DOI: 10.29298/rmcf.v14i77.1349

Research Article

Generación de rutas mediante ACH para detección de incendios forestales en el Estado de México

Generation of routes through ACO for detection of forest fires in the State of Mexico

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Fecha de recepción/Reception date: 4 de marzo de 2023
Fecha de aceptación/Acceptance date: 23 de mayo del 2023

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Abstract

Fires are part of the cycle of some ecosystems and can cause the degradation of others. Their main causes are anthropogenic, including, among others, poorly extinguished bonfires, agricultural activities, and dumping of garbage, all of which generate habitat loss and air pollution on a large scale. This paper refers to the application of a genetic algorithm based on an ant colony to generate, at a theoretical level, verification routes for the monitoring and early detection of forest fires in the State of Mexico by means of unmanned aerial devices, as it is one of the entities with the highest number of forest fires in Mexico. The data used in the proposal were drawn from the reports generated by the National Forestry Commission (*Comisión Nacional Forestal*, Conafor). During the analysis process, those municipalities that have been affected in at least three different geographic locations were filtered out. In the course of the evaluation process, the software developed displayed the routes with the shortest distances, reordering the filtered localities. Finally, a map is displayed pinpointing the localities where a forest fire has occurred and showing the approximate distance of the entire route. The new routes planned with this procedure resulted in an average 54 % reduction compared to a sequential route.

Keywords: Genetic algorithm, ant colony, forest fires, artificial intelligence, path planning, autonomous aerial vehicles.

Resumen

Los incendios forman parte del ciclo de algunos ecosistemas, los cuales pueden ser causantes de la degradación de otros. Algunas de sus causas son principalmente antropogénicas, entre ellas las fogatas mal apagadas, actividades de agricultura y liberación de basura, que generan la pérdida de hábitats y contaminación aérea a gran escala. El presente trabajo hace referencia a la aplicación de un algoritmo genético basado en una colonia de hormigas para generar, de forma teórica, las rutas de verificación para el monitoreo y la detección temprana de incendios forestales en el Estado de México mediante dispositivos aéreos no tripulados, debido a que es una de las entidades con mayor número de este tipo de incidencias en México. Los datos que se emplearon en la propuesta se extrajeron de los registros que genera la Comisión Nacional Forestal (Conafor). Durante el proceso de análisis se realizó el filtrado de los municipios en donde se han presentado afectaciones en al menos tres localidades geográficas distintas. En el proceso de evaluación, el *software* desarrollado desplegó las rutas en las que se obtuvieron las distancias más cortas, reordenando las localidades extraídas. Finalmente, se despliega el mapa en el cual se ubican aquellas en donde se ha presentado un incendio forestal, así como la distancia aproximada del recorrido total de la ruta. Los resultados presentaron 54 % de media de reducción en las nuevas rutas planificadas, en comparación con una ruta secuencial.

Palabras clave: Algoritmo genético, colonia de hormigas, incendios forestales, inteligencia artificial, planificación de recorridos, vehículos aéreos autónomos.

Introduction

The causes of forest fires are diverse, given the number of elements that intervene in them, such as available fuel, low humidity in the environment (Cárdenas-Salgado and Pizano, 2019), and direct or indirect human interference, the latter being responsible for 75 to 96 % of forest fires (Hirschberger, 2016). It should be taken into account that fires have the capacity to renew ecosystems (Manríquez, 2019) and thus bring about their continuity.

According to Conafor records of 1970 to 2022, there have been 374 742 forest fires in Mexico, which have affected 14’829 944 hectares, the most affected entities being the State of Mexico, Mexico City, *Michoacán*, *Chihuahua*, and *Jalisco* (Conafor, 2022).

The current climate variations have generated a series of changes in seasonal cycles, leading to a greater release of greenhouse gases, and the loss of natural areas responsible for reducing carbon concentration aggravates the problem (Semarnat, 2018). Today, the rise in global temperatures and droughts have caused forest fires to increase in intensity, as observed in Europe, Australia, and the Western United States (Williams *et al*., 2019; Dupuy *et al*., 2020; Haque *et al*., 2021). When a large number of medium-sized or large-scale forest fires occur, human populations are affected by the release of gases such as carbon monoxide, carbon dioxide, sulfur dioxide, and particulate matter, the latter being the most dangerous (Sandoval *et al.*, 2019; Correa, 2020).

In Mexico, forest fires tend to occur in times of low rainfall, particularly in spring (Alanís-Rodríguez *et al.,* 2008), and their number increases with such phenomena as droughts (Espinoza and González, 2019). The main forms of fire management are related to the formation of fire control brigades (Aguilar *et al.*, 2021), as well as to controlled burn planning to reduce the concentration of available fuel that might generate a large-scale fire (Pérez-Salicrup *et al.*, 2018; Rodríguez *et al.*, 2020).

