degree of threat produces a larger effect in the final target priority than the lower value of hostility. The second area corresponds to degrees of threat varying 0.5–1 and low levels of hostility. Like the previous situations, the resulting priority increases as a consequence of rises in the degree of threat or hostility. Nonetheless, the behavior is different from the one in the previous area: the sensitivity to increases in degree of threat is greater than the sensitivity to the degree of hostility. This may be explained by considering situations where, having low probabilities of being the enemy, targets move on threatening trajectories towards the radar platform. In this case, the way the target is approaching the radar has greater effect in the final priority than its identity. Of course, the manner in which these relationships are formulated is itself a variable and one in which expert input plays a key role. Inevitably there will be a learning process during which the rules and relationships are refined as a result of experience.

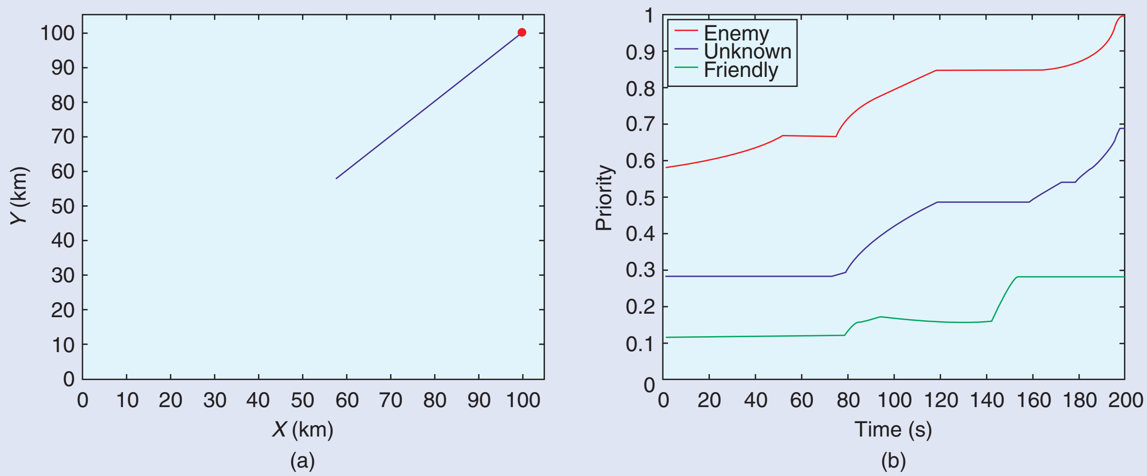


[FIG9] Graphic representations of the fuzzy rules, considering fixed three variables: Position, track quality, and weapon systems.

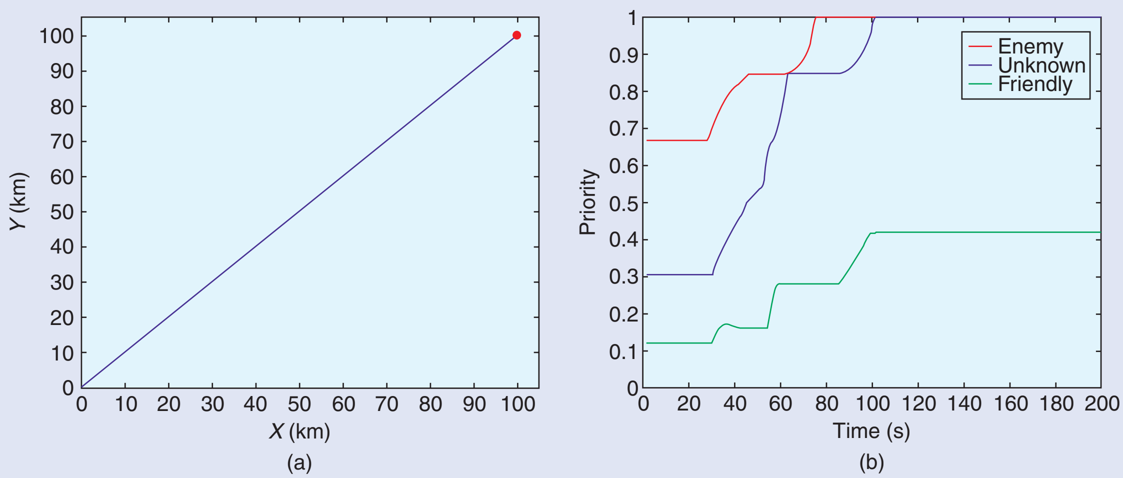
Having defined and tuned the fuzzy if-then rules, the method for prioritizing the relative importance of tracked targets is then validated against test trajectories, for all test trajectories scenarios consist of targets with different identities. The analysis shows that by knowing the identity of the targets, their priorities may vary. This provides valuable information to be accounted for when deciding how to allocate radar resources in overload situations. Two cases are presented here for targets moving towards the radar platform on constant-velocity straight line trajectories. These have been chosen as they represent situations of a high degree of threat where targets may be moving towards the radar platform to start an attack. In addition, they present the behavior of the method when a variable such as approach is fixed. This helps simplify the analysis and evaluation of the reasons for the results of the prioritization. The system can also be examined in more complex scenarios where all variables involved in the prioritization are changing over the simulation.

