



# A Fully Autonomous Search and Rescue System Using Quadrotor UAV

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Received ## Mon.20##, Revised ## Mon. 20##, Accepted ## Mon. 20##, Published ## Mon. 20##

**Abstract:** In order to deal with critical missions a growing interest has been shown to the UAVs design. Flying robots are now used for fire protection, surveillance and search & rescue (SAR) operations. In this paper, a fully autonomous system for SAR operations using quadrotor UAV is designed. In order to scan the damaged area, speed up the searching process and detect any possible survivors a new search strategy that combines the standard search strategies with the probability of detection is developed. Furthermore the autopilot is designed using an optimal backstepping controller and this enables the tracking of the reference path with high accuracy and maximizes the flying time. Finally a comparison between the applied strategies is made using a study case of survivors search operation. The obtained results confirmed the efficiency of the designed system.

**Keywords:** UAV, SAR, Autopilot, Optimization, Trajectory generation, targets geo-localization.

## 1. INTRODUCTION

During a disaster event, the infrastructure conditions are disrupted, as communication links are interrupted, roads are blocked and buildings are collapsed. Under this situation roads are covered with debris and disaster region is completely unreachable. Subsequently, the need for immediate support to the survivors is necessary, due to the fact that the probability to remain alive is reduced as time advances. The need for robot assistant in crisis management is shown.

An overview for the use of UAVs for SAR applications could be found in [1]. The growing use of UAVs is supported by researches in many areas, including human detection and localization [2], mission planning [3], networking and data processing [4], collaborative SAR missions [5], assisted UAV task allocation and trajectory planning [6], etc. Many types of the SAR missions are defined depending on the environment and the situation of the targets. Survivors could be on mountain in an avalanche events [7,8], in marine [9], facing a fire [10], or even in a closed building [11]. Reference [12] explains an Autonomous Unmanned Aerial System (AUAS) namely the ROLFER (Robotic Lifeguard for Emergency Rescue). This system aims to provide SAR services. However the previous cited works describe the different parts of a SAR system, but

no one has presented a full designed autonomous system that takes into consideration all the contributed parts (i.e. mission planning, autopilot system, search strategy and targets geo-localization).

Reference [13] studies the searching targets strategies based on greedy heuristics, potential-based algorithms and partially observable Markov decision. In [14] bio-inspired self-organized search strategy is proposed. Reference [15] search strategies provided by the international maritime organization and international civil aviation organization, and published annually in IAMSAR (International Aeronautical and Maritime Search and Rescue) manual are used. Despite the development of many heuristics and probabilistic problem-solving techniques for SAR search problem, published procedures still deliver approximate solution and mostly fail to cover the integrity of searching area and include the probability of detection/observation model, questioning their real expected relative efficiency.

Quadrotors are type of Vertical Take-off Landing (VTOL) systems able to hover with vertical takeoff landing. For an overview of quadrotors modeling and identification the reader may refer to [16]. Compared to the fixed-wing UAVs, the VTOL capability gives them a big facility for survivors detection. However, they are dynamically unstable, multi-variable, highly coupled systems with limited onboard energy. In order to deal

with these drawbacks, it is necessary to design an autopilot that stabilizes the quadrotor and allows it to track the desired SAR strategy trajectory. Many works have been published on the control of quadrotor [17-21], the designed controllers were for the sake of stabilization, regulation and trajectory tracking. In fact, SAR missions outdoor, critical, long endurance missions. The need of control performance, energy optimization and robustness is fundamental. Where all the previous controllers may fail to deal with this raised issues. Hence, controller design that maximizes the flying time and has a good set point tracking (meets the SAR operations requirements) is a real design problem.

This paper aims to design a fully autonomous SAR system with respect to all the requirements of a typical SAR operation. The efficiency of the designed system is proofed via a study case scenario. The contributions of the paper are:

- 1- The designed system will use quadrotor to scan the disaster area, collect information about any possible survivals, and send back their positions to the base station.
- 2- New Search strategy that combines the standard searching strategies with the probability of detection, which then, speeds up the searching

process and covers the integrity of the searching area in order to detect all the possible targets.

- 3- Introducing a novel autopilot design using a non-linear optimal backstepping controller in order to stabilize the vehicle while tracking the search paths with good performance even in presence of disturbances and maximize the flying time.
- 4- Comparison between the applied SAR strategies is made using a study case of survivals detection.

Throughout this paper, a particular attention is paid to the tracking accuracy and energy consumption of the control strategy considering some performance criteria, such as the Integral Absolute Error (IAE).

This paper is organized as follow: Section 2 introduces a presentation of the designed SAR system. Section 3 presents the different SAR strategies and their path patterns. Section 4 discusses the trajectory generation, sensor coverage and target detection algorithms used for the navigation system. Section 5 gives the full quadrotor dynamic model as well as the attitude and trajectory tracking control strategies using the non-linear optimal backstepping controller. Simulations and SAR strategies comparison are in section 6. Finally Section 7 a conclusion and the future recommendations are given.

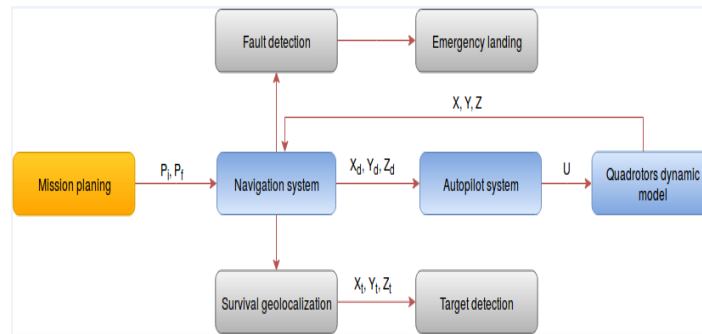


Fig.1. SAR System

## 2. SYSTEM DESIGN

The designed SAR system is composed of the following parts as illustrated in Fig.1. :