There are different methods and technologies available for fire detection through the analysis of elements such as fire, smoke, and hot spots, among others (Ramos, 2010). One of the most widely used is satellite technology, which can capture virtually any surface and can verify events such as smoke and fire; an example of this technology is the Early Warning System for Forest Fires (*Sistema de Alerta Temprana de Incendios Forestales*, SATIF) (Conabio, 2022). Another type of mechanism for estimating fire danger are sensor networks (SN), i. e., electronic devices that are deployed in different areas to obtain such data as humidity, temperature, and wind speed, among others (Aakvaag and Frey, 2006; Cama *et al.*, 2012); the information extracted by the sensors is usually sent wirelessly to a control station.

Other detection systems, such as convolutional neural networks (CNN), usually employ artificial intelligence for efficient pattern recognition (Berzal, 2019); they are one of the most common applications of deep learning (Wiatowski and Bölcskei, 2016; Zhou, 2020) and are responsible for classifying objects in digital images. On the other hand, there are genetic algorithms, which are tools that represent the evolutionary and learning behaviors of living beings, allowing the generation of solutions to problems that require optimization processes, such as the process of calculating routes for the control of forest fires using drones (Wang *et al.*, 2018; Zhou *et al.*, 2019; Shaji, 2022).

When forest fires grow rapidly, the number of personnel needed to contain them is often insufficient, and the associated costs can be high (Mendoza *et al.*, 2012). Today, the application of unmanned aerial vehicles (UAV) allows monitoring and control of forest fires, as can be seen in Kinaneva *et al.* (2019), Sungheetha and Sharma (2020), and Li *et al.* (2022). Madridano (2020) proposes an architecture for coordinating drones to fight forest fires; similar proposals are presented by Pérez-Sánchez *et al.* (2017), with the use of a geo-referenced system for drone use.

On the other hand, there are other types of proposals for drone coordination models, as shown in Casbeer *et al.* (2005), Harikumar *et al.* (2018), and Momeni *et al.* (2022), to show optimal routes, and for coordinating of this type of devices without wasting battery power, as this is an element that conditions their mobility. The papers by Chowdhury *et al.* (2019), Shao *et al.* (2021), and Sun *et al.* (2022) analyze proposals for route calculation. This type of device requires route planning, due to the complexity of the distances, as well as to the number of elements available for monitoring (Wu *et al.*, 2020; Dinh *et al.*, 2021; Saeed *et al.*, 2022). One of the algorithms that stand out for route planning in complex environments is the ant colony algorithm (ACO). High-impact works, such as those by Yang *et al.* (2020), Wang and Han (2021), and Stodola *et al.* (2022), highlight the implementation of the ACO because it is very proficient in solving the routing problem based on the traveler's problem, as shown in the study by Chaudhari and Thakkar (2019), compared to other algorithms like particle swarm optimization (PSO), artificial bee colony (ABC), and others.

Based on the above information, the objective of this research is to develop a proposal for the theoretical prevention and detection of forest fires with UAVs whose displacement is planned automatically using the ACO algorithm, as these devices can incorporate fire detection sensors and fire extinguishing mechanisms, and have flight capabilities that allow them to move through different types of terrain. For this reason, the implementation of UAV devices in the State of Mexico along routes defined through an ACO will help solve the currently existing issues in the detection and containment of forest fires.

Materials and Methods

The State of Mexico is the state in which historically there have been the highest number of forest fires in the country. This state is located in central Mexico; its coordinates are 18°25' and 20°17' N, and 98°33' and 100°28' W; its geography exhibits a cover of temperate forests of approximately 62 % (Ceballos *et al.*, 2008), and these forests are more susceptible to wildfires. Taking into account the above, a proposal has been designed for the generation of routes dedicated to the prevention and detection of forest fires using UAVs. The basis of this work is a procedure that consists in identifying geographic locations where forest fires have occurred, reordering these locations in order to obtain the shortest route, and finally, displaying the route proposed by the ACO.

An ACO is a recurrent algorithm for solving problems like that of the traveler; it consists in simulating the behavior of ants to calculate the probability of a path by creating a pheromone trail and indicating the route to be taken (Goss *et al.*, 1989; Dorigo *et al.*, 1996). In this algorithm, the ants are represented by simple computational agents (computer program) which take an edge (path); the pheromones (information related to the previously explored paths) are then selected; once the agent finishes the task, the result is evaluated in order to subsequently modify the level of pheromones in the trail and determine the best possible route, favoring the shortest edges (also known as the shortest path) with the largest amount of pheromones, the best agent being the one that can update the trail (Merkle and Middendorf, 2000). Figure 1 shows an example of a colony of ants, which illustrates the process of travel to find the best route in search of a target (O) and return to a base point (B), in this case, it is observed that after the generation of the traces, the one that represents the shortest distance to be covered is chosen at the end. For the purpose of the proposal, the algorithm will allow the UAV to find the shortest distance route in the fire verification process.