Figure 10(a) shows the first test trajectory where a target moves towards the radar platform on a straight line, having a constant velocity of 300 m/s. The red circle indicates the origin of the trajectory. Three targets are assumed in the analysis. They have the same dynamics and flight height; however, their probabilities of being enemy are different as follows: 1 (enemy), 0.5 (unknown), and 0.1 (friendly), corresponding to the red, blue, and green curves, respectively. The evolution of the resulting priorities is shown in Figure 10(b), which shows that, in general, all priorities increase as the targets move towards the radar platform; and the greater the probability of being enemy, the greater the resulting priority. Figure 10 also suggests that priorities of targets that have unknown identity present a similar behavior to friendly targets in the early stages of the trajectory. This may be explained by the fact that during that period, the range of the targets is longer than the tactical range of the platform weapon systems. This happens until around 60–80 s. From that instant, as the target is moving close to the boundaries of this weapon systems tactical range, the degree of threat of the unknown target is likely to increase. Thus, its priority evolution has the similar behavior to the priority evolution of the enemy target: the closer the unknown target is, the higher and the closer to the enemy target its priority will be. At short ranges, if the identity of the target is still unknown, the target is assumed to be enemy, and its resulting priority is assessed as that.

Figure 11 presents the results of a simulation where targets are assumed to move on a straight line trajectory with 800 m/s of velocity. The same probabilities of being enemy of the previous analysis are considered. Due to the high velocity and short ranges, the evolution of the priorities is rather different from the previous case. During the first few seconds of simulation, both unknown and enemy targets have slightly higher priorities than in the first example. This may be explained by their high velocities. All target priorities remain fixed until about 30 s,



[FIG10] Resulting priorities for three targets with different probabilities of being enemy, moving on the same trajectory.



[FIG11] Resulting priorities for three targets with different probabilities of being enemy, moving on the same trajectory. Target velocity: 800 m/s.

when the target position is getting close to the weapon system operational range. Before 30 s, all targets have the maximum priority possible for the set of characteristics of their dynamics, identity and the capabilities of the weapon systems. Thereafter, the priorities are increased in order to allow the radar platform to face the threat. It is observed that, from around 30–60 s of simulation time, the priority of the unknown target presents a high rate of increase. The analysis indicates that more importance is progressively given to this target which is gradually assumed to be like an enemy target, because its velocity is very high, the target is approaching the radar fast, and its identity is unknown over this period. From around 60–85 s, the unknown target has the highest priority possible for the combination of input variables which determine its importance. From 85 s, its priority increases again, reaching its highest at around 100 s, when the target position is within operational range of the platform weapon systems and as a consequence both enemy and unknown targets have the same priority. Such an unknown approaching target is considered to be of highest importance because of its potential degree of danger, represented by its velocity, the way it is approaching the radar platform. Like the unknown target, the priorities of both enemy and friendly targets increase from around 30 s, as they are getting close to the weapon system operational range. These priorities continue to increase reaching their maximum values not later than 100 s of simulation, when the position in within the operational range with a degree of membership of 100%.

The results of the situations examined here suggest that the fuzzy logic approach is an intelligent and valid means for evaluating the priority of targets. By imitating the human decision-making process and by combining dynamic characteristics about radar tracking and military aspects, such as the ability of the weapon systems of the radar platform to face potential threats, the fuzzy approach may represent an effective and intelligent support for decisions regarding radar resource management.

SCHEDULING IS AN IMPORTANT SUBPROBLEM OF RADAR RESOURCE MANAGEMENT AND HAS BEEN THE FOCUS OF INTENSIVE RESEARCH.

