Development of search strategy for single / multiagent UAVs in cooperative environment for Search and Rescue (S&R) / Area Surveillance

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A thesis submitted in partial fulfillment of the requirements for the degree of

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Thesis Supervisor

Dr. Muhammad Jawad Khan

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The following research effort, named "*Development of search strategy for single / multiagent UAVs in cooperative environment for Search and Rescue (S&R) / Area Surveillance*," is my original work, which I certify. The work has not been submitted to another institution for evaluation. All other sources of information have been appropriately recognized and cited for the content that has been utilized.

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I am grateful to my mother for always supporting and praying for me throughout my life. My mother has always inspired me by setting a good example of hard work, honesty, devotion and commitment in all aspects of her life.

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Dedicated to my teachers, parents and family

Abstract

The first decade of the current millennium witnessed limited use of Unmanned Aerial Vehicles (UAVs) technology mostly by the defense organizations. Rising accessibility of UAV technology to civilian especially commercial sectors; mostly, dangerous and high-paid jobs are being rapidly replaced by the UAVs. Off late, UAVs technology has outperformed human operators in search & rescue, fire protection and area surveillance due to technological advancement in the field of micro-electromechanical systems, collision-avoidance algorithms, precision and accuracies in sensor technologies. Many different sorts of SAR missions are dependent on the environment, the survivor's location (land or sea), and search techniques.

In this thesis, different search strategies (Expanding-Square Exploration, Creeping-Line Exploration, Parallel-Track Exploration etc.) expounded by “International Aeronautical and Maritime Search and Rescue (IAMSAR) Manual” have been explored. I have proposed a hybrid solution based on Ant Colony Optimization (ACO) Algorithm for single / multi agents UAV system for SAR missions in a cooperative environment. The suggested Algorithm allows UAVs to examine the disaster region, gather data about the probable survivors, and transmit their positions to the ground station.

Keywords: *Unmanned Aerial Vehicles, Search & Rescue, Area Surveillance, Ant Colony Optimization, International Aeronautical and Maritime Search and Rescue Manual*

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List of Acronyms

Ant Colony Optimization	: ACO
Aera of Interest	: AoI
Proportional Integral Derivative	: PID
Graphic User Interface	: GUI
Unmanned Aerial Vehicle	: UAV
Search and Rescue	: SAR
International Aeronautical and Maritime Search and Rescue	: IAMSAR
United Arab Emirates	: UAE
Nuclear, Biological, Chemical	: NBC
Dynamic Exploration Planner	: DEP
Probabilistic Roadmap	: PRM
Euclidean Signed Distance Function	: ESDF
Probability of Detection	: POD
Command and Control	: C2
Communication, Command and Control	: C3
Commence Search Point	: CSP
High Altitude Long Endurance	: HALE
Medium Altitude Long Endurance	: MALE
Virtual Robot Experimentation Simulator Platform	: V-REP

1. Introduction

During a catastrophe; infrastructure, buildings, bridges, communication setup etc. roads may get blocked due to damage caused by the destruction. Once roads get blocked with debris, disaster region gets completely unapproachable. Therefore, immediate search and rescue of the survivors is critical as the probability of survival is reduced with passing time. With advancement in drone technology, search operations under these crisis conditions can now be made precise. The utility of a robot in crisis management is very significant. A machine with artificial intelligence, especially drones, can be used for taking ariel images of the area; these can also be used for dropping aid supplies in the affected area; some of these may be used to spray the fumigation (anti COVID-19 sprays) over markets etc. The possibilities of using intelligent drones for crisis pre-emption and crisis management are endless. This technology can also be used in agriculture (Klauser, 2021) where large fields can be scanned for timely identification of crop diseases or routine pesticides spraying.

1.1 Problem Statement

During first decade of the current millennium there was limited utilization of Unmanned Aerial Vehicles (UAVs) technology mostly by the defense organizations. Rising accessibility of UAV technology to commercial sectors; generally, dangerous and high-paid jobs are being rapidly replaced by the UAVs. Off late, UAVs technology has outperformed human operators in Search & Rescue (SAR), surveillance and fire protection operations due to technological advancement in the field of micro-electromechanical systems, collision-avoidance algorithms, precision and accuracies in sensor technologies.

Many types of SAR missions depend on environment, location of the survivor (land / sea) and search strategies. In this thesis, different search strategies (Creeping Line Search, Parallel Track

Search and Expanding Square Search etc.) provided by “International Aeronautical and Maritime Search and Rescue (IAMSAR) Manual” (Organization, 2016) have been analyzed. I have proposed hybrid solution by using Ant Colony Optimization (Dorigo, 2006) for multi agents UAV system in cooperative environment. The proposed strategy would enable UAVs to examine the desired area in order to gather evidence about the possible survivors and send back their locations to Base Station.

1.2 Objective

Objectives of the thesis include:-

- Surveillance of preselected Areas of Interest (AoI) by the UAVs
- Deciding optimal search pattern / path for the UAVs in accordance with the environment to properly scan AoIs
- To find optimal trajectories to reach scanned locations from an initial position
- Implementation of motion limitations (e.g., physical obstacles, and non-fly zones, etc.) on employed UAVs

1.3 Areas of Application

Drones are employed in a variety of situations related to public safety. During COVID-19 outbreak, the use of drones for public safety has increased. Authorities employed drones to monitor cities to enforce lockdown and social isolation when humanity was on the verge of an universal shutdown. Drones were deployed to sterilize marketplaces against the COVID-19 virus in the United Arab Emirates (UAE). Ariel drones are being used for mainly three sectors; military, commercial/industrial/public sector and for the household use (Sim, 2016).

1.3.1 Military use

Drone technologies can be extensively used by armed forces or civil institutions of a country for safeguarding its territorial boundaries as well enhancing the operational capacity of many civil institutions. If military use of the drones is analyzed, it becomes clear that in army these can be used for carrying out various operations e.g., surveillance, misleading missiles by sending false signals, Nuclear, Biological, Chemical (NBC) emissions monitoring, destructions of land-mines, jamming of radars, assessing damage to the airfield etc.

1.3.2 Civil use

Many civilian institutions deploy ariel drones for effective service delivery. These are being used both in industries and commercial sectors for reducing costs and enhancing precise, effective and timely services. The details are tabulated below:-

Industrial	Parcel Delivery Drones, Gaming & Sports Drone, Drones for Agriculture, Drone for use at Ranches, etc.
Household	Smart Home Drones
Local Authorities	Drone use for information gathering/ Ariel Surveys
Coastguards	SAR Operations

(Table 1: UAVs Usage)

1.4 Thesis Overview

The thesis has been divided into 6 Sections. Section 1 contains the introduction and the preliminaries. Section 2 briefly explains the previous work done by several researchers and comprises all the study of different theories for this proposed work. Section 3 contains the complete methodology and Implementation including software environment utilized for the thesis. Section

4 includes the complete results acquired after implementing the Ant Colony Optimization Algorithm with several configurations. Section 5 consists of discussion of the complete work and also concludes the entire work. Section 6 describes all the possible future work which can be held in this domain.

2. Related Work

2.1 Previous Work

Several research works have been done for collision free, optimal path planning, in complex 3-D spaces, for the UAVs. However, its specific application for SAR & surveillance missions in the presence of complex obstacle is required. Some of the examples are given below:-

In 2021, Zeefan Zu (Xu, 2021) proposed dynamic exploration planner concept for exploring unfamiliar environments using incremental selection and Probabilistic Roadmap. Nodes are progressively created and dispersed equally throughout the unknown region in this sampling technique. Paths are designed based on Euclidean Distance to save exploration time and ensure safety.

In 2019 (Zhang, 2019) Chao Zang presented idea of path planning using a self-heuristic ant-based approach for UAV in a complicated three-dimensional space with several U-shaped obstructions. The findings demonstrate that diverse ant search techniques can successfully minimize the standoff situation.

(Tolstaya, 2020) investigates the operator for a cluster of four duplicate UAVs employing proportional integral derivative (PID) command as the input signal and probabilistic scaled regulation as the transfer function. It is shown that by adjusting several other characteristics in the proportional scaled system, which utilizes four controller variables sources, the functionality of surveillance drones (UAVs) may be rapidly changed during validation process. In comparison, individual node keeps its own spectrum of traveled abroad, and coordinated data is not disseminated for the advantage of the cluster overall.