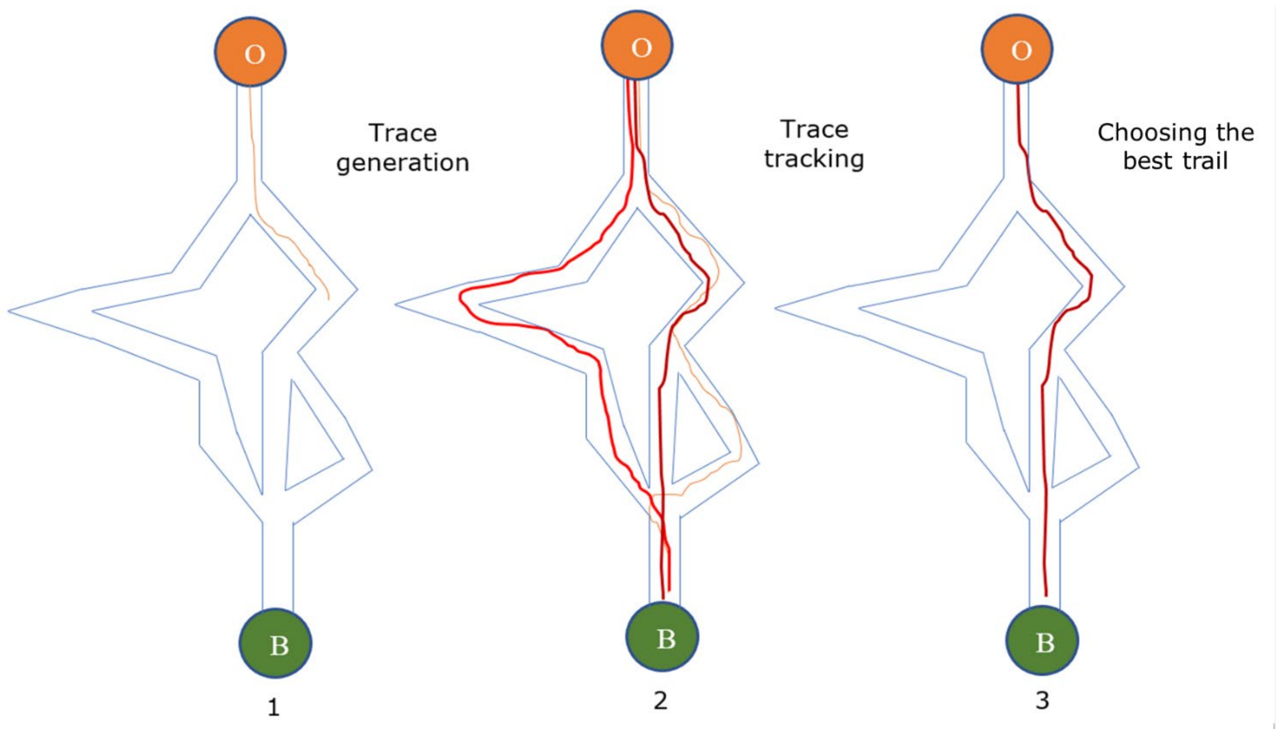


Figure 1. Example of the ACO process for distance travel.

Each agent moves from state *x* to state *y*, corresponding to a temporary solution. An agent *k* is in charge of computing a set of $a_k(x)$ of feasible routes from its current state in each iteration, moving probabilistically. For an agent p_{xy}^k, the transition from state *x* to state *y* depends on the combination of the values of the n_{xy} (movement); it is computed by a heuristic indicating the feasibility of the trace, and the level of the τ_{xy} trace of the movement, which indicates its competence in the previous cycle. Agent kth moves from state *x* to state *y* with a probability estimated using Equation (1) (Gambardella and Dorigo, 1996).

$$p_{xy}^k = \frac{(\tau_{xy}^{\alpha})(\eta_{xy}^{\beta})}{\sum_z(\tau_{xy}^{\alpha})(\eta_{xy}^{\beta})} \quad (1)$$

Where:

τ_{xy} = Indicates the amount of pheromones used in the transition from state *x* to state *y*; 0≤ α is the parameter that controls the influence of τ_{xy}

η_{xy} = Indicates the desirability of the *xy* state transition

$^1/_{d_{xy}}$ = *m*, where d is the distance

$\beta \geq 1$ = Parameter in charge of controlling the influence of η_{xy}

When all the agents complete a solution, the traces are updated with $\tau_{xy} \leftarrow (1-p)\tau_{xy} + \sum_k \Delta\,\tau_{xy}^k$. In the process of evaluating the edge distances, Equation

(2) is applied to determine the distance between two points, as it is an important element in determining the routes along which the agents will move.

$$d(A,B) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad (2)$$

Where:

d = Distance

A = First point

B = Second point

x_n = Abscissae of the different points

y_n = Ordinates of the different points

Equation 2 is used to calculate the distances in order to determine the edges that the agents are traveling and the shortest distance between the total distance of the route that is being planned.

