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Sensor Allocation in a Forest Fire Monitoring System: A Bi-objective Approach

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Abstract. Forests worldwide have been suffering from fires damages, provoking incalculable losses in fauna and flora, economic losses, people and animals' deaths, among other problems. To avoid forest fires catastrophes, it is fundamental to develop innovative operations, such as a forest fire monitoring system. This work concentrates efforts on defining the optimum sensor allocation in a forest fires monitoring system based on a wireless sensor network. Thus, a bi-objective mathematical model is developed to solve the problem, in which the first objective consists of minimising the forest fire hazard of a given forest region, and the second objective refers to the sensors spreading into this region. The developed mathematical model was solved by genetic algorithm and the results demonstrated that the methodology was capable of presenting suitable solutions for the problem.

INTRODUCTION

Developing strategies to monitor forests and avoid forest fires catastrophes is urgent and essential all over the world. Previous studies present methodologies where it is possible to mitigate fire damage considerably through an efficient forest fire monitoring system [1, 2]. In this context, the project Forest Alert Monitoring System (SAFe) aims to develop innovative technologies to allow efficient forest monitoring. Besides, the developed technologies will also provide decision-making support when a fire ignition is detected. Thus, the firefighters and civil protection could have precious information in real-time, such as fire evolution and propagation direction, that help the fire fighting.

The techniques proposed in this work are addressed to "Serra da Nogueira" located in the North region of Portugal, belonging to the municipality of Bragança. To monitor a vast forest region is an arduous task, and it demands a high computational cost. For this reason, the proposed methodology will be tested in a small experimental area. The selected region is composed of three different forest fire hazards and several forest density values. The results obtained will guide the improvement and the expansion of the real monitored area.

As a visualisation database and geographic data provider, the QGIS software [3] is used combined with the Coper-nicus [4]. The coordinate system has the ETRS89/PT-TM06 (EPSG:3763) UTM Zone 29N standard with Mercator Transverse Universal projection, the unit of measurement used is in meters. To define the optimal sensor modules' position, besides the sensor technical characteristics, two critical parameters are considered to develop the optimisa-tion model: *forest fire hazard* (probability of potentially destructive phenomena, associated with the terrain conditions [5, 6]) and *forest density* (parameter related to the quantity of vegetation in a specific area). More details about both parameters can be verified in [2].

According to [6], it is possible to estimate a fire hazard scale from 0 to 5. In this way, a level 0 indicates low forest fire hazard, and a level 5 indicates high forest fire hazard. As to the forest density, it is a parameter related to the quantity of vegetation in a specific area. In this work, the forest density varies from 0 to 100, where 0 indicates no presence of vegetation and 100 indicates a high concentration of vegetation in 40 m^2.

This work is addressed to deal with the problem of sensor optimum allocation in a forest fire monitoring system

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through wireless sensors network, considering the bi-objective approach, in which it is intended to minimise the forest fire hazard and, at the same time spread the sensors, maximising the distance between them.

BI-OBJECTIVE MODEL

In this work the problem of sensor allocation will be treated as a nonlinear optimisation problem, considering a bi-objective approach. To solve the mathematical model the NSGA algorithm was used [7], through the *gamultiobj* function implemented on MATLAB Software. A set of sensors (ns sensors) is available to be allocated into a pre-defined region and its ability to cover a point, at a certain distance, is considered as a problem constraint. Besides, forest density f^d and the forest fire hazard f^h of each point are considered as environmental constraints.

Consider a sensor s_j that can be placed on a point p_j with a given coverage that depends on the forest density and the forest fire hazard parameters. As closer a given forest point p_i is to the sensor s_j, as higher will be the protection. Besides, in the forest environment, the sensor's coverage also depends on the forest density where the sensor s_j and the point p_i are located. When a sensor s_j, for $j = 1, ..., ns$, is assigned to a point p_j, it is necessary to identify which points p_i are covered by this sensor, and consequently, how much the sensor coverage reduces the forest fire hazard on the point p_i.

To define if a sensor covers a point, the Euclidean Distance, d_{ji}, between the sensor s_j, placed on the point p_j, and a given point p_i, is evaluated by Equation (1).

$$d_{ji} = \|p_j - p_i\|_2 \text{ for } j = 1, ..., ns \text{ and } i = 1, ..., np. \quad (1)$$

The coverage sensor distance function depends on the forest density of the sensor position f_j^d, the forest density of the point f_i^d, and the sensor maximum covered distance d_{max}. Thereby, the coverage sensor distance is given by Equation (2).

$$CD(p_j, p_i) = CD_{ji} = d_{max}\left(1 - \frac{f_j^d + f_i^d}{2f_{max}^d}\right). \quad (2)$$