Assuming three aircraft fly in group spontaneously, the scientists (Mo, 2019) recommend using a Control strategy for the input signal and an enhanced dynamic behavior reversal regulation for the outside loop, although both are complicated phenomena. Given the volatility associated with the system's response time performance and error estimations, the system's flexibility and the top–down/bottom–up impact of kinetics on the system have received little attention.

However according (Giordano, 2011), combined PD control and multi-agent-based consensual control are utilized to synchronize drifting in longitudinal and transverse directions using three drones.

The possibility of using a Type 2 technology in the model development process is being investigated. (Giordano, 2011) details the results of tests on the flight test of a rotor equipped with a PD configuration.

A commander uav with four supporter UAVs is also used to show swarm phenomena via the usage of a synchronized flight path between the two. (Moon, 2013) investigates a decentralized Model Predictive Control (MPC) method for governing equation of three drones.

(Loayza, 2017) present each uav exchanges data with its surroundings and is triggered by environmental events. explores a fuzzy logic approach for specific tasks and supervision of any swarm operation representing UAVs in a pervasive system using models. The investigators evaluate the numbers of colliding occurrences and timeframes for centralized and decentralized methods. I can replicate the suggested model using the Unity3D environment, and the basic control paradigm is dependent on finite state machines.

As per (Hua, 2017), the SMC and integrated SMC are also discussed in completeness for unstructured second-order distributed databases with undefined dynamic interactions. On the other side, the method is not adaptable as the population of drones grows.

Three drones performing in a centralized environment and employing SMC for the inner feedback controller and LQR for the outside controlled system are examined in (Gheorghiţă, 2015), (Bandyopadhyay, 2015), and (Tsykunov, 2018) to ascertain their functionality. As per the suggested technology's results do not demonstrate a high efficiency, and the observability matrix for straight oscillations of the maintain connections in does not include the full row score, suggesting that the observations are inconclusive. Due to a research problem, the provided mathematical model is not feasible for creating control algorithm of x and y by using suggested method.

2.2 Search Patterns

Different visual search strategies given in IAMSAR manual (Organization, 2016) are utilized for this thesis

2.2.1 Patterns for searching

The most basic method for searching an area is to use look-outs who follow conventional patterns. The following are some of the advantages of this technique:

- A consistent, structured search pattern guarantees that the entire given region is uniformly covered.
- When compared to random, disorganized searching, regular patterns boost the probability of detection (POD), especially when search conditions are not perfect.
- It's easier to communicate precise patterns when they're standard.
- They make coordinated multi-facility searches easier to coordinate and safer to carry out.

2.2.2 Sector shape exploration

Once the exact location of the search item is well-known, and the search area is limited; they are the most effective. A crew member witnessing another crew member fall from a ship or a reported distress from an aircraft that offers a fairly precise location are two examples. They are looking for a datum point in a circular area. They're simple to use and cover a large region towards the center, where the search object is most likely to be discovered. This procedure cannot be employed by numerous airplanes at the same heights or by many vessels at the same time because of the tiny region involved. Instead, an airplane and a vessel could work together to undertake independent sector search and rescue operations.

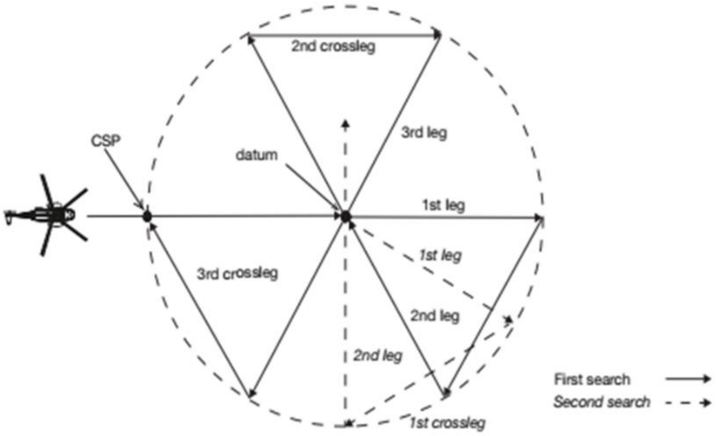


Figure 1: Sector pattern search

2.2.3 Increasing squares exploration

Once the position of the aim of the quest is well-known with reasonable accuracy, this pattern works best. The datum position is always the Commence Search Point (CSP) for this pattern. The pattern then extends outward in concentric squares, covering the space around the datum in a roughly uniform manner. The pattern can be altered to an expanding rectangle if the datum is a short line rather than a point. Due to the small area involved, risks about the use of multiple search facilities are also applicable to expanding square pattern.

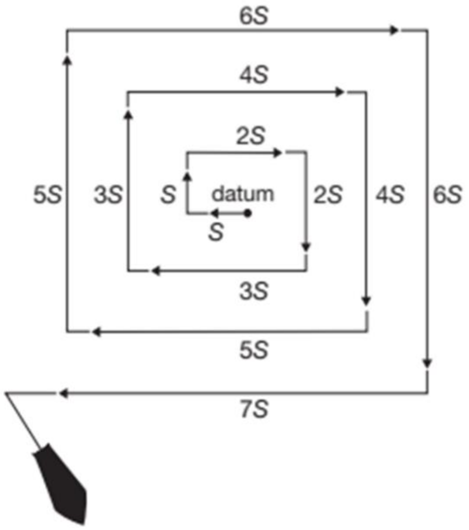


Figure 2: Expanding square exploration

2.2.4. Track line exploration pattern

It's usually used when a plane or ship has vanished without a trace while en way from one location to another. It is presumptively based on the fact that the stranded aircraft has crashed and made an emergency landing near the intended path. The survivors are normally considered to be capable of attracting attention from a long distance using a signaling mirror, colored smoke (daylight), flares, flashing light, or signal fire. It entails a quick search of the stricken aircraft's projected itinerary. Aircraft are regularly used for track line searches due to their great speed, usually at a height of 1,000 ft to 2,000 ft over the surface during daylight or 2,000 ft to 3,000 ft at night. Because it involves less planning and can be performed fast, this pattern is employed as an initial search effort. If the track line search fails to find the survivors, a more thorough search over a larger region should be conducted.

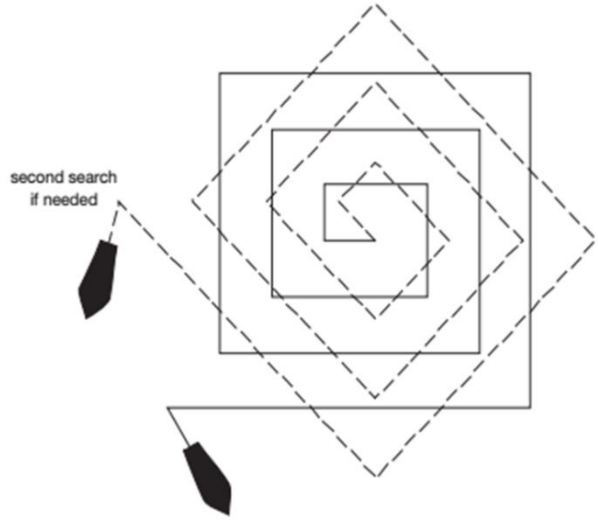


Figure 3: Track line search

2.2.5 Parallel sweep exploration

This search pattern is typically utilized when there is a lot of doubt about the survivor's whereabouts and a vast region needs to be searched uniformly. When utilized over water or flat ground, it is most effective. A rectangular area is covered by a parallel sweep search pattern. It is used to sweep a vast search area that can be subdivided into smaller sections so that many searches can be conducted at the same time. Except that the exploration legs are corresponding to the shorter axes in the creeping line exploration design. It normally takes more rounds to traverse the same area, thus it is inefficient.