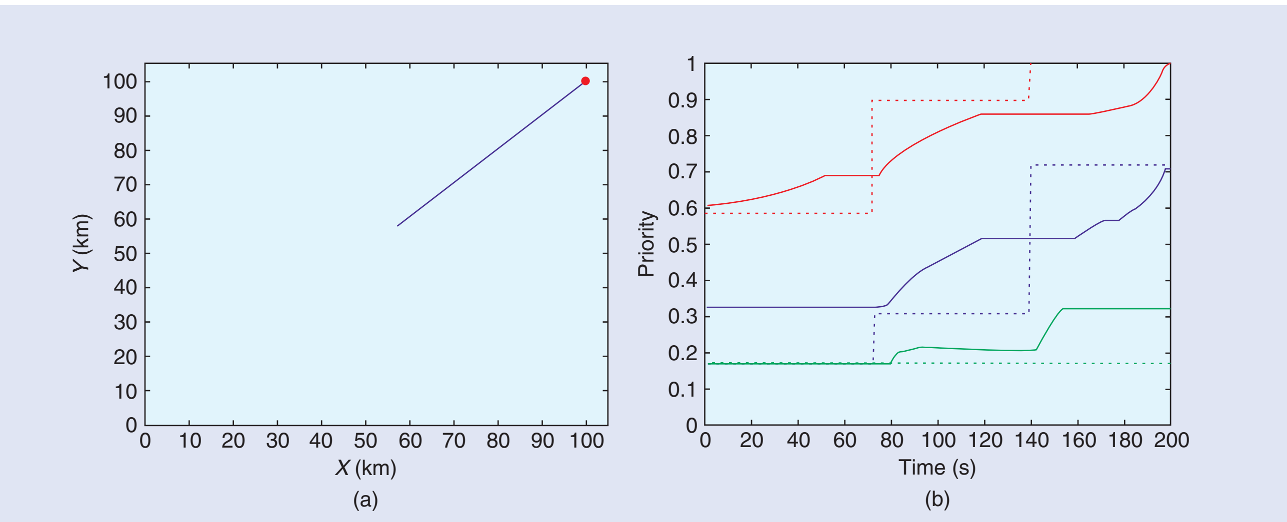
[TABLE 3] FIXED PRIORITIZATION ORDER FOR RADAR TASKS.

PRIORITY	RADAR FUNCTION
1	SURVEILLANCE (LOWEST PRIORITY)
2	TRACK UPDATE
3	TRACK INITIATION
4	PLOT CONFIRMATION
5	TRACK MAINTENANCE (HIGHEST PRIORITY)

FUZZY AND HARD LOGIC FOR PRIORITIZATION

Here, performance is assessed and compared using two prioritization methods: a fixed priority and a hard logic prioritization. The fixed priority method is based on the prioritization order typically used in radar scheduling. In this analysis, the prioritization order of Table 3 is used, where tasks related to the tracking function have greater importance than tasks related to surveillance.

The prioritization method called *hard logic* can be described by a set of rules similar to the ones proposed for the fuzzy logic approach. However, for each operational condition, only one rule is fired, determining the priority of the radar task. In this case, the input variables are classified in sets using the same labels which described the fuzzy variables. These variables are crisp numbers, which means that at any time they will only belong to one labeled set. In practice, this method works like the fuzzy logic approach but using sharp edge membership functions. The main advantage of this method is the reduced computational burden in assigning the priorities of the radar tasks.



[FIG12] Resulting priorities for three targets with different probabilities of being enemy, moving on the same trajectory.

[TABLE 4] REQUIREMENTS FOR THE EXAMPLE SURVEILLANCE VOLUME.

SECTOR	AZIMUTH COVEEERAGE	ELEVATION COVERAGE	FRAME TIME	BROADSIDE DWELL TIME
1	0–45°	0–20°	2 *s*	4 ms
2	−45–0°	0–20°	2 *s*	4 ms
3	−45° to +45°	20–50°	3 *s*	1 ms

As before, one face of a static multifunction radar consisting of a four-faced phased array antenna is considered. Thus, a region coverage spanning from $-45°$ to $+45°$ away from the antenna broadside is assumed. In this section, this region is subdivided into three different sectors of surveillance. For each sector, both frame and dwell times are defined to determine the desired surveillance performance. Sector 1 spans 0–45° in azimuth and 0–20° in elevation. Likewise, sector 2 spans 0° to $-45°$ in azimuth and 0–20° in elevation. These sectors require the highest search rate as targets may be detected at short ranges in low elevations. Finally, sector 3 extends from the top of sectors 1 and 2 to an elevation of 50°, spanning from $-45°$ to $+45°$. Table 4 shows the frame times and broadside dwell times of this surveillance requirement.

To compensate for the expected decrease in gain when static systems are scanning away from array broadside, not only is coherent integration assumed but also the waveforms used for surveillance are increased in length. The scan loss is assumed to be proportional to $\cos^3 \theta$, where θ is the scan angle off broadside. The tracking load is represented by a number of enemy targets that, after being inserted in the system, are detected and tracked using Kalman filters.