If the distance (d_{ji}) between the sensor located on p_j to the point p_i is smaller than the coverage sensor distance CD_{ji}, the point p_i is covered by the sensor s_j placed on p_j position. In this case, it is necessary to define the level of coverage, establishing the forest fire hazard reduction on the point p_i. The forest fire hazard reduction function H_{ji}, expressed by Equation (3), depends on the locations of s_j, placed on p_j, and also the point p_i location.

$$H(p_j, p_i) = H_{ji} = \frac{w_{max}f_{max}^h - w_{min}f_{min}^h - w_{ji}(f_{max}^h - f_{min}^h)}{w_{max} - w_{min}}, \quad (3)$$

where f_{max}^h is the maximum forest fire hazard, f_{min}^h is the minimum forest fire hazard, and w_{max} and w_{min} are the maximum and minimum coverage distance, respectively. The value w_{ji} refers to the interference generated by the distance d_{ji}, the forest density (f_j^d and f_i^d), and the quantities d_{max}, and CD_{ji}. The w_{ji} value is calculated as the average of both values as expressed on Equation (4).

$$w_{ji} = \frac{d_{ji} + (d_{max} - CD_{ji})}{2}. \quad (4)$$

The forest fire hazard value on the point p_i is updated with the forest fire hazard reduction, associated to the sensor s_j coverage, according to the following function, in Equation (5).

$$f_i^h = f_i^h - H_{ji}. \quad (5)$$

When f_i^h is positive, it means no sensor covers the point p_i or the coverage level received by a sensor or a set of sensors s_j is not enough to completely eliminate the forest fire hazard of the point p_i, in few words. If the f_i^h is zero, the point is fully covered by a sensor or a set of sensors. Finally, when f_i^h is negative, it means that more than one sensor is covering that point, resulting in excess coverage (overlap), what should be avoided.

Thereby, the optimisation problem aims to identify the optimum sensor locations $x = (s_1, ..., s_{ns})$ with $s_j \in \{p_1, ..., p_{np}\}$ for $j = 1, ..., ns$ in order to cover as much area as possible, using a fixed quantity of sensors, and avoid overlap of sensor range. Thus, the first objective function of the problem is defined by Equation (6).

$$\min_{x} f_1(x) = \sum_{i=1}^{np} \max\left(f_i^h, 0\right) + \max\left(-f_i^h, 0\right) \tag{6}$$

On the second objective function, define the sensor spreading, in order to guarantee that the distance between the sensors will be maximised. Thence, the Euclidean distances between the location of sensor s_j, p_j, and the other sensors available s_k, with p_k locations, are evaluated, with the aim to maximise this distance, as presented in (7):

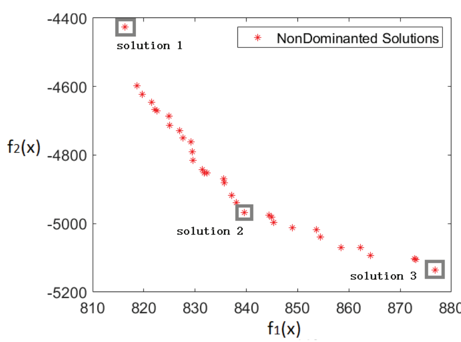
$$\min_{x} f_2(x) = -\sum_{j=1}^{ns} \sum_{k=1}^{ns} ||p_j - p_k||_2 \tag{7}$$

RESULTS AND DISCUSSION

The sensors will be fixed on the tree trunks, so at least one tree is required to allocate the sensor. Besides, it is known that the forest fire in Bragança region starts typically in regions with high forest density [2]. In this sense, only points with forest density over or equal to 80 were considered candidates to receive a sensor. This value also ensures that there are appropriated trees in the region to fix the sensors. The region considered has 3 level of forest fire hazard, varying from 3 (lowest level) to 5 (highest level). There are 253 points on the map to allocate the sensors, being 1060 the sum of the forest fire hazard initially. Two types of sensors, named A and B, are considered, having 7 units of sensor A and 3 of sensor B. The sensors A can cover a distance between 0 and 50 meters, depending on the forest density interference; and the sensors B can cover between 0 and 100 meters.

The parameters used for the optimisation problem were: $f^d_{min} = 0$, $f^d_{max} = 100$, $f^h_{min} = 0$, f^h_{max} is the initial forest fire hazard of the point p_i, $d_{min} = 0$ and d_{max} varies according to the sensor type, being $d^A_{max} = 50$ for the sensor A and $d^B_{max} = 100$ for the sensor B. The parameters used for the GA termination criterion are $MaxStallGenerations$ equal to 100 and maximum number of iterations before the algorithm halts equal to 2000. Since GA is a stochastic method, the algorithm was executed 30 times for build the Pareto front with 0.35 of Pareto fraction parameter [7].