- 1- *Mission planning*: At this level the human operator selects the desired search strategy. Once selected, the system generates the optimal path to be tracked (i.e the coordinates of initial and final point ( $P_i$  and  $P_f$ ) for every leg from the path).
- 2- *Navigation system*: This sub-system is the heart of the designed system, it includes the following functions: first it provides the autopilot sub-system with the optimal path to track ( $X_d, Y_d, Z_d$ ) for each

time step of the path leg. The sub-system also uses a survivals geo-localization algorithm to estimate the target coordinates ( $X_t, Y_t, Z_t$ ) and send back their positions to the base station based. The target detection depends on the probability of detection and the sensor range of the embedded camera. Finally the system monitors any failures that can occur such as a divergence from the desired path, an engine failure, or the battery energy consumption. Once happened an emergency landing occurred, this option would save the quadrotor from a sudden crash. Moreover the base station is informed about the mission failure.

- 3- *Autopilot System*: This sub-system has to track the search strategy path generated by the navigation



sub-system. The autopilot is designed using a double loop control strategy for the position and attitude tracking based on backstepping controller. The designed autopilot aims to assure the path tracking accuracy and the quadrotor stability.

**3. MISSION PLANNING**

As illustrated in Fig.2. The proposed mission planning aims to use UAVs to deploy the disaster area, detect any possibility of a victim presence, and report the collected information to the control ground station.

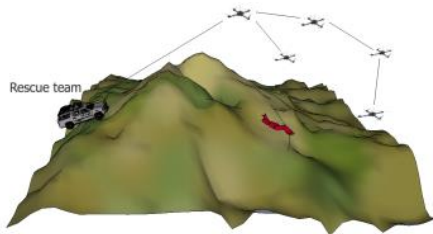


Fig.2. SAR Operation Using Quadrotors UAVs

For surface and aircraft facilities to search effectively, search patterns and procedures must be pre-planned so ships and UAVs can cooperate in coordinated operations with the minimum risks and delay. In order to meet varying circumstances, standard search patterns are defined.

Many search strategies are recognized by the International Maritime Organization and International Civil Aviation Organization. These are published annually in IAMSAR manual. These are designed to provide simple and effective visual search patterns that can be applied in various situations. The standard search patterns for a desired area are as follow:

- Parallel Track and Creeping line Search
- Expanding Square Search
- Contour Search

The following sections discuss the main characteristics of the previous standard searching patterns and the conditions under which they are being utilized.

**3.1. Parallel Track and Creeping line Search**

Both parallel track and creeping line search are based on covering (sweeping) the search area by maintaining parallel tracks as shown in Fig.3.

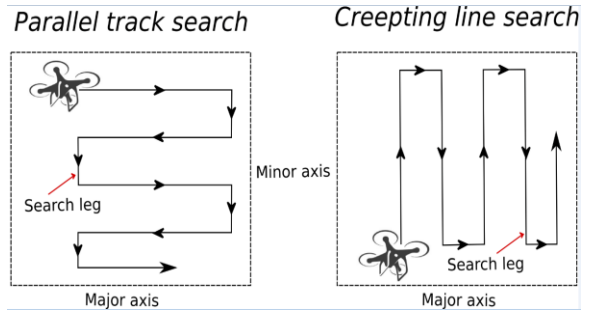


Fig. 3. Parallel track search and Creeping line search pattern

The only difference between these two is in the orientation of the search legs, i.e. if the search legs are parallel to the long sides (major axis) or short sides (minor axis) of the designated search area.

**3.2. Expanding Square Search**

For this search strategy the pattern begins at the center of the designated search area and expands outward in concentric squares as shown in Fig.4.

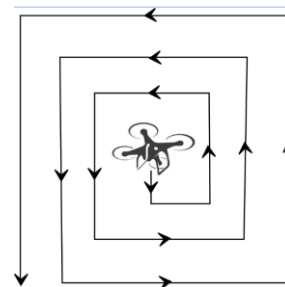


Fig.4. Expanding Square Search Pattern

**3.3. Contour search**

The search pattern of this search strategy may be described as a downward spiral motion as shown in Fig.5. This search strategy is applied around mountains or valleys with sharp changes in elevation as the other search patterns are not practical in these circumstances.

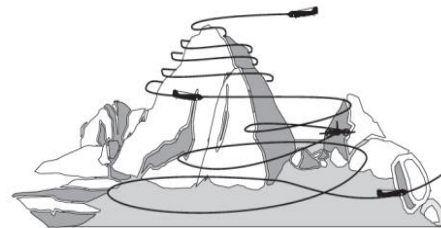


Fig. 5. Contour Search Pattern

**4. NAVIGATION SYSTEM**

**4.1. Trajectory Generation**

The search trajectory generation problem can be solved by optimizing the distance between the initial and final points for each leg from the search strategy pattern.

By assuming that the running costs are proportional to average velocity, the objective function,  $\Phi$ , can be defined as:

$$\Phi = \frac{1}{T} \int_0^T \sqrt{(P_1 \dot{x}^2 + P_2 \dot{y}^2 + P_3 \dot{z}^2)} dt \quad (1)$$

Where  $P_1, P_2, P_3$  are weighting factors.

#### 4.2. Sensor Coverage

The sensor's ability to detect a victim in the prevalent conditions will significantly affect the maximum altitude at which the UAVs can operate.

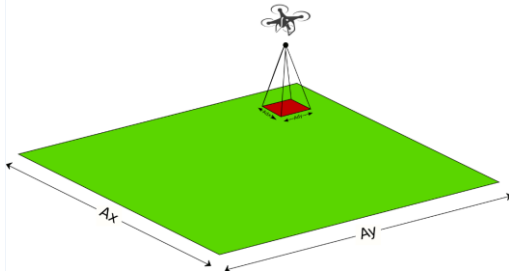


Fig. 6. Sensor Coverage

Let's consider that the sensing areas on the ground cover surface  $A = A_x * A_y$  (green area in Fig.6.) a set of  $A_d(h)$  cells, where the surface  $A_d = A_{dx} * A_{dy}$  (red area in Fig.6.) depends on the altitude of the UAV. The dimension of the sensing area increases with the height of the UAVs.