Examples regarding prioritization of targets is examined using the test trajectory presented earlier in Figure 10. The first example assumes that three targets are moving towards the radar platform on a straight-line trajectory with a velocity of 300 m/s, as shown in Figure 12(a). Once again the targets have different probabilities of being enemy, being considered enemy (red curves), unknown (blue curves) and friendly (green curves). The solid lines represent the priority evolution for the targets when the fuzzy logic approach is used; the dotted lines represent the results using the hard method.

The main difference that can be identified is the soft transition between the different levels of priority when using the fuzzy logic approach. The hard method produces such transitions in steps. In general this results in a more efficient deployment of radar resources.

The analysis of the priority evolution when the target is considered to be enemy suggests that both fuzzy and hard results have similar trends in respect of priority assignment in spite of the different shapes. Similar behavior is observed when comparing the priority evolution of an unknown target. As explained earlier, when the target is far away from the radar platform, its importance is evaluated as of the friendly target. In the case of the hard method, in the early stages of the simulation, the unknown target is even considered as important as the friendly target. However, as the target moves to positions close to the radar platform, its priority increases at a consequence of the target being assessed as dangerous. The priority evolution is, therefore, similar to the evolution of an enemy target; the unknown is not assessed to be as important as the enemy target because of the ranges and absolute velocities considered in this example. The comparison of the results for the friendly targets shows that the hard method maintains the target priority constant throughout the period of the simulation. This behavior may be explained by the fact that both range and velocity of the targets are not sufficient to provoke a change in the priority level at which the target is assessed by the hard method. This comparison shows that both methods may be used to evaluate the relative priority of the radar targets. Depending on the situation, the priority resulting from the utilization of the fuzzy logic may be greater or not than the priority obtained by the use of the hard method. At first, there is a tendency to consider that if two systems execute the same set of tasks, the system that assesses these tasks with lower priority should be considered more effective, because fewer resources would be allocated to execute the tasks. However, this analysis is not always valid in radar scheduling, where the resources are demanded by the radar function in order to achieve their performance requirements. The task priority, therefore, is important for preparing the set of measurements to be executed by the radar. However, it should also be noted that this does not necessarily mean less resources. For example in the first 70 s of the scenario, the priority of the enemy target is above that of the hard case and hence will tend to demand greater radar resource.

CONCLUSIONS

In this article, we have compared the performance of two scheduling methods and highlighted both differences and similarities. This analysis also indicated that prioritization is a key component to determining overall performance. A fuzzy logic approach for prioritizing radar tasks in changing environment conditions was introduced. Key to the success of this is the prior knowledge base that sets the fuzzy logic relationships. By assessing the priorities of targets and sectors of surveillance according to a set of rules it is attempted to imitate the human decision-making process such that the resource manager can distribute the radar resources in a more effective way. Results suggest that the fuzzy approach is a valid means of evaluating the relative importance of the radar tasks; the resulting priorities have been adapted by the fuzzy logic prioritization method, according to how the radar system perceived the surrounding environment. The analysis of these fuzzy logic methods has been further developed by comparison with a fixed prioritization order. From the test configuration examined the nonsmooth transition characteristics associated with the hard prioritization suggest that this may lead to very dissimilar and, sometimes, undesirable results.

One aspect, however, must be highlighted. By using the fixed prioritization method the resource manager may not allocate any resource to low priority sectors, degrading surveillance substantially or even preventing it from being performed. Similar results could be found as a result of using the hard and the fuzzy logic approach. Sectors in which no target is detected and in which a priori information about the environment suggests that no threat should be expected may have all surveillance stopped in extreme overload situations. It might be important to determine a minimum surveillance performance to be achieved in all sectors to avoid dropping the search for new targets in less important sectors completely. In real systems, the use of a fuzzy logic method may represent a useful support for radar resource management decisions. It is also very important that the information in respect of radar resource management is presented to the radar operator at all times. This knowledge-based information must include aspects regarding the priorities of the targets and sectors of surveillance, how the resources are distributed over the main radar functions, and which functions have their performances degraded as a consequence of radar management decisions in resource constrained scenarios. Therefore, the operator may intervene in the resource allocation as a result of their own assessment of the environment or to correct undesirable behavior. Finally, characteristics related to growth and maintainability may make the fuzzy logic approaches attractive for military applications.

AUTHORS

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REFERENCES

[1] G. Van Keuk and S.S. Blackman, "On phased array tracking and parameter control," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 29, no. 1, pp. 186–194, Jan. 1993.