To perform the Pareto front, the solutions of the 30 executions were compared to each other. In this way, the Pareto front is presented in Figure 1, with 50 points that describe the non-dominated solutions. Each solution in this front is equally optimum, but each of them prioritise the objectives differently. Three strategic points were selected to evaluate the Pareto front and they are highlighted and described in Figure 1.



Solution 1		
f1(x)	f2(x)	overlap
816.33	-4425.99	11.85

Solution 2		
f1(x)	f2(x)	overlap
839.67	-4966.76	6.73

Solution 3		
f1(x)	f2(x)	overlap
876.83	-5135.05	7.58

FIGURE 1. Pareto front and selected solutions

Solution 1 represents the optimum solution in terms of objective function $f_1(x)$, and at the same time it is the worst solution in terms of objective function $f_2(x)$. For priorities Objective 1, this solution reduces 23.34 units of forest fire hazard than the Solution 2 and 60.50 units than Solution 3. On the other hand, evaluating the Solution 1 in terms of Objective 2, the spreading is 540.77 meters less than Solution 2 and 709.06 less than Solution 3. Regarding the overlap value, Solution 1 presented 11.85 units of overlap.

Solution 2 can be considered a intermediate solution for both functions, this solution can balance the objectives requirement of objectives functions $f_1(x)$ and $f_2(x)$. Solution 2 reduces 23.34 units less forest fire hazard than the Solution 1 but it reduces 37.16 units more than Solution 3. In terms of sensor spreading, this solution spreads 540.77 meters less than Solution 1 and it reduces 168.29 more than Solution 3. In this case, the overlap presented is equal to 6.73 units, which is the best value obtained in relation to other solutions.

Solution 3 represents the optimum solution in terms of objective function $f_2(x)$, however, it is the worst solution in terms of objective function $f_1(x)$. This solution reduces 60.5 units less forest fire hazard than the solution 1 and 37.16 units less than solution 2. For prioritises the objective function $f_2(x)$, solution 3 spread 168.29 meters more than solution 2 and 709.06 more than solution 1. Regarding the overlap value, solution 3 presented 7.58 units of overlap.

As we can observe, the Solution 2, is the solution that balances the objective function 1 and 2, for this reason, if no priority was done for one of the objective functions, the Solution 2 is the most appropriated solution to be tagged as problem final solution. Thus, the arranged of this solution on the forest fire hazard map (left side), and also on the forest density map (right side), is presented in Figure 2.

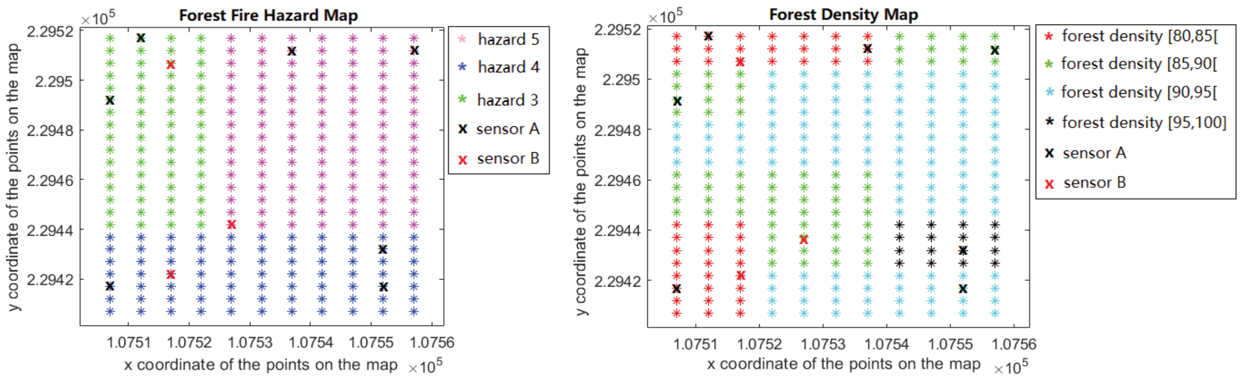


FIGURE 2. Forest fire hazard map and forest density map with sensors allocated

CONCLUSIONS AND FUTURE WORKS

This work was addressed to deal with the problem of sensor optimum allocation in a forest fire monitoring system through wireless sensors network. In general, the applied methodology was able to solve the sensor allocation problem considering two objectives, firstly to minimise the forest fire hazard and secondly to spread the sensors into a given forest region. As future perspectives, it is intended to explore new methodologies to spread sensors, since all solutions presented of Pareto front have considerable overlap value, which should be as lower as possible.

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