Table 1 shows the pseudocode that represents the general form of the ACO, itemizing the basic functions, such as the generation of solutions, the agents involved, and, finally, the update of the pheromones, being these the solution space used by the model. In each cycle, the routes that were most successful for the agents are chosen to determine the order of the points to be used for the route.

Table 1. Pseudocode of the ant colony algorithm.

Main procedure

```
ACO procedure
Until the solution is found, carry out the following
Generate solutions()
Actions agents()
Update pheromones()
Repeat
End of the procedure
```

The route calculation model for forest fire detection is displayed in 4 main stages, which are as follows:

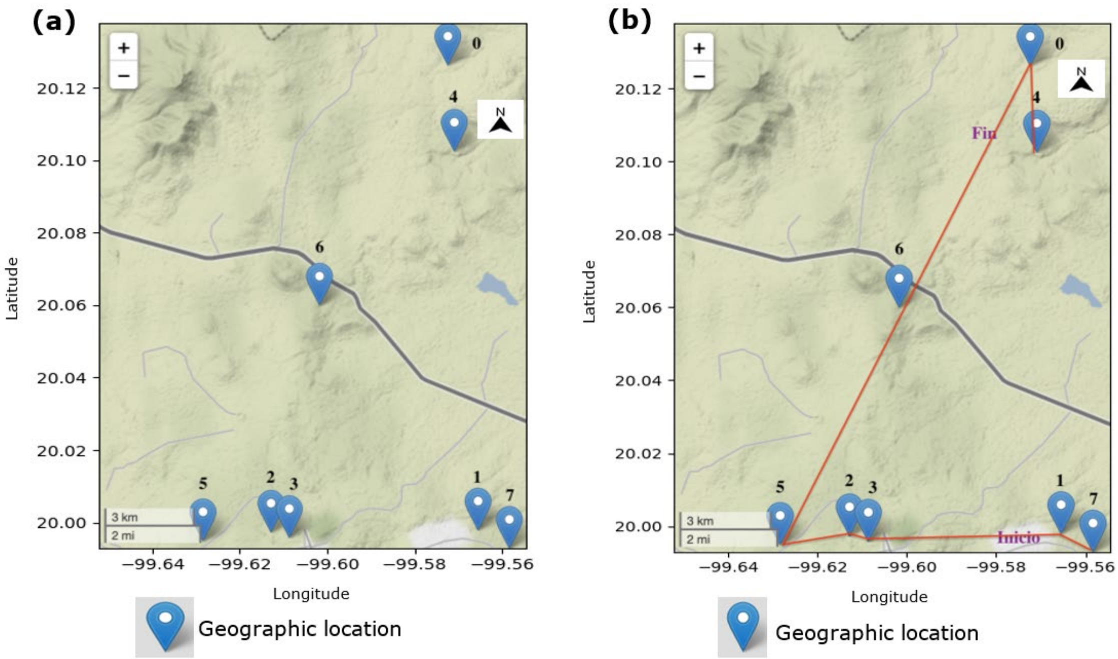
1.- Data filtering. This is the main stage of the model; it allows to extract the data from the file showing the geographic positions where a forest fire has occurred in the State of Mexico and it selects those municipalities where there have been at least three forest fires, taking into account that, with locations where only two forest fires or less have occurred, the total distance obtained will be the same if the ACO is not applied, as there will be only one combination for calculating the route.

2.- Listing of positions. Geographic localities are first grouped by municipality, in alphabetical order; then, they are assigned a numerical index ranging from 1 to *n*, in chronological order of the occurrence of the fire, for the purpose of estimating the shortest route for the UAV to traverse when reordering with the ACO.

3.- Reordering by ACO. The geographic localities are analyzed by the ACO, municipality by municipality, to reorder the localities according to the shortest route that a UAV will be able to execute.

4.- Presentation of results. Two evaluation scenarios are formed: A and B. The former corresponds to the distance that would be obtained if the route were calculated according to the extraction order of the localities, while the latter scenario applies the ordering with ACO. The results are then compared to calculate the percentage of difference between these and verify the minimization of the travel distance. When the solutions are obtained, a map is generated showing, by means of markers, the fires previously recorded. The order of the geographic localities is then presented by the new positions acquired according to their indexes, e.g., a set of indexes [1 2 3] may change to [2 1 3]; this new order must be sent to the UAV to determine its route. Finally, the theoretical total distance of each route is shown.