[2] E.R. Billam, "Parameter optimisation in phased array," in *Proc. Radar 92*, 1992, IEE conf publ., No. 365, pp. 34–37.

[3] J.M. Butler, "Multi-function radar tracking and control," Ph.D. dissertation, University College London, 1998.

[4] A.J. Orman, C.N. Potts, A.K. Shahani, and A.R. Moore, "Scheduling for a multi-function array radar system," *Euro. J. Operational Res.*, no. 90, pp. 13–25, 1996.

[5] A. Izquierdo-Fuente and J.R. Casar-Corredera, "Optimal radar pulse scheduling using a neural network," in *Proc. IEEE Int. Conf. Neural Networks*, June–July 1994, vol. 7, pp. 4588–4591.

[6] A.P. Stoffel, "Heuristic energy management for active array multifunction radars," in *Proc. 1994 IEEE Nat. Telesystems Conf.*, San Diego, USA, 1994, pp. 71–74.

[7] D. Strömberg and P. Grahn, "Scheduling of tasks in phased array radar," in *Proc. IEEE Int. Symp. Phased Array Systems Technology*, Oct. 1996, pp. 318–321.

[8] M.T. Vine, "Fuzzy logic in radar resource management," in *Multifunction Radar and Sonar Sensor Management Techniques* (Ref. No. 2001/173), IEE colloquium Dig., pp. 5/1–5/4, 2001.

[9] S.L.C. Miranda, C.J. Baker, K. Woodbridge, and H.D. Griffiths, "Phased array radar resource management: A comparison of scheduling algorithms," in *Proc. 2004 IEEE Radar Conf.,* Philadelphia, USA, 2004, pp. 79–84.

[10] J.M. Molina Lopez, F.J. Jimenez Rodriguez, and J.R. Casar Corredera, "Fuzzy management of surveillance sensors," in *Proc. 37th IEEE Conf. Decision Control*, Tampa, USA, 1998, pp. 245–250.

[11] W. Komorniczak, T. Kuczerski, and J.F. Pietrasinski, "The priority assignment for detected targets in multi-function radar," in *Proc. 13th Int. Conf. Microwaves, Radar, and Wireless Communications.*, Poland, 2000, pp. 244–247.

[12] W. Komorniczak, J. Pietrasinski, B. Solaiman, "The data fusion approach to the priority assignment in the multifunction radar," in *Proc. 14th Int. Conf. Microwaves, Radar and Wireless Communications*, Poland, 2002, pp. 627–650.

[13] S.L.C. Miranda, C.J. Baker, K. Woodbridge, and H.D. Griffiths, "Phased array radar resource management: A fuzzy logic approach for prioritization of radar tasks and sectors of surveillance," in *Proc. Radar 2004 Conf.*, Toulouse, France, Oct. 2004.

[14] W.K. Stafford, "Real time control of a multifunction electronically scanned radar (MESAR)," in *Proc. IEE Colloquium Real Time Management Adaptive Radars*, June 1990, pp. 7/1–7/5.

[15] G. Bojadziev, and M. Bojadziev, *Fuzzy Sets, Fuzzy Logic, Applications*. Singapore: World Scientific, 1995.

[16] S. Gopalakrishnan, and M. Caccamo, S. Chi-Sheng, L. Chang-Gun, and L. Sha, "Finite-horizon scheduling of radar dwells with online template construction," in *Proc. 25th IEEE Int. Real-Time Systems Symp.*, 5-8 Dec. 2004, pp. 23–33.

[17] H. Sun-Mog and J. Young-Hun, "Optimal scheduling of track updates in phased array radars," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 34, no. 3, pp 1016–1022, July 1998.

[18] A.G. Huizing and A.A.F. Bloemen, "An efficient scheduling algorithm for a multifunction radar," in *Proc. IEEE Int. Symp. Phased Array Systems Technology*, 15-18 Oct. 1996, pp. 359–364.

[19] K. Tei-Wei, C. Yung-Sheng, Chin-Fu Kuo, and C. Chang, "Real-time dwell scheduling of component-oriented phased array radars," *IEEE Trans. Comput.*, vol. 54, no. 1, pp. 47–60, Jan. 2005.

[20] W. Komorniczak and J. Pietrasinski, "Selected problems of MFR resources management," in *Proc. 3rd Int. Conf. Information Fusion 2000*, 10-13 July 2000, vol. 2, pp. WEC1/3–WEC1/8.

[21] D. Stromberg, "Scheduling of track updates in phased array radars," in *Proc. IEEE Nat. Radar Conf.*, 13-16 May 1996, pp. 214–219.