The sensing model accounting for false positive and false negative can be modeled as follow:

- The probability of sensing a target at height  $h$  in the presence of the target =  $1 - \beta_h$
- The probability of not sensing a target at height  $h$  in the presence of the target =  $\beta_h$
- The probability of not sensing a target at height  $h$  with no target =  $1 - \alpha_h$
- The probability of sensing a target at height  $h$  with no target =  $\alpha_h$

With  $\alpha_h$  ( $0 \leq \alpha_h \leq 1$ ) and  $\beta_h$  ( $0 \leq \beta_h \leq 1$ ) are the false alarm and missed detection probabilities. The values accorded to  $\alpha_h$  and  $\beta_h$  at the different searching heights  $h$  are summarized in Table.I.

For this work a fixed searching high of 100m above the earth is used in order to maintain an acceptable values of  $\alpha_h$  and  $\beta_h$  that avoid any possibility of missed detection and minimize a false alarm.

TABLE I. OBSERVATION MODEL

Altitude (m)	$\alpha_h$	$\beta_h$
50	0.243599	0.000000
100	0.028369	0.000000
150	0.026099	0.046211
200	0.001110	0.046745

#### 4.3. Target Detection

Algorithm.I. presents the searching algorithm used depending on the searching strategy, where the UAV scan the hall area and report any target detection to the base station. The mission is completed whenever all the targets are detected (if the number is limited) or the hall area is scanned, it also can be canceled if any fault is occurred, for all the cases the base station is reported about the mission situation.

Algorithm 1. Targets Searching and Detection Algorithm

```

Initialization
 $P_i (X_i, Y_i, Z_i)$  = Initial location
Ad (Adx , Ady) = Detection Area
A (Ax , Ay) = Searching Area
Update(Searching Strategy)
While true do
    P=P'
    GetObservation(P)
    if target detected then
        | Report Base Station
    end
    Searching Strategy (P)
    P'=NextMove(P)
end

```

### 5- AUTOPILOT SYSTEM

#### 5.1. Quadrotor Modeling

For representing the dynamical model of a quadrotor, the following set of equations is used:

$$\begin{aligned} \dot{R}(t) &= R(t)S(\omega_b(t)) \\ J\dot{\omega}_b(t) &= -S(\omega_b(t))J\omega_b(t) + \tau(t) \end{aligned} \quad (2)$$

With:  $J$  introduces the inertia matrix,  $R$  the rotation matrix,  $\tau(t)$  the input torque and  $S(\omega_b(t))$  is the skew-matrix of the angular velocity  $\omega_b(t)$  as in Equ.3. :

$$S(\omega_b(t)) = \begin{bmatrix} 0 & -\omega_{b3}(t) & \omega_{b2}(t) \\ \omega_{b3}(t) & 0 & -\omega_{b1}(t) \\ -\omega_{b2}(t) & \omega_{b1}(t) & 0 \end{bmatrix} \quad (3)$$



Consequently the complete dynamic model is as follows:

$$\begin{aligned}
 \ddot{\phi} &= \frac{J_y - J_z}{J_x} \dot{\theta} \dot{\psi} + \frac{J_r}{J_x} \dot{\theta} \Omega + \frac{l}{J_x} U_2 \\
 \ddot{\theta} &= \frac{J_z - J_x}{J_y} \dot{\phi} \dot{\psi} - \frac{J_r}{J_y} \dot{\phi} \Omega + \frac{l}{J_y} U_3 \\
 \ddot{\psi} &= \frac{J_x - J_y}{J_z} \dot{\phi} \dot{\theta} + \frac{U_4}{J_z} \\
 \ddot{x} &= \frac{1}{m} \{ (C_\phi S_\theta C_\psi + S_\phi S_\psi) U_1 \} \\
 \ddot{y} &= \frac{1}{m} \{ (C_\phi S_\theta C_\psi - S_\phi S_\psi) U_1 \} \\
 \ddot{z} &= \frac{1}{m} \{ C_\phi S_\theta U_1 \} - g
 \end{aligned} \tag{4}$$

Where  $m$  and  $g$  represent the vehicle's mass and gravity vector respectively.  $J_r$  is the moment of inertia of the rotor.

The model developed in Eq.4. can be rewritten in the state-space form  $\dot{x} = f(x) + g(x, u)$  with  $x = [x_1, \dots, x_{12}]$ , is the state vector of the system such as:

$$x = [\phi \ \theta \ \psi \ \dot{\phi} \ \dot{\theta} \ \dot{\psi} \ x \ \dot{x} \ y \ \dot{y} \ z \ \dot{z}]^T \tag{5}$$

From Equ.4. and Equ.5. the following state representation can be obtained:

$$f = \begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_1 x_4 x_6 + a_2 x_4 \Omega + b_1 U_2 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = a_3 x_2 x_6 + a_4 x_2 \Omega + b_2 U_3 \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = a_5 x_2 x_4 + b_3 U_4 \\ \dot{x}_7 = x_8 \\ \dot{x}_8 = \frac{U_1}{m} U_x \\ \dot{x}_9 = x_{10} \\ \dot{x}_{10} = \frac{U_2}{m} U_y \\ \dot{x}_{11} = x_{12} \\ \dot{x}_{12} = \frac{1}{m} (C_{x_1} S_{x_3} U_1) - g \end{cases} \tag{6}$$

With:

$$\begin{cases} a_1 = \left(\frac{J_y - J_z}{J_x}\right), a_2 = \left(\frac{J_r}{J_x}\right) \\ a_3 = \left(\frac{J_z - J_x}{J_y}\right), a_4 = \left(-\frac{J_r}{J_y}\right) \\ a_5 = \left(\frac{J_x - J_y}{J_z}\right) \\ b_1 = \left(\frac{l}{J_x}\right), b_2 = \left(\frac{l}{J_y}\right), b_3 = \left(\frac{l}{J_z}\right) \end{cases} \begin{cases} U_x = (C_{x_1} S_{x_3} C_{x_5} + S_{x_1} S_{x_5}) \\ U_y = (C_{x_1} S_{x_3} C_{x_5} - S_{x_1} S_{x_5}) \end{cases}$$

### 5.2. Controller design

The trajectory tracking controller consists of two parts as depicted in Fig .7.