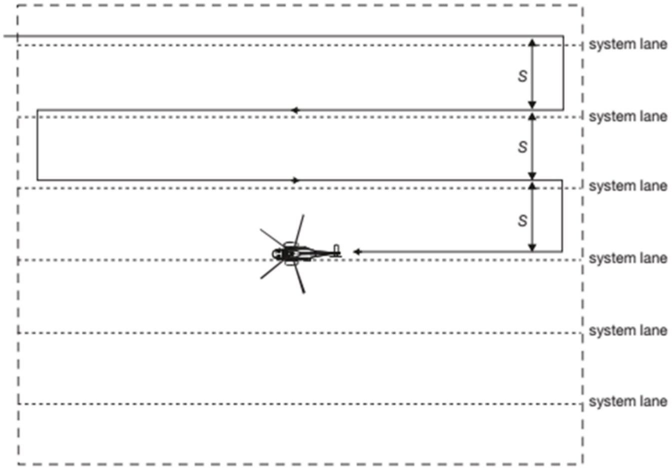


Figure 4: Parallel sweep exploration

2.2.6 Contour exploration

It's employed in and around mountains and valleys when dramatic elevation changes make other patterns impossible. From top to bottom, the mountain is searched. The search begins above the highest peak, with search aircraft circling the mountain altogether. A contour search could be quite hazardous. When searching for mountains and valleys, exercise extreme caution. Multi-engine aircraft with a tiny turning radius and a high rate of climb are required, as well as an experienced crew, suitable weather, and an accurate chart.

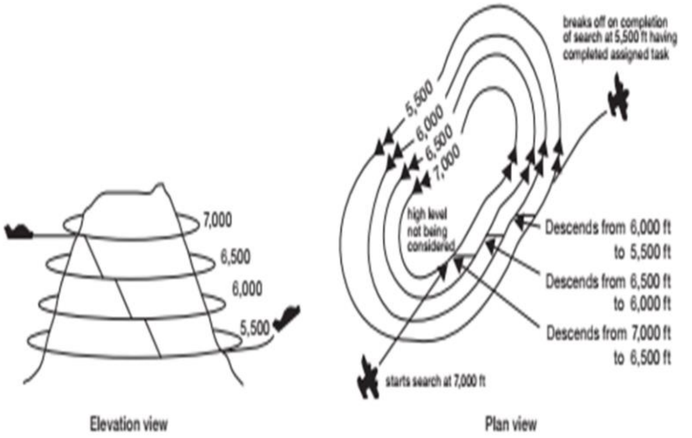


Figure 5: Contour search

2.3 Ant Colony Optimization Algorithm

It's a problem-solving algorithm based on how ants transmit directions to one another in an indirect manner. ACO is inherently applicable to any sequencing problem, such as scheduling, vehicle routing, assignment, and travelling salesman, among others.

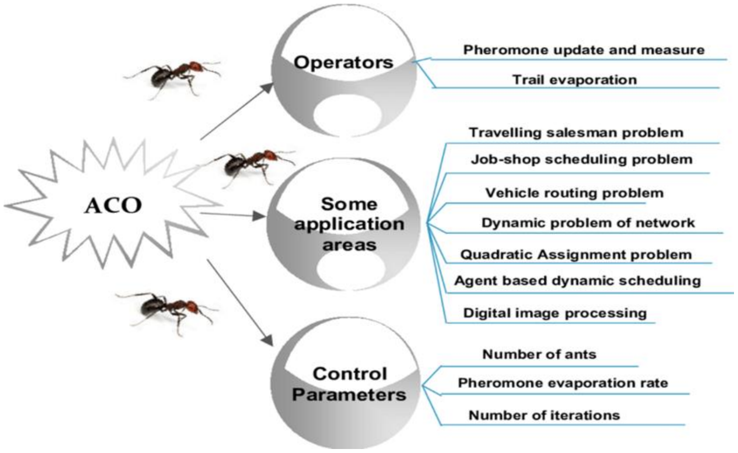


Figure 6: ACO applications

2.3.1 Pheromone Trail

Ants have simple behaviors, but they can work together to complete complicated tasks (Dorigo, 2006). Ants have a highly developed stigmergy system based on signs (indirect communication via interaction with the environment). Pheromones are used to communicate between them. They leave pheromone trail that other ants can follow.

2.3.2 Basic idea of ACO

Ants are a type of agent that:

- They move between nodes in a graph, deciding where to go based on the strength of pheromones and heuristic value.
- The journey of an ant represents a particular solution.
- When an ant finishes a solution, it updates a pheromone trail, which affects the behavior of other ants via stigmergy, depending on the quality of the solution.

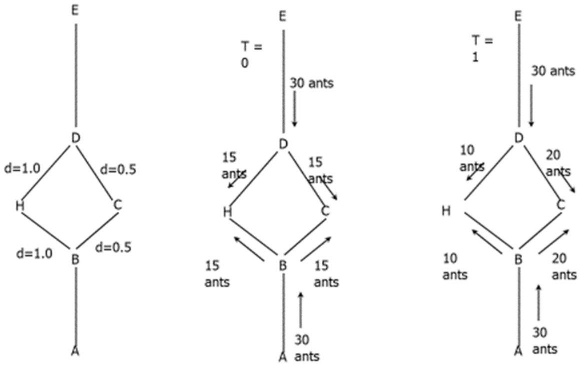


Figure 7: Pheromone Trails

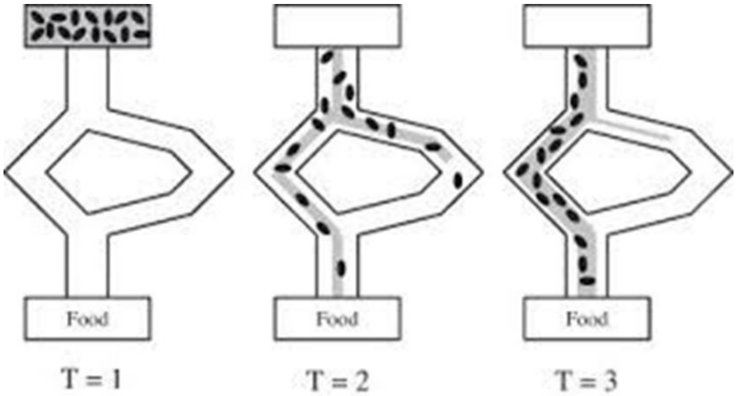


Figure 8: Basic ideas of ACO

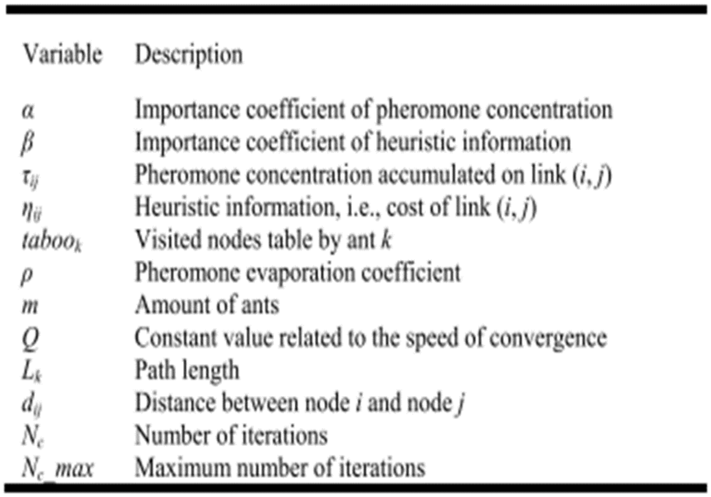
2.3.2 Probability selection formula to select next node

Equation 1 is utilized to compute the state-transition possibility of “j” as the succeeding node from “i” (the formula for selecting options employed by any ant “k” to select the next node). The behavior of ants is greatly influenced by Equation 1. If “α” is greater than “β”, ants are more inclined to explore along trails marked by pheromones (left behind by preceding ants). Aside from that, ants prefer to choose paths based on heuristic-information, which is similar to the “greedy-exploration” method.

$$P_{ij}^{k}(t) = \begin{cases} \dfrac{\tau_{ij}^{\partial}\eta_{ij}^{\beta}}{\sum\limits_{s\notin \mathrm{taboo}_k} \tau_{is}^{\partial}\eta_{is}^{\beta}} & \mathrm{i,s,j} \notin \mathrm{taboo}_k \\ 0 & \text{otherwise} \end{cases}$$