Figure 2 consists of two maps; the map in Figure 2a shows the geographic localities that have been extracted from a municipality where forest fires have occurred, Figure 2b shows the route to be taken by a UAV for the verification of a possible fire according to the result obtained by the ACO. The corresponding order of the path shown in Figure 2b is [7, 1, 3, 2, 5, 6, 0, 4].



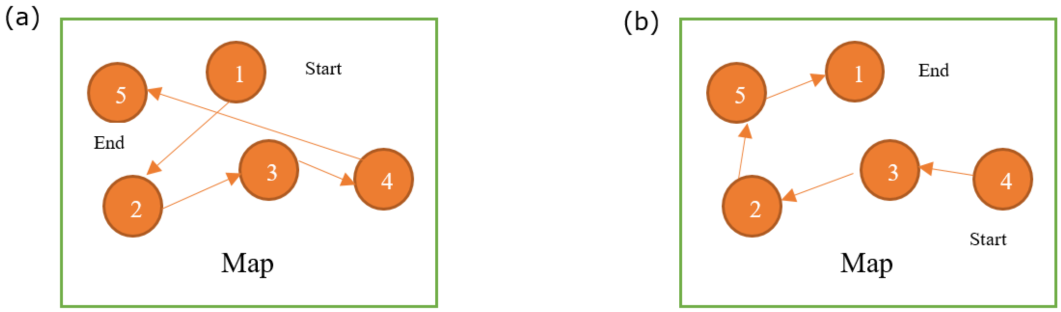
(a) Map with the geographic localities presented in the map for *Jilotepec*; (b) Route calculated by the ACO for *Jilotepec*. *Inicio* = Start.

Figure 2. Geographic coordinates extracted automaticallyt.

The proposal is designed to enter data in real time for the calculation of routes in time intervals of minutes to avoid manual calculation.

Experimental conditions

During the experimental phase, Conafor records on forest fires that occurred in the State of Mexico during the year 2022 were obtained; they included only those municipalities where at least three fires occurred in different geographic locations. Two scenarios have been proposed for the experimentation process: A and B. In scenario A, the distance by municipality is calculated as the geographical locations where forest fires occurred were identified; in scenario B, the ACO was applied in each municipality in order to obtain the shortest route with respect to the identified localities. In both scenarios, the total distance of the route is displayed; the reordering of the localities is shown exclusively in scenario B, and, finally, a map is generated with markers indicating, by municipality, the localities where forest fires have previously occurred. The results obtained from each scenario are compared using a statistical average to verify the reduction in the route travel distances by ACO. Figure 3 shows an example of the two experimental scenarios.



(a) Scenario A; (b) Scenario B.

Figure 3. Experimental proposal for distance traversal using ACO.

The proposal was developed using Python programming software and executed on a Mac Book Air® device with an M1 processor and 8 GB of RAM. The total number of agents generated for the use of ACO were 1 000.

Results and Discussion

Table 2 shows the results obtained from scenarios A and B, for 51 selected municipalities. As may be seen, the routes generated in scenarios A and B display notable contrasts between each municipality per scenario, with the most efficient cases including more than 16 localities where forest fires have occurred; as can be seen in the case of the municipalities of *Acambay*, *Atlacomulco*, *Ixtapaluca*, and *Ocuilan*, with verified geographic localities of 45, 18, 49 and 75, respectively. The results of minimization of distances between routes show an average of 54 %, with a maximum of 93 % in the best of cases. The latter percentage was observed with the data obtained in *Ocuilan*, while in such municipalities as *Xalatlaco* and *Xonacatlán*, which include three locations where forest fires occurred, the reduction in the distance was only slightly above 2.5 %.

Table 2. Results of the evaluation of the linear sequential and ACO points of travel.

Municipality	Distance traveled in km in sequential form (Scenario A)	Distance calculated in km by ACO (Scenario B)	Difference percentage	Total No. of points
Acambay de Ruíz Castañeda	475.795370	102.647187	78.426190	45
Aculco	115.717489	53.2015923	54.024588	10
Amanalco	64.7940969	33.4645787	48.352426	6
Amatepec	56.7129613	46.1921931	18.550905	6
Amecameca	71.8760222	34.4136285	52.120849	16
Atlacomulco	146.688067	53.6525422	63.424058	18
Atlautla	59.7395439	22.3597813	62.571221	12
Axapusco	8.24465249	4.58868830	44.343460	5
Calimaya	11.1576808	6.75384667	39.469081	3
Chalco	92.4847109	33.6455081	63.620464	11
Chapa de Mota	54.5967691	28.5308325	47.742635	9
Coatepec Harinas	139.561149	43.3919041	68.908321	26
Donato Guerra	92.6024808	29.6915317	67.936569	30
El Oro	7.39867909	6.05324432	18.184796	4
Isidro Fabela	23.2551310	14.1598843	39.110709	6
Ixtapaluca	227.335759	52.1543733	77.058438	49
Ixtapan de la Sal	25.2407404	20.3233401	19.481997	6
Jilotepec	71.2687924	31.0893913	56.377272	8
Jilotzingo	97.3415749	33.3383085	65.751213	22
Joquicingo	12.6388953	12.0147468	4.9383145	7
Juchitepec	11.4747209	10.1182171	11.821671	5
Lerma	115.530005	38.2361832	66.903677	28
Luvianos	28.4607759	21.2292671	25.408684	6
Malinalco	27.5241960	15.0006512	45.500129	3