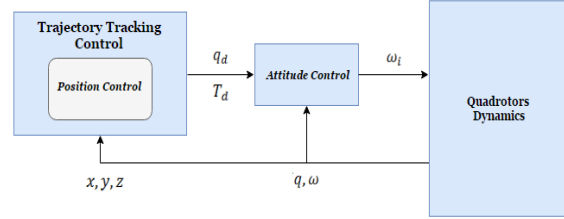


Fig.7. Block diagram of the proposed control structure

The inner loop for attitude control and the outer loop for the position control. The position controller generates the desired attitude vector  $q_d$  and the desired trust  $T_d$  for the attitude controller.

Let's consider the tracking error:

$$e_i = \begin{cases} x_{i_d} - x_i & i \in \{1,3,5,7,9,11\} \\ \dot{x}_{(i-1)_d} - \dot{x}_i + k_{(i-1)} e_{(i-1)} & i \in \{2,4,6,8,10,12\} \end{cases} \tag{7}$$

Using the Lyapunov functions as:

$$V_i(x) = \begin{cases} \frac{1}{2} e_i^2 & i \in \{1,3,5,7,9,11\} \\ V_{(i-1)} + \frac{1}{2} e_i^2 & i \in \{2,4,6,8,10,12\} \end{cases} \tag{8}$$

By applying the following algorithm:

For  $i = 1$

$$\begin{cases} e_1 = x_{1_d} - x_1 \\ V_1 = \frac{1}{2} e_1^2 \end{cases} \tag{9}$$

And:

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1 (\dot{x}_{1_d} - \dot{x}_2) \tag{10}$$

The  $e_1$  stability is derived using the Lyapunov function as follow:

$$x_{2_d} = \dot{x}_{1_d} + k_1 e_1 \tag{11}$$

With  $k_1 > 0$  the Equ.17. is then:  $\dot{V}_1 = -k_1 e_1^2$ . Let consider a variable change by making:

$$e_2 = x_2 - \dot{x}_{1_d} - k_1 e_1^2 \tag{12}$$

For  $i = 2$ :

$$\begin{cases} e_2 = x_2 - \dot{x}_{1_d} - k_1 e_1^2 \\ V_2 = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 \end{cases} \tag{13}$$

And:

$$\dot{V}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 \quad (14)$$

Finally:

$$\dot{e}_2 = a_1 x_4 x_6 + a_2 x_4 \Omega + b_1 U_2 - \ddot{x}_{1d} - k_1 \dot{e}_1 \quad (15)$$

The control signal  $U_2$  is obtained such that  $\dot{V}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 \leq 0$  as follow:

$$U_2 = \frac{1}{b_1} (-a_1 x_4 x_6 - a_2 x_4 \Omega + \ddot{\varphi}_d + k_1 (-k_1 e_1 + e_2) + k_2 e_2 + e_1) \quad (16)$$

In order to extract the control signals the same steps are followed:

$$\begin{cases} U_3 = \frac{1}{b_2} (-a_3 x_2 x_6 - a_4 x_2 \Omega + \ddot{\theta}_d + k_3 (-k_3 e_3 + e_4) + k_4 e_4 + e_3) \\ U_4 = \frac{1}{b_3} (-a_5 x_2 x_4 + \ddot{\psi}_d + k_5 (-k_5 e_5 + e_6) + k_6 e_6 + e_5) \\ U_x = \frac{m}{U_1} (\ddot{x}_d + k_7 (-k_7 e_7 + e_8) + k_8 e_8 + e_7) \\ U_y = \frac{m}{U_2} (\ddot{y}_d + k_9 (-k_9 e_9 + e_{10}) + k_{10} e_{10} + e_9) \\ U_1 = \frac{m}{C_{x_1} C_{x_3}} (g + \ddot{z}_d + k_{11} (-k_{11} e_{11} + e_{12}) + k_{12} e_{12} + e_{11}) \end{cases} \quad (17)$$

With:  $U_1 \neq 0$  and  $k_i > 0 \quad i \in \{2, \dots, 12\}$

All the control parameters are obtained using Multi-Objective Genetic Algorithms such as in [29], and shown on Table.II.

Table II. Control parameters

Controller	k1	k2
Attitude	[0.8 0.8 0.5]	[0.1 0.1 1.2]
Position	[0.2 0.2 3]	[0.1 0.1 1.5]

## 6. Simulations Results

The second part discusses the track of the different SAR strategies patterns and compares them over a case study of survivals SAR operation. Three types of search areas are designed for the SAR strategies in order to simulate different scenarios: a flat, mountainous and a hybrid area for the study case. All the areas are supposed to be with a total surface of 1000m \* 1000m. For the mountainous simulation environment, an exponential function, is introduced to emulate mountains which are the main threats of the UAVs in this experiment:

$$z(x, y) = \sum_{i=1}^n h_i * \exp\left(-\left(\frac{x - c_{x_i}}{g_{x_i}}\right)^2 - \left(\frac{y - c_{y_i}}{g_{y_i}}\right)^2\right) \quad (18)$$

This function gives altitude of the given coordinate (x, y) in the simulated terrain. Where,  $h_i$  controls height of peak  $i$ ;  $c_{x_i}$  and  $c_{y_i}$  mark central position of peak  $i$ ;  $g_{x_i}$  and  $g_{y_i}$  control peak gradient in x and y orientation respectively.