Equation 1: Probability Selection formula to select succeeding node

All relevant variables are stated in Table 2, appended below:-



Variable	Description
α	Importance coefficient of pheromone concentration
β	Importance coefficient of heuristic information
τ_{ij}	Pheromone concentration accumulated on link (i, j)
η_{ij}	Heuristic information, i.e., cost of link (i, j)
$taboo_k$	Visited nodes table by ant k
ρ	Pheromone evaporation coefficient
m	Amount of ants
Q	Constant value related to the speed of convergence
L_k	Path length
d_{ij}	Distance between node i and node j
N_c	Number of iterations
N_c_max	Maximum number of iterations

Table 2: Variable of Ant-based algorithm

2.3.3 Updating Pheromone

Pheromone reinforcement and evaporation are both part of this process. Equation 2 depicts the updating process whereas all relevant variables are stated in Table 2, above.

$$\tau_{ij}^{\mathrm{now}} = (1-\rho)\tau_{ij}^{\mathrm{past}} + \rho \sum_{k=1}^{m} \Delta\tau_{ij}^{k}$$

Equation 2 Pheromone Update

The quantity of pheromone dropped by any ant “k” on a link between “i” and “j” nodes is calculated using Equation 3 based on the Ant-Cycle algorithm. All variables specified are available in Table 2.

$$\Delta\tau_{ij}^{k} = \begin{cases} \frac{Q}{L_k} & \text{if the } k^{th} \text{ ant walks along link}(i, j) \\ 0 & \text{otherwise} \end{cases}$$

Equation 3: Pheromone update on link

The pheromones are updated in such a way that shorter path gets more pheromone than longer path.

2.4 Definition and Categories of UAVs

2.4.1 Definition of Unmanned Air Vehicle (UAV)

UAVs are commonly called drones. Drones are aircrafts without any human pilots or passengers etc. They are part of an Unmanned Air-vehicle Systems (UAS), which consists of UAV and ground-based remote controller (Doherty, 2007).

2.4.2 Categories of Unmanned Air Vehicle (UAV)

UAVs are classed based on the capabilities and size required to complete the mission (Berger, 2015). Nonetheless, it’s possible that a single system will use several UAVs to accomplish different missions. The definitions (given below) are constantly changing as advancement in technology allows a smaller system to replace the older system. Therefore, the boundaries are quite blurred and following definitions are evolving with advancement in technology. The present terminology includes a wide variety of systems, beginning with an airplane with a wing span of 35 meters or more (HALE), to a UAV with just 40 mm wing span (NAV)

2.4.3 High Altitude Long Endurance

These can be operated above an altitude of 15000 and for 24+hours. They conduct long range missions and would be weaponized shortly. Air Force bases are often in charge of them.

2.4.4 Medium Altitude Long Endurance

They can operate at altitudes of 5000–15000 meters and have a 24-hour endurance. Their missions are similar to the HALE system, nevertheless they typically work over shorter distances (in excess of 500 kilometers) and from fixed bases.

2.4.5 Tactical UAV

Their range is amid 100 to 300 kilometers. They are comparatively smaller and are operated from land / naval bases using simpler equipment.

2.4.6 UAVs with a close range

They are often deployed by mobile army units; these may be used to perform various civilian tasks. Operating at ranges of around 100 meters, they are conducive for surveillance, powerlines' inspection, traffic management and for pesticide spray on crops.

2.4.7 Mini UAV

These UAVs have a weight of around 20 kgs, but these are bigger than the MAVs mentioned next. These can be launched from hand and can cover a range of about 30 kilometers.

2.4.8 Micro UAV

These small unmanned aerial vehicles (UAVs) (wing span: 150 mm) are used for urban activities, such as within buildings. Less conventional UAV (flapping wing aircraft) configurations are being investigated in order to make it fly slowly, hover, or stop/sit on a wall/post. MAVs are typically expected to be launched, which necessitates extremely low wing loadings, making these UAVs vulnerable to turbulence in the atmosphere. In the rain, all sorts of UAVs have issues..

2.4.9 Nano Air Vehicles

Of the size of sycamore seeds (9mm-2mm) (Narayanan, 2012), NAVs are used in swarms. They are used for radar confusion and ultra-short-range surveillance.

2.4.10 Remotely Piloted Helicopter / Vertical Takeoff and Landing UAV

These UAVs have the ability to take off and land vertically. During a mission, these are also capable of hovering. Air turbulence is less of an issue for rotary-wing aircraft than it is for fixed-wing aircraft.

2.4.11 Unmanned Combat Rotorcraft

A specialized armed fixed-wing UAV is being developed to utilize weapons from the ground or participate in air-to-air combat. Unmanned Combat Air Vehicle (UCAV) is an acronym for unmanned combat air vehicle. Helicopters with weapons (under development).

2.5 Tello Quadrotor

Figure 9(a): Tello quadrotor

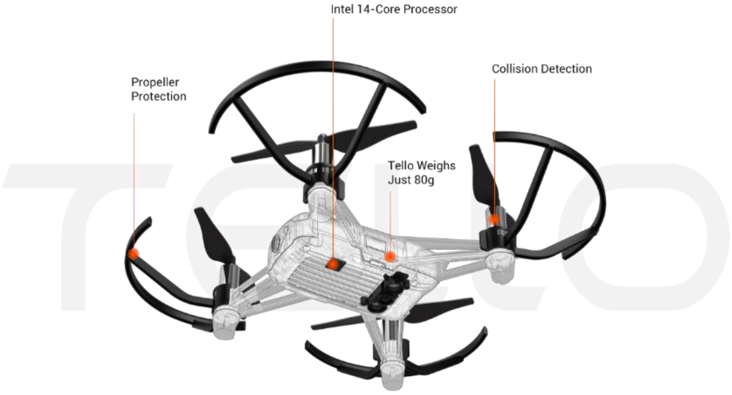


Figure 9(b): Tello quadrotor

2.5.1 Sizes

- **Mass**: Approx. 80 grams (Included Battery & Propellers)
- **Size**: 99×91.5×40.5 mm
- **Propeller**: 3”
- **Built-in Functions**: Barometer, LED, Range Finder, Vision System, 2.4 GHz 802.11n Wi-Fi, 720p live-view
- **Charging Ports**: Micro USB

2.5.2 Flight Performance

- **Maximum Distance:** 100 meters
- **Maximum Speed:** 8 m/s
- **Maximum Flying Time:** 13 minutes
- **Maximum Flying Height:** 30 meters

2.5.3 Battery

- **Type:** Detachable
- **Power:** 1.1Ah/3.8V

2.5.4 Camera

- **Photo:** 5 Mega Pixels (2592x1936)

- **Field of View (FoV):** 82.6°
- **Video:** High Definition 720P30
- **Format**: Joint Photographic Experts Group (Photo); MPEG-4 (Video)
- **Electronic Image Stabilization** : Yes

2.6 Dynamic model

Dynamic Model is given below in figure 9.

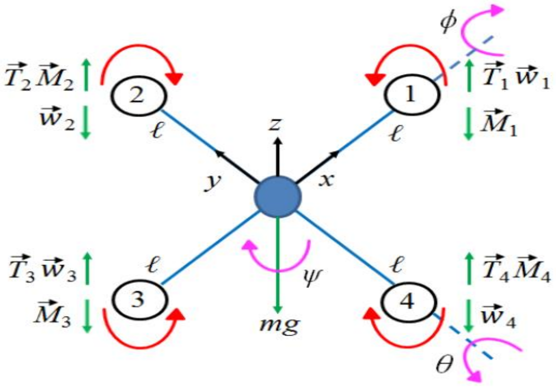


Figure 10: Tello dynamic model

Each rotor in the quadcopter produces thrust and torque and drag forces. To achieve a stable flight, usually two motors of quadcopter spin clockwise while other two spin anti-clockwise. The torque generated by opposite sipping motors cancels each other thus producing zero net torque. The flight control varies each motor’s speed to control the overall movement of the quadcopter. For example, to gain the altitude flight controller will increases all motor’s torque and to lose the altitude it will reduce the speed of all motors and quadcopter will move down due to gravity. Similarly, yaw is achieved by differential torque while pitch and roll are achieved by increasing speed of motors of one and decreasing others. The quadcopters are fixed pitch propeller vehicles. That is why we have to achieve roll and pitch in above-described manner. The roll and pitch cause lateral movement of vehicle.