Morelos	195.203301	54.2233766	72.222100	14
Naucalpan de Juárez	45.1311380	22.6778688	49.751169	15
Nicolás Romero	422.575669	67.3822026	84.054405	57
Ocoyoacac	74.0007935	29.4023493	60.267521	19
Ocuilan	725.232098	45.9514755	93.663893	75
San Felipe del Progreso	69.2611200	29.0239926	58.094826	8
San José del Rincón	327.678765	96.1962544	70.643122	38
San Martín de las Pirámides	3.24954378	2.31584122	28.733342	4
Sultepec	51.0358086	24.4415740	52.108970	4
Tejupilco	240.471197	75.5886026	68.566463	21
Temascalcingo	152.750511	47.8811699	68.654003	16
Temascaltepec	381.595986	95.1915567	75.054361	32
Tenancingo	133.138862	44.3652242	66.67748	25
Tenango del Valle	171.105803	45.3239168	73.511174	24
Tepetlaoxtoc	32.5046854	29.4524634	9.3900987	6
Texcoco	78.3423554	28.5990137	63.494825	11
Tlalmanalco	74.9889762	28.2149889	62.374484	15
Tlalnepantla de Baz	41.9447468	13.1923293	68.548315	9
Valle de Bravo	1056.56617	125.012732	88.168016	110
Villa de Allende	236.115220	72.8293532	69.155163	22
Villa del Carbón	309.749449	77.9311694	74.840578	33
Villa Guerrero	89.0352670	34.7741147	60.943437	14
Villa Victoria	204.061896	58.0877317	71.534258	26
Xalatlaco	5.94543065	5.79518474	2.5270820	3
Xonacatlán	5.31337491	5.12475651	3.5498793	3
Zinacantepec	189.094685	55.5089530	70.644889	18

Figure 4 shows a graph of the most relevant results, where it is possible to compare the reduction in the route traveled by each municipality. The most notable being *Valle de Bravo*, going from a total route in scenario A of 1 056.56 km to 125.01 km in scenario B. For the previous case, the advantage of the ACO over the calculation of routes that are generated without a distance minimization process is clearly observed. On the other hand, it is observed that in sites where there are three localities with distances of a few kilometers, the reduction is less than 5 %. In municipalities with three localities, but with greater distance between them, better results can be obtained in the minimization process, as observed in the cases of *Calimaya* and *Malinalco*.