The integral absolute error (IAE) is used to judge the controller's performance. The index IAE is expressed as follows:

$$IAE = \int_0^t |e(t)| dt \quad (19)$$

### 6.1. SAR strategies path tracking

#### 6.1.1 Expanding Square Search (ESC)

Let's suppose that the quadrotor scans a flat surface from a departure point  $P_0\{X,Y,Z\} = \{500, 500, 0\}$  then track the reference trajectory generated by strategy.

As shows Fig.8. the quadrotor UAV was able to pass over all the prescribed waypoints, and track the reference path using straight lines without any oscillations and with a high accuracy. The control outputs are shown in Fig.9. where a good accuracy of the path tracking is presented specially for the altitude hold. High attitude degrees (up to 1 rad) are used during curving movements when passing from a waypoint to another. Fig.10. shows that the control signals are within the limits of the actuators. These results show that all the constraints and the assumptions considered during the modeling and the control design are successfully respected.

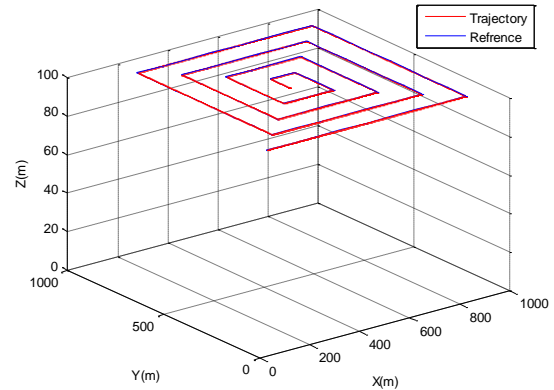


Fig.8. ESC Trajectory Tracking

#### 6.1.2 Parallel Track (PT) and Creeping line Search (CLS):

For this strategy the quadrotor is supposed to scan the same flat area used in the precedent strategy but this time from two different departure points  $P_{0C}\{X,Y,Z\} = \{50, 50, 0\}$  for the CLS and  $P_{0P}\{X,Y,Z\} = \{950, 50, 0\}$  for the PT strategy. The obtained results for both CLS and PT 3D trajectory tracking are shown in Fig.11. & Fig.12. respectively.