The main forces interacting with the quadcopter are thrust T and gravity g while T is equivalent thrust of all rotors. In the figure 1, the inertial frame of reference is the center of the vehicle. It is supposed that quadcopter is a rigid body and mass is evenly distributed. The orientation of quadcopter can be expressed as in (Frazzoli, 2000). While translational and angular accelerations can be determined as follow.

$$\begin{aligned}
\dot{v}_x &= -v_z w_y + v_y w_z - g\sin\theta \\
\dot{v}_y &= -v_x w_z + v_z w_x + g\cos\theta\sin\phi \\
\dot{v}_z &= -v_y w_x + v_x w_y + g\cos\theta\cos\phi - \frac{T}{m}
\end{aligned}$$

Equation 4: Translational Accelerations

$$\begin{aligned}
\dot{w}_x &= \frac{1}{J_x}\left(-w_y w_z (J_z - J_y) + M_x - \frac{k_{wT}}{k_{MT}} J_{mp} M_z w_y\right) \\
\dot{w}_y &= \frac{1}{J_y}\left(-w_x w_z (J_x - J_z) + M_y - \frac{k_{wT}}{k_{MT}} J_{mp} M_z w_x\right) \\
\dot{w}_z &= \frac{M_z}{J_z}
\end{aligned}$$

Equation 5: Angular Accelerations

While J_x, J_y and J_z are inertial moments along x, y & z axes and M_x, M_y and M_z are reactive motor torques along Cartesian (x, y & z) axes. Also, J_{mp} is moment of inertia of motor. The angular velocities of rotors are directly proportional to thrust produced.

$W_j = k_{wt}T$ and $M_i = k_{mt}T$. Based on configuration, different thrust of propellers will add up to total thrust. As we are using X configuration, so its relation is as follow.

$$\begin{bmatrix} T \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ \frac{\sqrt{2}}{2}\ell & -\frac{\sqrt{2}}{2}\ell & -\frac{\sqrt{2}}{2}\ell & \frac{\sqrt{2}}{2}\ell \\ \frac{\sqrt{2}}{2}\ell & \frac{\sqrt{2}}{2}\ell & -\frac{\sqrt{2}}{2}\ell & -\frac{\sqrt{2}}{2}\ell \\ k_{MT} & -k_{MT} & k_{MT} & -k_{MT} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}$$

Equation 6: Reactive Motor Torques

Where l is pitch of rotor. The velocities can also be expressed as follow.

$$\dot{x} = v_x cos\psi cos\theta + v_y(-sin\psi cos\emptyset + cos\psi sin\theta sin\emptyset) + v_z(sin\psi sin\emptyset + cos\psi sin\theta cos\emptyset)$$

$$\dot{y} = v_x sin\psi cos\theta + v_y(cos\psi cos\emptyset + sin\psi sin\theta sin\emptyset) + v_z(-cos\psi cos\emptyset + sin\psi sin\theta cos\emptyset)$$

$$\dot{z} = v_x sin\theta - v_y cos\theta sin\emptyset - v_z cos\theta cos\emptyset$$

$$\dot{\theta} = \omega_y cos\emptyset - \omega_z sin\emptyset$$

$$\dot{\emptyset} = \omega_x + \omega_y sin\emptyset tan\theta + \omega_z cos\emptyset tan\theta$$

$$\dot{\psi} = \omega_y \frac{sin\emptyset}{cos\theta} + \omega_z \frac{cos\emptyset}{cos\theta}$$

Equation 7: Translational and Angular Velocities

These equations correspond to a complete nonlinear model of a quadcopter. It has twelve states and for inputs T, Mx, My and Mz which are given below:

$$\mathbf{x} = \begin{bmatrix} v_x & v_y & v_z & w_x & w_y & w_z & \theta & \phi & \psi & x & y & z \end{bmatrix}^{\mathrm{T}}$$

$$\mathbf{u} = \begin{bmatrix} T & M_x & M_y & M_z \end{bmatrix}^{\mathrm{T}}$$

Equation 8: Nonlinear model of quadcopter

Assuming the system is fully observable the state vector can be expressed as stated below:

$$\mathbf{x_s} = \begin{bmatrix} v_x & v_y & v_z & w_x & w_y & w_z \end{bmatrix}^{\mathrm{T}}$$

Equation 9: State Vectors of quadcopter

This nonlinear model can be linearized using linearization principle and finally we can get the linear model of quadcopter as follow. This linear model will again be used to carry out the further analysis.

$$\dot{\mathbf{x}} = \begin{bmatrix} -g\theta \; g\phi \; -\frac{T}{m} \; \frac{M_x}{J_x} \; \frac{M_y}{J_y} \; \frac{M_z}{J_z} \; w_y \; w_x \; w_z \; v_x \; v_y \; -v_z \end{bmatrix}^{\mathrm{T}}$$
$$\mathbf{y} = \mathbf{x}$$

Equation 10: Nonlinear model of quadcopter

3. Methodology and Implementation

3.1 Proposed Scheme

In the proposed scheme I started with the simulation of different search strategies (Expanding-Square Exploration, Creeping-Line Exploration, Parallel-Track Exploration etc.) explained by “IAMSAR” Manual. Then, I implemented ACO algorithm on the search strategy in order to scan the complete disaster region. Subsequently, results were compared with the existing strategies. The ACO based search strategy has been tested on the Tello quadcopter (courtesy to CASE aeromodelling lab) to verify the model parameters.

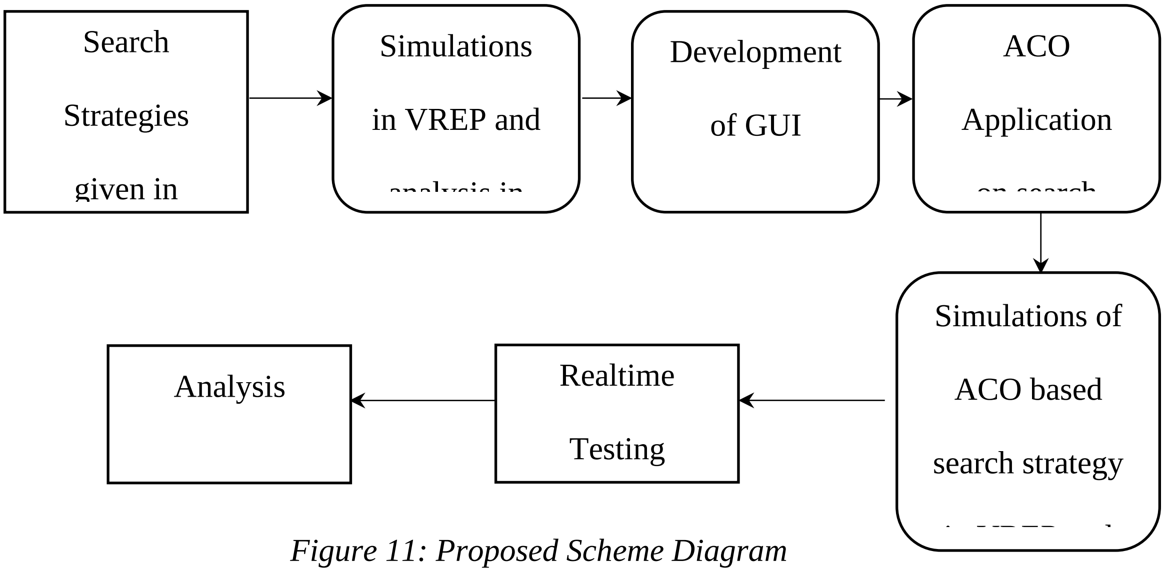


Figure 11: Proposed Scheme Diagram

3.2 Virtual Robot Experimentation Simulator Platform (V-REP) and Matlab Interfacing

I used the Coppeliasim simulator, formally known as the Virtual Robot Experimentation Simulator Platform (VREP)for my experiments. It simulates any robot by combining the capabilities of a physics engine with the API of recent popular programming languages. It has a modular framework and APIs, allowing it to expand its capabilities. While the data analysis was running in MATLAB, I used the MATLAB API to interact with the simulator. Coppelia Robotics created coppeliasim with the goal of general-purpose robot simulation. The simulator's main features include a user interface that can be customized and an integrated development environment with a modular architecture. Both the simulation objects and the control mechanisms have a large amount of modularity. The simulator's basic programming environment, which is available from any computer, may be used to create robots and simulation scenarios. Because of this capabilities, quick prototyping, algorithm design, and implementation are possible. This location can be used as a realistic 3D environment with active simulation, which provides real-time feedback based on model behaviors during the simulation. The coppeliasim is made up of three key components: the scene object, the control mechanism, and the computation modules. The scene in coppeliasim is usually consists of following components:

3.2.1 Shape

They are mesh objects that are used to construct forms, detect collisions with other obstacles, and measure distances between objects, among other things. Different sensors, such as cameras and proximity sensors, can be used to detect them.