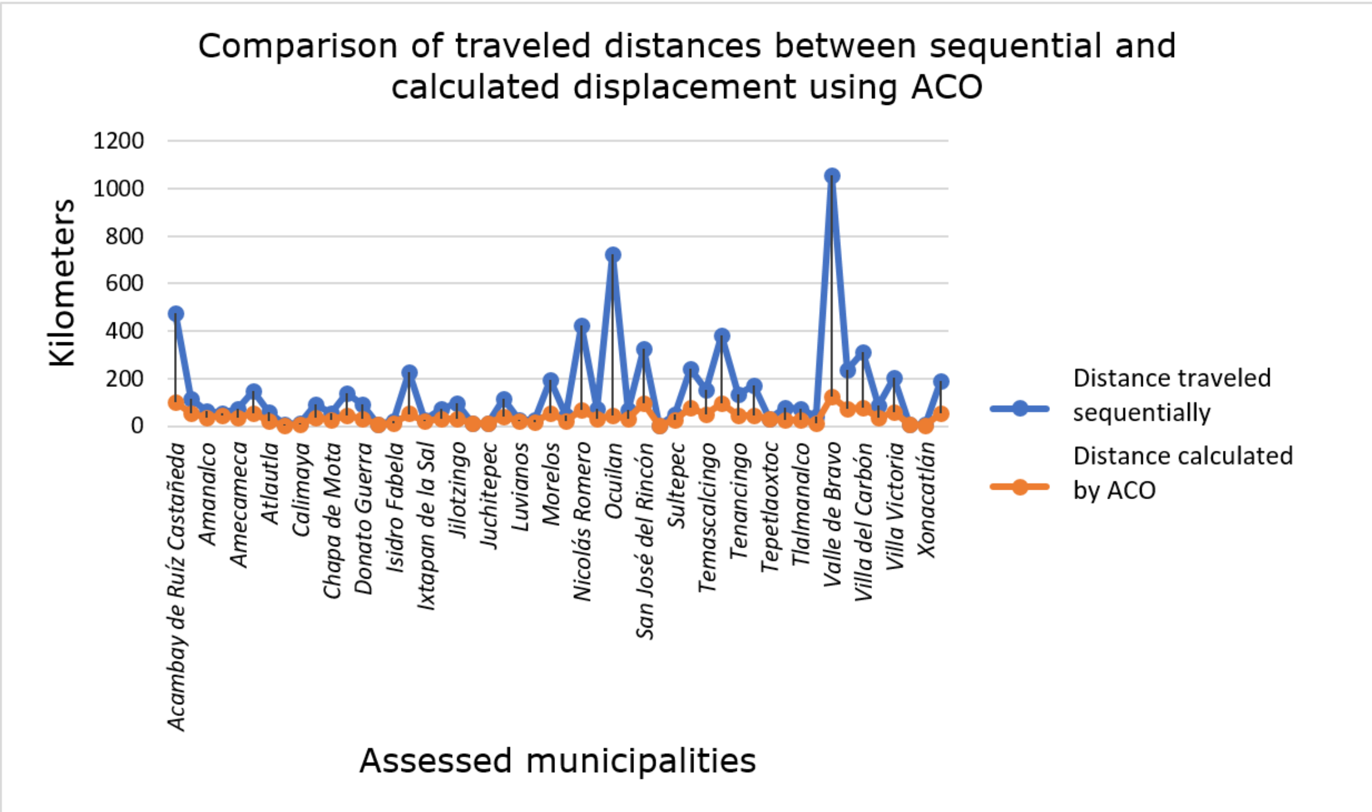
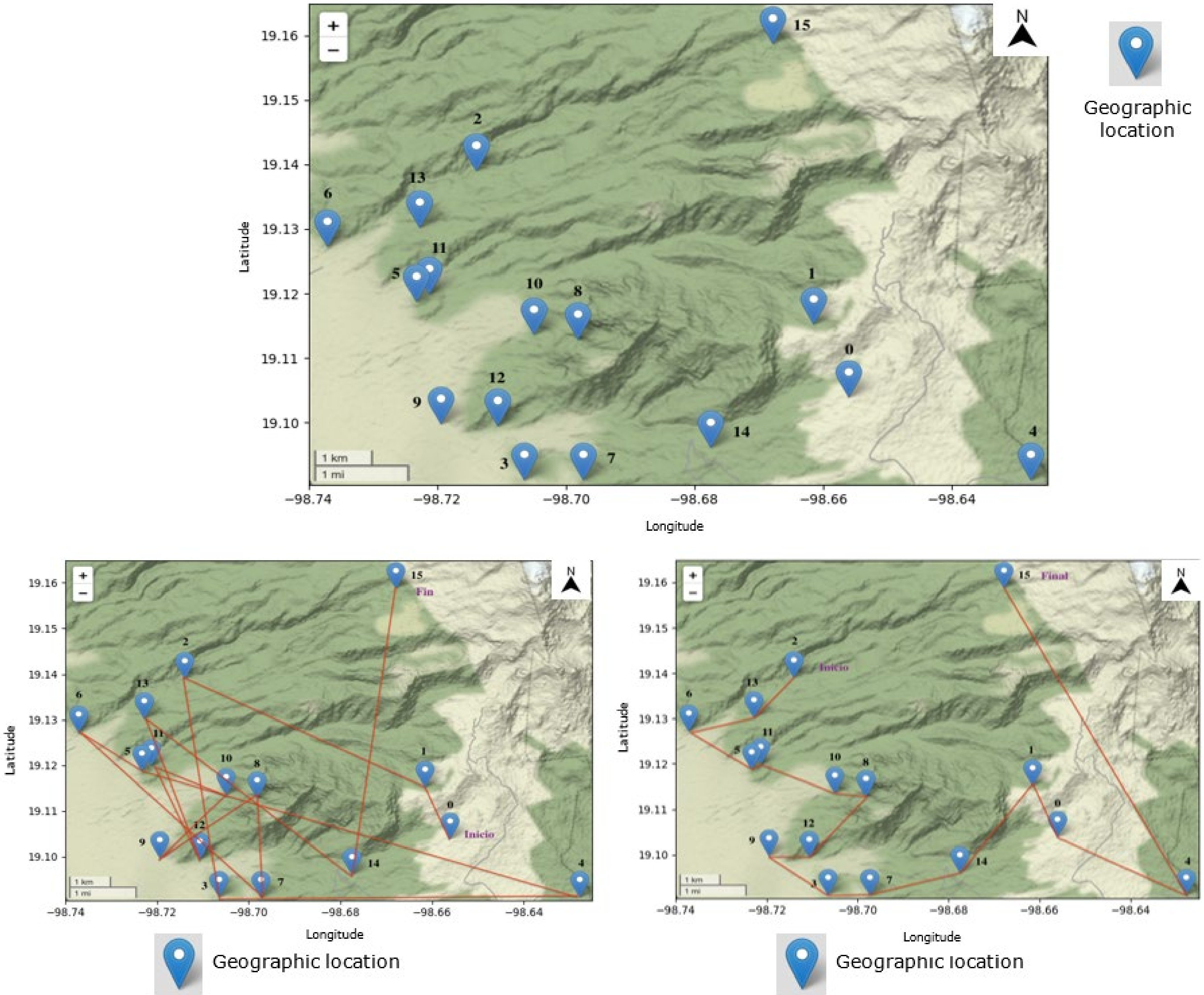