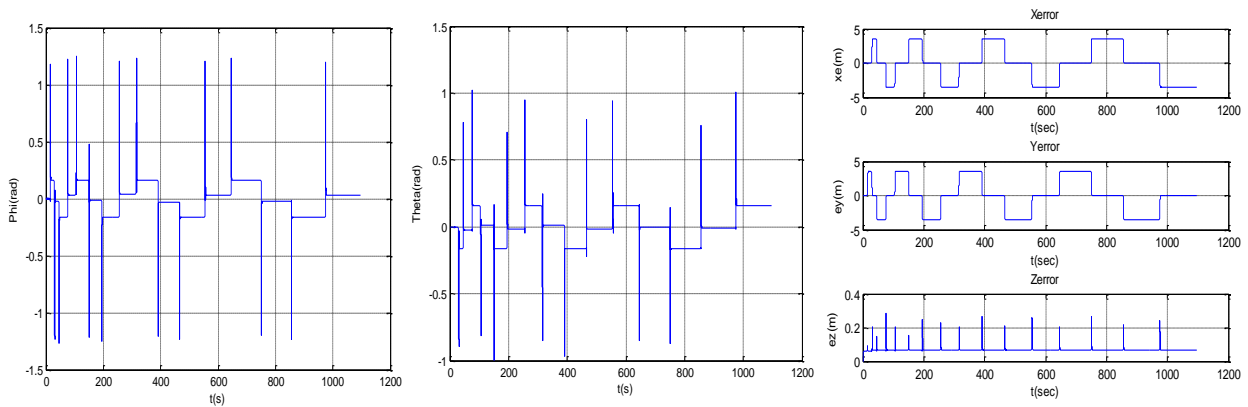


Fig. 9. ESC Control Outputs

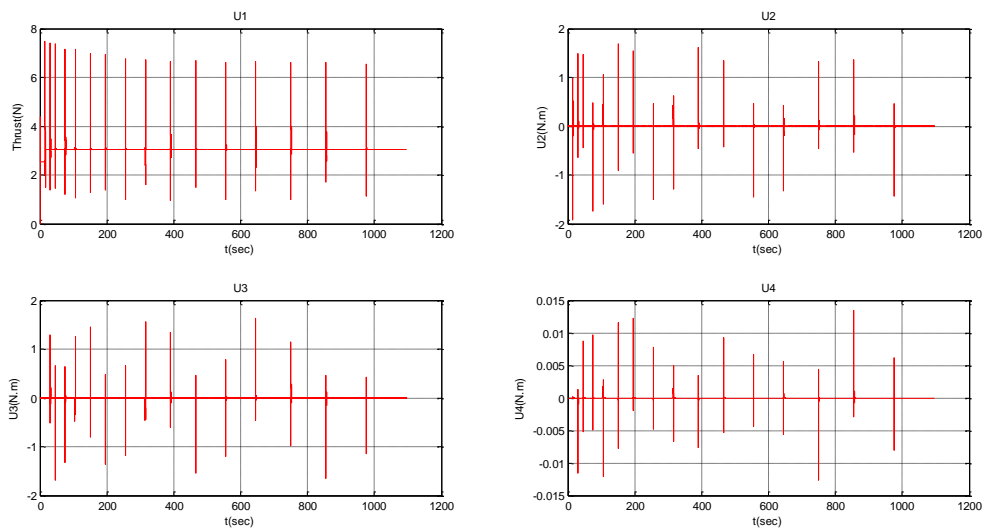


Fig. 10. ESC Control Inputs

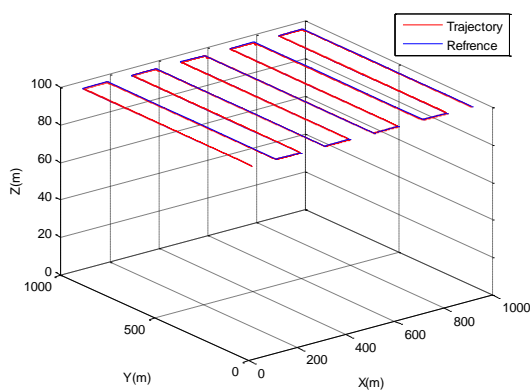


Fig. 11. CLS Trajectory Tracking

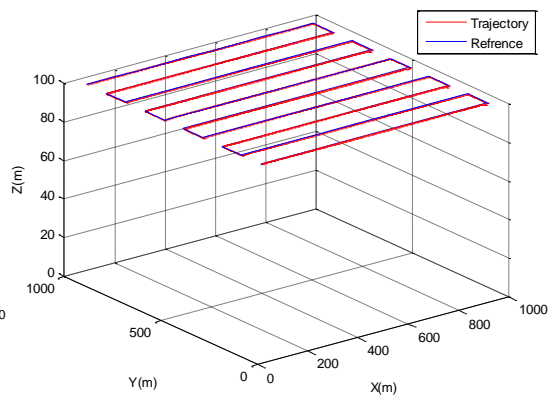


Fig. 12. PT Trajectory Tracking



From Fig.11. & Fig.12. it is clear that the quadrotors was able to track the waypoints with high accuracy in both cases and scan all the desired area. Fig.13. & Fig.14. decipate the control outputs, where the controller was able to maintain the

quadrotors stability during the path tracking and spetially on curving corners when changing the waypoints.

The obtained control inputs illustrated in Fig.15. & Fig.16. for the CLS and PT strategies are the same and remain within the desired functional range of the quadrotors engines.