3.2.2 Joints

Joints are the building blocks of all moving processes and objects. Revolute, prismatic, spherical, and standard joints are the four types of joints available. They can function in a variety of modes and can be used to represent a variety of actuators. Joints may be subjected to forces and torques, which aids in the development of robot controllers.

3.2.3 Camera/vision sensor

These sensors are designed to seem like a real camera and can collect photos from within a scene. These photos can be shared and processed using an image processing library, which is available both natively in Coppeliasim and via APIs. Cameras are also employed to get a better perspective of the entire scene.

3.2.4 Force Sensors

The force and torque acting on an item are measured using force sensors. These sensors are meticulously implemented, simulating real-life sensors by allowing for overshoot.

3.2.5 Proximity Sensor

This category includes ultrasonic sensors and laser rangefinders. They calculate the distances between observable objects with precision.

3.2.5 Graphs

In both 2d and 3d, graphs are used to plot and visualize data and curves.

3.2.6 Mills

Mills can be used to represent nearly any convex cutting volume. Mills have convex cutting volumes by default.

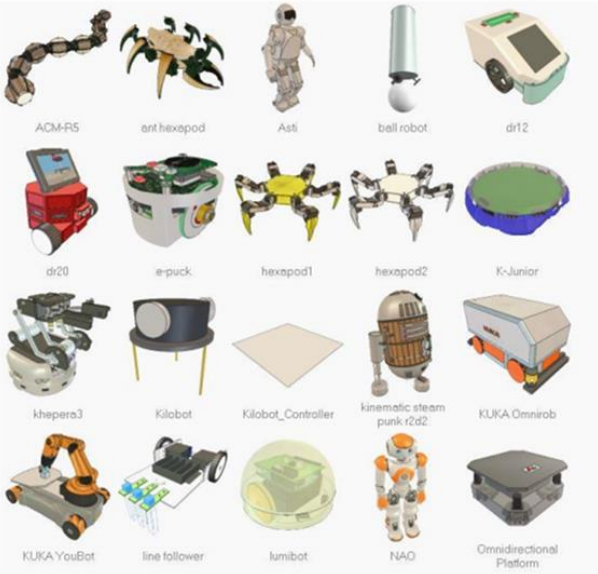


Figure 12: Built-in VREP mobile robots

Advanced sensors (accelerometer, gyroscope, GPS, Kinect, and so on) and complicated constructions (manipulators to wheeled robots) could be built by integrating scene elements. The

VREP software has a wide database of instrument and robot models that can be used in the scenario. These designs are also entirely customizable.

Several alternative search patterns can be used to control the behaviors of each simulator object. These settings are applicable both within and outside of the modelling model. The majority of interior monitoring is done through the use of child modules, which can react to any characteristic in the scenario. The child programs are an important part of the entity to which they are attached, and they are concerned with a specific aspect of the situation. They can be duplicated and serialized in conjunction with them because of this feature. As a result, they are packaged as a single file that contains both the boundary conditions and the simulation control, making them transferrable and expandable. For child scripts, there are two execution modes. Child scripts without threading take scripts that execute a task and then return to administration when required. The perforated kid scripts operate on a different thread from the main program. Interconnected child commands require far more complex coding skills than isolated child templates. Furthermore, connected child programming may consume more computational memory and storage than non-threaded child programming, and calculation instructions may be delayed. These embedded scripts may construct and manage communications networks, operate distant API data centers, start subdirectories, dismantle modules, and initiate and manage communication channels, among other things. Furthermore, V-REP has an implicit auxiliary controller approach for managing external simulations. The V-REP remote API interface control system communicates with the virtual scene via socket transmission. Remote-access API server activities and remote-access API clients make up this framework. The client side can be developed in any programming language, such as C/C++, Python, Java, MATLAB, or Urbi, and it can be integrated into any application that connects with remote control devices or actual robots. It allows for remote structure assembly as well as high-speed data transmission. Routines provide two alternative modes of operation to fit any setup: binding, which requires a response from the servers, and non-blocking, which accepts broadcasting instructions from a queue. This type of communication is diagrammatically depicted in Figure 12. The API server is built using V-REP extensions, allowing regular LUA operations to control the numerical simulation

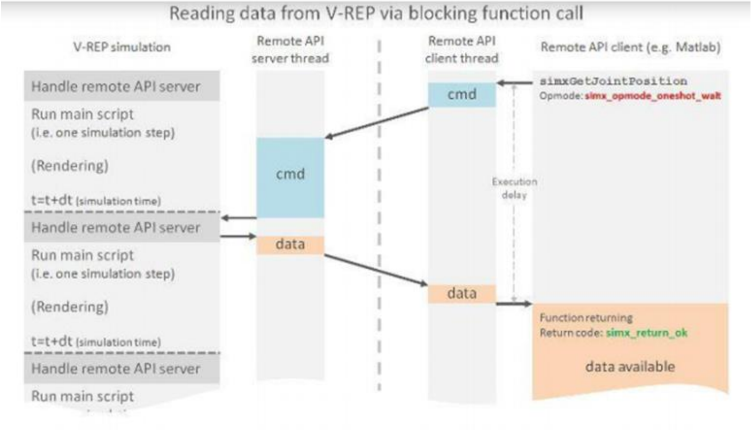


Figure 13: Asynchronous MATLAB VREP communication

The interaction between components in the simulation scenario is determined using a variety of computation modes. Bullet physics library, Open Dynamics, Vortex Dynamics, and Newton Dynamics engines are supported by V-dynamics REP's module. Depending on the simulation requirements, switching between engines is straightforward at any time. Since, physics modelling is a hard operation that necessitates varying degrees of precision, speed, and support for a variety of features, there is a wide spectrum of physics engine support.

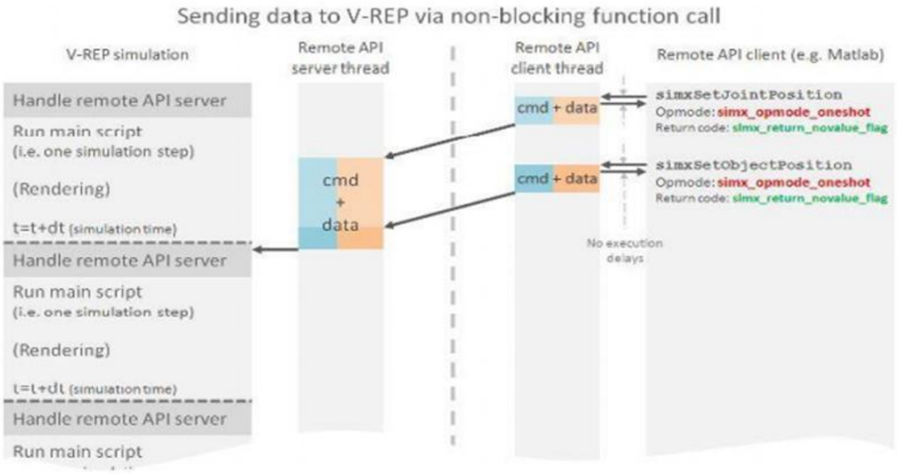


Figure 14: Synchronous MATLAB VREP Communication

3.3 Area of Interest (AoI)

Area of Interest is to be defined by the human operator. It should contain the information of all the physical obstacles and non-flying zones etc.