Figure 4. Comparative graph of mileage reduction when applying the ACO.

The largest percentage differences with respect to the distance traveled in the two scenarios for the analyzed municipalities were found in *Ocuilan*, *Valle de Bravo*, and *Morelos*, while the smallest decrease was obtained in the routes of *Villa Guerrero*, *Xonacatlán*, and *Jilotzingo*. The difference between a greater or lesser reduction in the distance of the route generated depends on the number of locations, the distance between these, and the probability of a greater number of existing returns.

Figure 5a shows the geographic localities in which forest fires have occurred in the municipality of *Amecameca*, which are indicated by markers in the form of blue balloons; these contain a reference name (name of the municipality and index of the locality) to provide a spatial reference of where the forest fire has occurred previously. Figure 5b shows the route calculated sequentially, while Figure 5c shows the route calculated with ACO.



(a) Map with aggregate coordinates; (b) Sequentially calculated route; (c) Route calculated by ACO.

Figure 5. Areas where forest fires have occurred, municipality of *Amecameca*.

Based on the experimental results thus obtained, it is possible to verify that the ACO offers a viable solution for reducing route travel distances, estimating similar values in the minimization of distances to those cited in the works of Zhou *et al.* (2019) and Wu *et al.* (2020). Compared to works involving drones flying in forested areas like those of Sungheetha and Sharma (2020) and Li *et al.* (2022) —based on UAV devices with cameras or IoT devices deployed on an area of land, but without applying an analysis of the routes in order to reduce the travel distance—, it has the advantage of allowing, through the use of previous fire records, to generate routes to carry out the process of preventing and detecting forest fires, as well as to optimize the energy expenditure in the route of the UAV units.

During the development of the experimental scenarios A and B, no excessive consumption of computational resources such as RAM memory and CPU time was observed; however, the existence an internet connection error was apparent when calculating the distance of the routes to cover all the municipalities, which proved insufficient, as well as when using the data from the selected library, in this case, GeoPy. Therefore, it was necessary to carry out the evaluation by groups of 10 in 10 municipalities in order to avoid this particular result. The operational characteristics of the software allow it to process more data inputs than those used in the experimental phase to obtain data from all the municipalities in the country, as well as to provide real-time solutions, considering that the routes can remain in force for up to 5 years, as long as there are no drastic changes in the areas analyzed, due to changes in the composition or in the precipitation cycle and weather conditions.

Conclusions

Computational evolutionary algorithms, such as ant colony-based genetic algorithms, provide solutions to optimization problems, specifically for the generation of routes that can be traversed in the shortest possible distance by unmanned aerial vehicles. During the experiments, it was observed that despite the large number of points that have been extracted in different municipalities, the tendency was always oriented towards a reduction with respect to the sequential route initially proposed, obtaining in the best case a 93 % reduction of the initial distance, which indicates that, in regions where a large number of fires are detected in a seemingly random fashion, the gain in route planning is highly significant, with a mean of 54 % of all the municipalities analyzed, as well as when the points are distant (more than 10 kilometers).

While it is true that in Mexico there are groups for the prevention and control of forest fires, resources such as staff and time available are limited. Therefore, implementing UAV systems with route generation through ACO for the prevention and detection of fires at strategic points will allow the development of this type of activity in an efficient and effective way in coordination with human personnel. Since the calculation of routes involves a high degree of automation, the amount of data entered can be greater than hundreds of geographic locations, making it highly flexible to contemplate the entry of new locations, which can be implemented in real time to obtain new routes according to the needs that arise in specific contexts.

Acknowledgments

The authors are grateful to the Council for Science and Technology of the State of Mexico (*Consejo Mexiquense de Ciencia y Tecnología*, Comecyt) for the support granted for this project.

Conflict of interest

The authors declare that they have no conflict of interest.

Contributions by author

Héctor Caballero Hernández: conception of the idea, design and implementation of the ACO algorithm and drafting of the manuscript; Vianney Muñoz Jiménez: writing of the Introduction and Methodology sections: Marco A. Ramos Corchado: experimental design, writing of the Results and Conclusions sections. All the authors reviewed the manuscript.

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