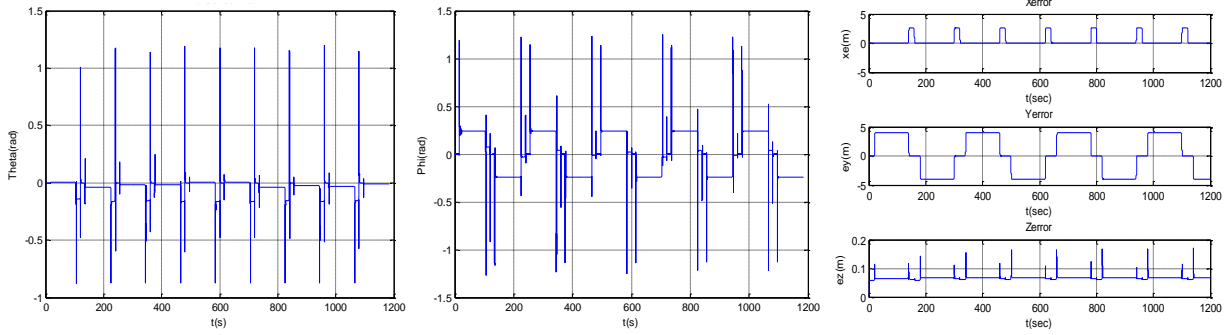


Fig. 13. CLS Control Outputs

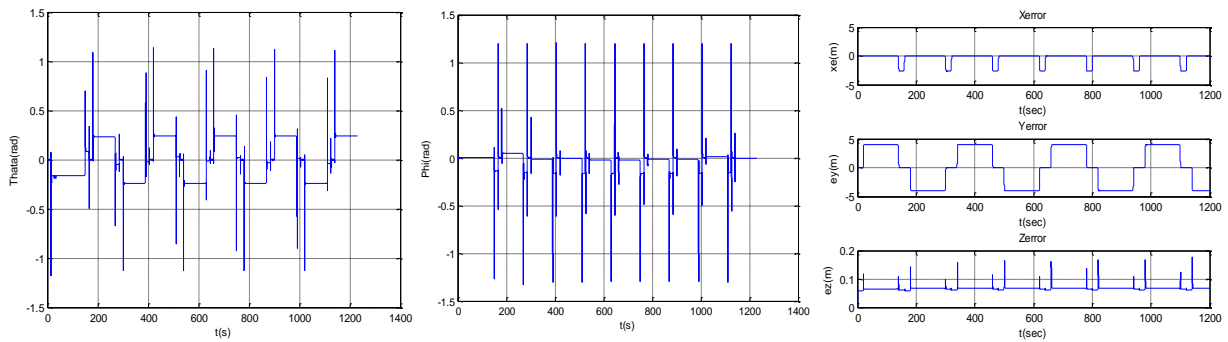


Fig. 14. PT Control Outputs

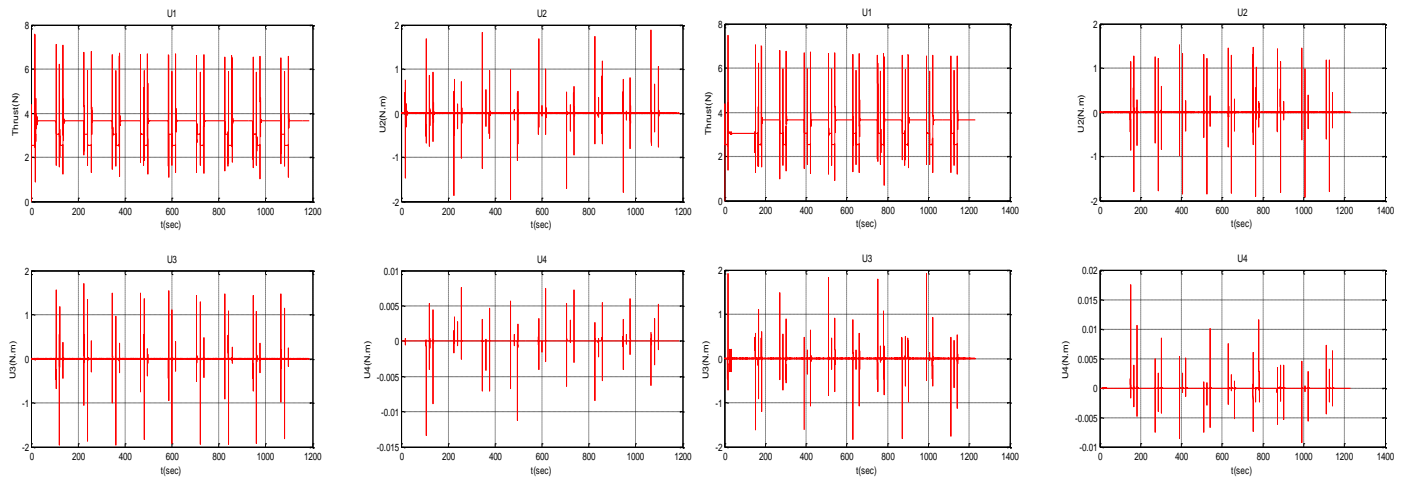


Fig. 15. CLS Control Inputs

Fig. 16. PT Control Inputs





Table .III. shows the comparison between the different SAR strategies.

From the obtained results it is clear that the controller was able to optimize the energy consumption and with high accuracy for all the strategies, but the PT strategy is supposed the best since it offers a more complete covered area with an acceptable searching time and controller path tracking accuracy.

TABLE III. FLAT AREA SAR STRATEGIES COMPARISON

Strategie	Search Time (min)	Battery Consumption (%)	Covered area (%)	Fitness (IAE)
ESC	17	76.31	80	0.1584
PT	20	81.22	100	0.1534
CLS	20	80	100	0.8161

#### 6.1.4 Contour Search (CS)

This strategy is often used when scanning a mountain area because of its spiral path that creates a contour.

A virtual mountain with a 100m of altitude is simulated, where the quadrotor is starting from a departure point  $P_0\{X,Y,Z\} = \{50, 50, 0\}$  and track the desired path around the mountain. Fig.17. & Fig.18. & Fig.19. illustrate the simulation environment as same as the obtained trajectory generation and tracking of the quadrotor. The obtained results are shown in Table IV.

Fig.17. shows that the quadrotor was able to track the generated path and cover the entire mountain with a very high accuracy, and a minimum of battery consumption (Table IV) in less than 6 min.

The control outputs dissipated in Fig.18. are validating the controller effectiveness and optimality where a high accuracy is reached with low attitude degrees. The obtained control inputs shown in Fig.19. oscillates with low frequency supported by the quadrotor engines.

TABLE IV. CS STRATEGY SIMULATION RESULTS

Strategie	Search Time (min)	Battery Consumption (%)	Covered area (%)	Fitness (IAE)
Spiral	6	13.44	-	0.0046