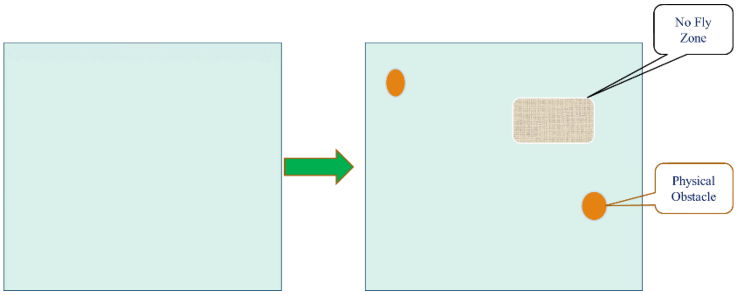


Figure 15: Defining area of interest

3.3.1 Resizing AoI

The AoI needs to be adjusted /squeezed according to the requirements in order to avoid wastage of resources. The Graphic User Interphase (GUI) has 300 preloaded shapes and its corner has be further adjusted according to actual requirements.

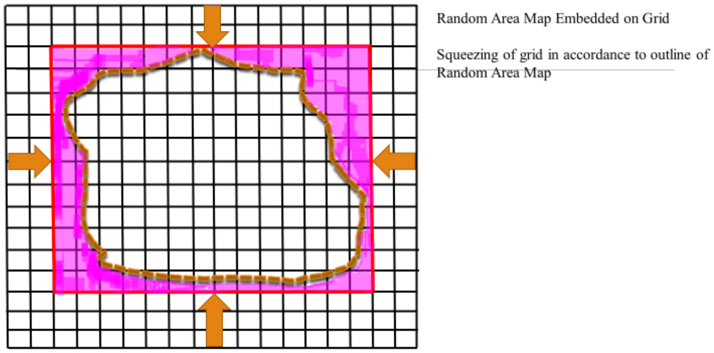


Figure 16: Adjustment of area of interest

3.3.2 Dividing AoI according to available resources

The AoI can be divided geometrically into further equal regions as per availability of resources (quadcopter, communication network, human operators etc.)

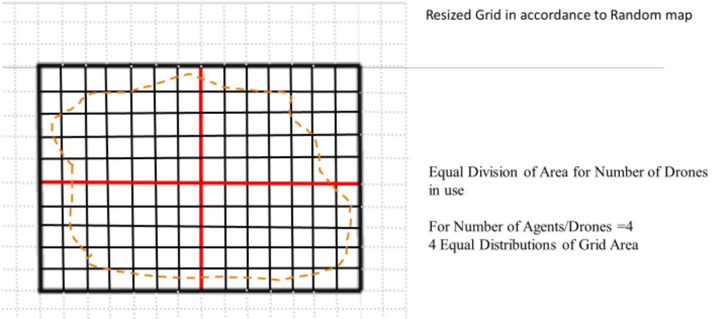


Figure 17: Dividing AoI in four equal regions

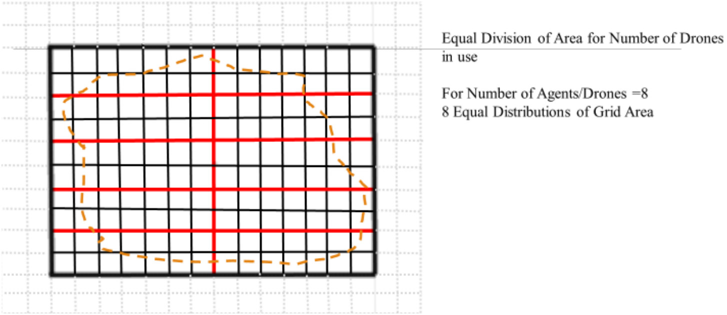


Figure 18: Dividing AoI in eight equal regions

3.3.3 Integration of obstacles in AoI

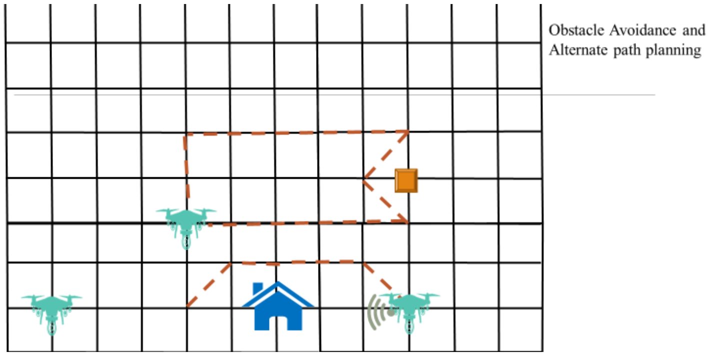


Figure 19: Integration of obstacles in AoI

3.4 Coverage by the Sensor

The greatest height at which the UAVs can operate will be determined by the sensor's ability to detect a target in the given conditions.

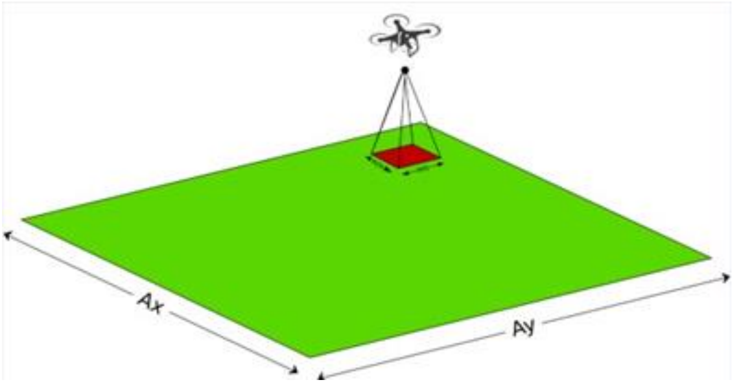
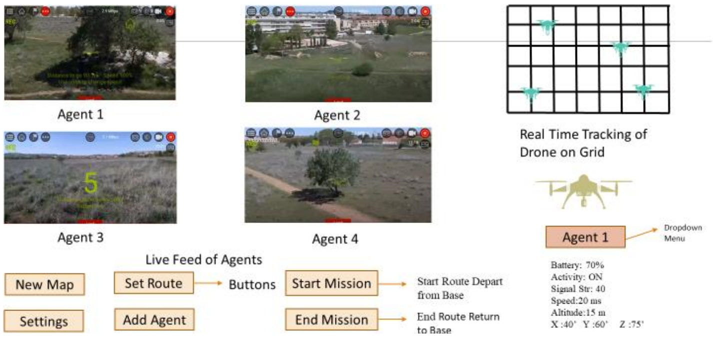


Figure 20: Coverage by the sensor

The scan region on the ground includes surface A = A_x x A_y (shaded olive in Figure 20). Total cells $A_d(h)$, with surface A_d = A_{dx} x A_{dy} each (brown area in Figure 20) is UAV’s altitude dependent. The sensing area may increase with increase in UAV’s altitude but may result in false positive and false negative detections.

3.5 Graphic User Interface (GUI)

GUI for search strategies including ACO implemented strategy was been also prepared. It resulted in better control, coordination and easy use. Human operator can directly coordinate with autonomous quadcopters.



Battery: 70%
Activity: ON
Signal Str: 40
Speed:20 ms
Altitude:15 m
X :40' Y :60' Z :75'

Figure 21: Graphic User Interface (GUI)

4 Results and Discussion

4.1 Parallel track search with two agents

In this section, results obtained from simulations in VREP and Matlab will be discussed. An Area of Interest (AoI) of 14 meter x 13 meter was initially selected without any physical or soft obstacles. The heights of UAVs were adjusted 2 meters above ground level throughout the simulation.

Figure 22: Multiagent UAVs parallel track search simulation in VREP

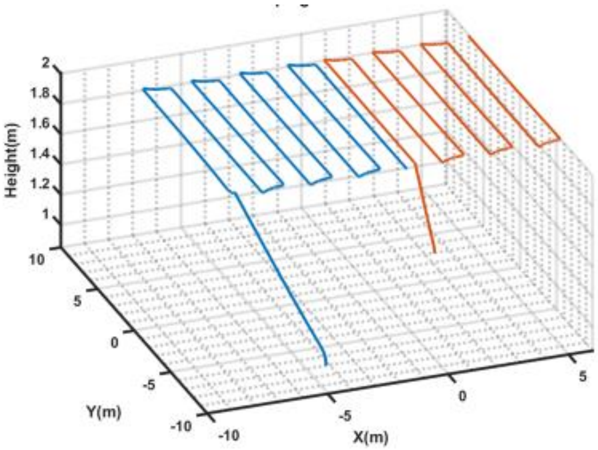


Figure 23: Search tracking by multiagent UAVs in Matlab

Both UAVs were able to cross all the predefined waypoints and successfully scanned the disaster region entirely, as shown in Figure 23.

4.2 Hybrid pattern search with two agents

The AoI conditions (dimensions without obstacles) were kept same as above. Herein UAVs followed different patterns (parallel track and ACO based search pattern).

Figure 24: Multiagent UAVs hybrid search simulation in VREP

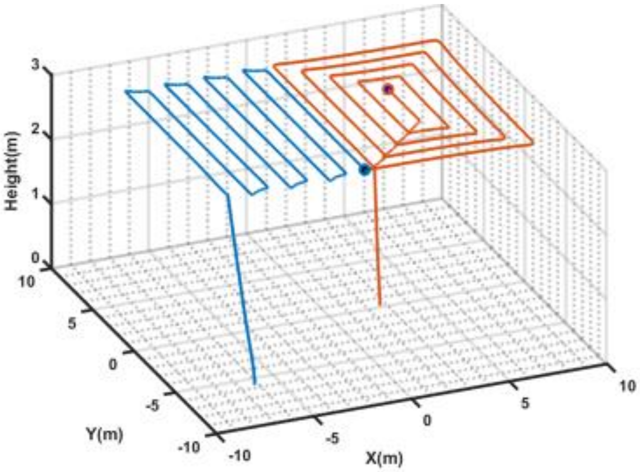


Figure 25: Hybrid search by multiagent UAVs in Matlab

Both UAVs were able to cross all the predefined waypoints and successfully scanned the disaster region entirely, as shown in Figure 25.

4.3 ACO based search pattern

The AoI conditions (dimensions without obstacles) were kept same as above. Herein UAVs followed ACO based search patterns (converging square search pattern).

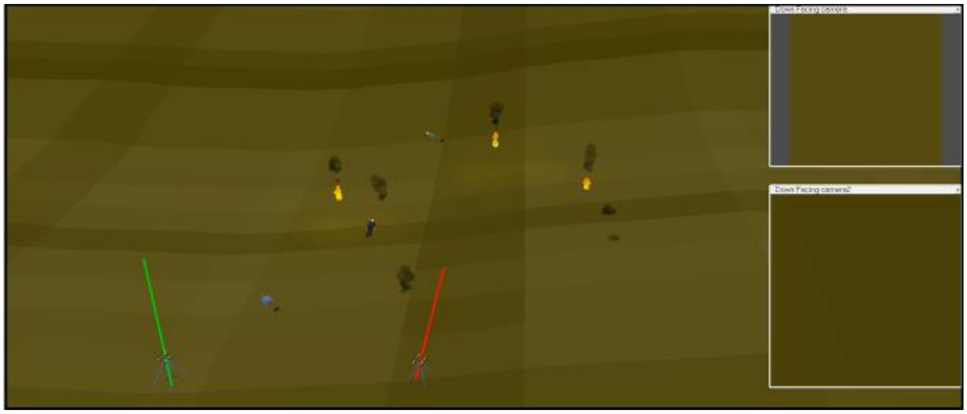


Figure 26: Multiagent UAVs ACO based search simulation in VREP

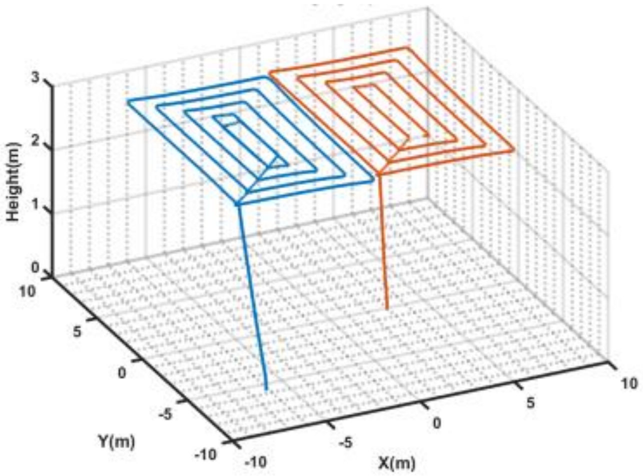


Figure 27: ACO based search by multiagent UAVs in Matlab

Both UAVs were able to cross all the predefined waypoints and successfully scanned the disaster region entirely, as shown in Figure 27.

4.4 Parallel track search with obstacles

An Area of Interest (AoI) of 14 meter x 13 meter was selected with one physical soft obstacles. The heights of UAVs were adjusted 2 meters above ground level throughout the simulation.

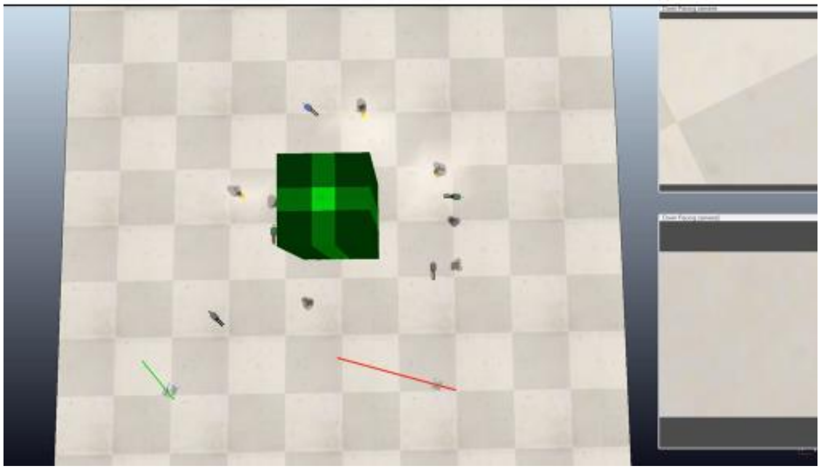


Figure 28: Multiagent UAVs parallel track search with obstacle simulation in VREP

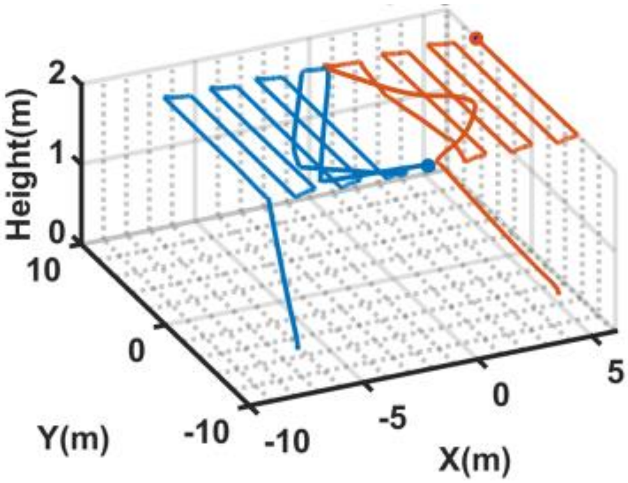


Figure 29: Multiagent UAVs search tracking with obstacle in Matlab

As shown in Figure 29 both the UAVs were able to avoid obstacle while following preselected way points present in free space able to scan the disaster area successfully.

4.5 Comparison

Search Pattern Type	**No. of Waypoints**	**Time (minutes)**
Creeping line	16	5.5
Hybrid Search	Creeping=16,ConSq=30	9.1
Converging Square (ACO)	30	8.2
Creeping Line (obstacles)	16	9

Table 3: Waypoints comparison between different search strategies

5. Future Work

Following work is recommended for future work: -

- Motion planning for follow on Life Support UAV using travelling salesman problem and Dijkstra algorithms
- Involvement of autonomous unmanned ground vehicles with existing aerial based system
- Mobile application of SAR and aerial surveillance

6. Conclusion

Various search tactics from “IAMSAR” manual were used in this thesis. For a multi-agent UAV system in a collaborative environment, I suggested a solution based on “ACO” algorithm. The method allows UAV to revisit all path nodes while preventing UAV from returning to the preceding node of the current node. Suggested motion planning pattern allows UAVs to scan the catastrophe area, collect info about the potential survivors, and transmit their coordinates to the ground station.

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