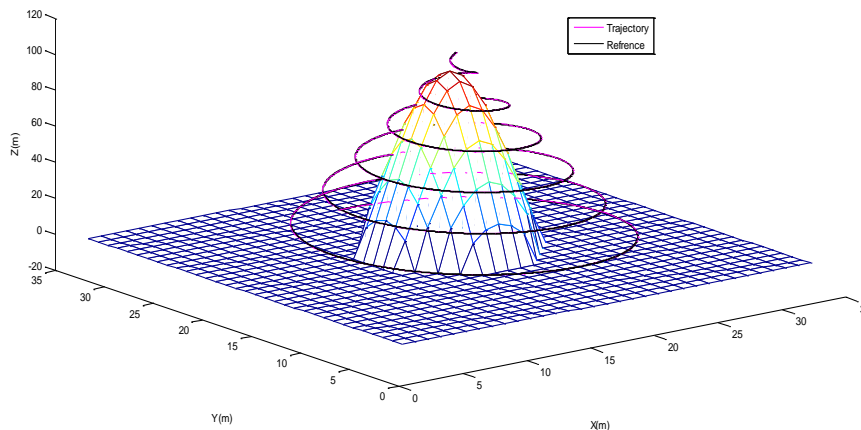


Fig. 17. CS Trajectory Tracking

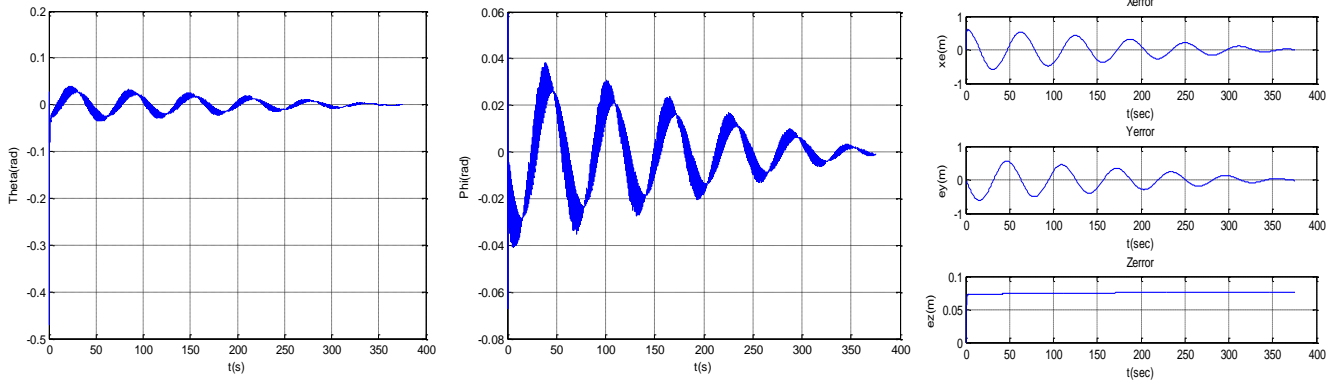


Fig. 18. CS Control Outputs

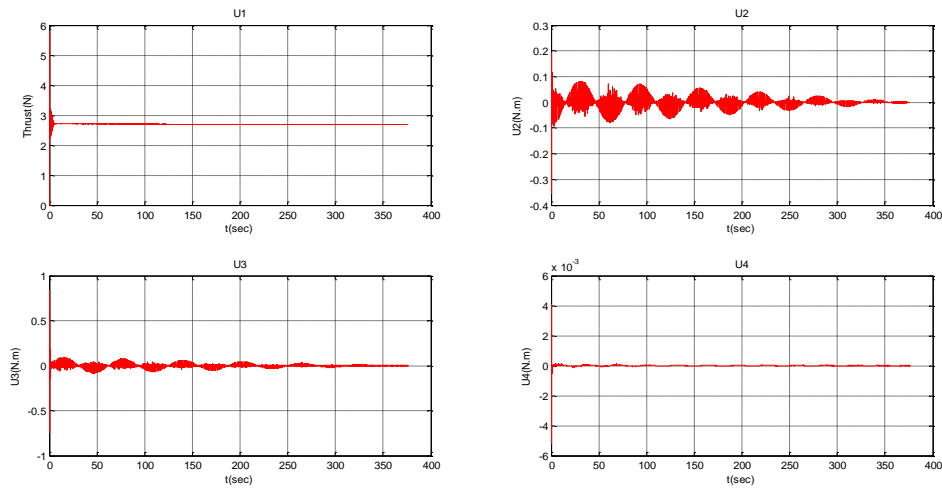


Fig. 19. CS Control Inputs

6.2 SAR STRATEGIES COMPARAISON

In this section the study case is to scan a hybrid flat and mountainous area and search for possible survivals. The surface is of 1000m \* 1000m and contains two mountains of

100 m of altitude. All the previous SAR strategies are applied in order to find 10 persons (red dots in Fig.20.) that are randomly distributed all over the area.

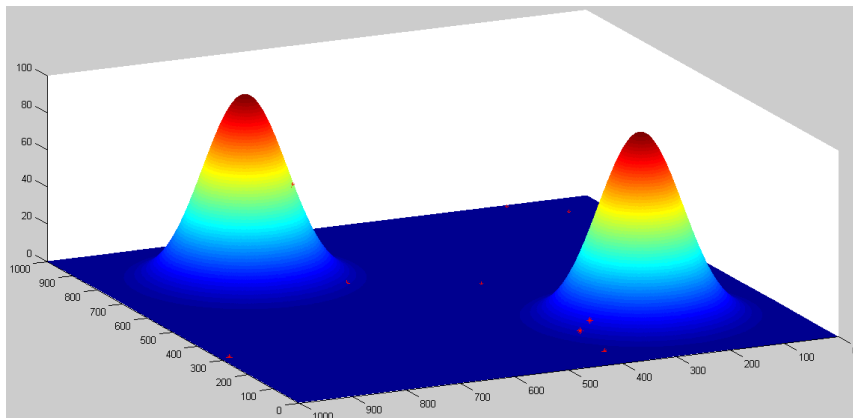


Fig. 20. SAR Study Case Environment

A comparison between the different SAR strategies is made, the obtained results are shown in Fig .20. From Fig .21. it is clear that only the CLS and PT strategies were able to cover the desired area and detect all the 10 survivals but after a long time (about 25 min). For the ESC strategy only 70% of the survivals was detected in less than 20 min. For the CS strategy, 60 % of the survivals are detected in only 9 min, which is a very interesting time when comparing with the other strategies for the same percentage. The explication behind these results is that the CS is local concentrated searching strategy that covers the surfaces with a high detection probability which means a less searching time, where the other strategies are more generalized searching strategies that cover the entire area and detect all the possible survivals but with a long searching time. The departure searching point is also an other comparison parameters that must be cited, because generally it is so critical from a point and not from the other due to the complicated nature of the SAR operations.

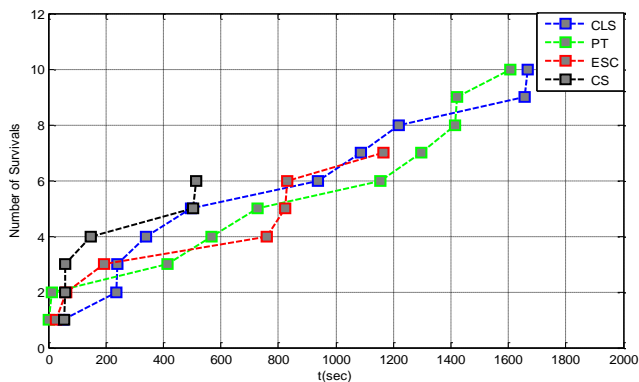


Fig. 22. SAR Strategies Comparison

## 7 CONCLUSION

This paper studied the design of a fully autonomous SAR system that includes all the necessary elements during a typical SAR operation.

For the autopilot system a double loop control structure based on a non-linear optimal backstepping controller was applied. The designed controller was able to deal with the SAR operations requirements such as: vehicle stability, searching trajectories tracking with good performance. The obtained results of the trajectory generation and the path tracking were judged to be satisfactory since the quadrotor has successfully followed the desired SAR strategy generated path within the functional range and with respect to all the limitations.

A study case of an area scanning for possible survivals geo-localization and detection was simulated. Different SAR strategies were applied and compared; the final results speed up the searching process and cover the integrity of the searching area in order to detect all the possible targets.

The next step for this research will focus over the use of a UAV swarming as a multi-agents system to reduce the research time and improve the efficiency. A combination of the different SAR strategies can also applied to benefit of the advantages of every strategy.

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