Minimal-time trajectories for interception of malicious drones in constrained environments

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Abstract. This work is motivated by the need to improve existing systems of interception of drones by using other drones. Physical neutralization of malicious drones is recently reaching interest in the field of counter-drone technologies. The exposure time of these threats is a key factor in environments of high population densities such as cities, where the presence of obstacles can complicate the task of persecution and capture of the intruder drone. This paper is therefore focused on the development and optimization of a strategy of tracking and intercepting malicious drones in a scenario with obstacles. A simulation environment is designed in Matlab-Simulink to test and compare traditional interception methods, such as Pure Pursuit which is quite common in missile guidance field, with the proposed strategy. The results show an improvement in the interception strategy by means of a reduction in the time of exposure of the threat with the developed algorithm, even when considering obstacle environment.

Keywords: Counter-drone, interception trajectory, guidance.

1 Introduction

Currently, there is growing concern about the malicious use of drones, and physical neutralization by other drones is considered a solution of interest by companies and security agencies. In the last years there has been a significant increase of drone usage which is making it an accessible technology for the open public, becoming highly popular among them. The proliferation of cheap and very simple drones has led to an increase in the number of incidents where the security of people and properties on ground and also other airspace users have been compromised. These drones can pose a threat to society when used with malicious intentions, which is the reason why Law Enforcement Agencies are concerned about security regarding dangerous usages of drones. Many drone countermeasures techniques have recently been developed and tested. The problem can be split in two main stages: the first one regards to detection, localization, tracking and classification of the intruder drone; and the second one refers to the neutralization of the intruder drone so that it cannot carry out its mission. Fig. 1 shows the use case representation of the formulated problem.

NASA has published in [1] a technical report evaluating different alternatives for the detection of intruder drones: radar, acoustic sensors, computer vision, etc. Many companies are developing their own system such as the radar of IDS [2], systems with a combination of different sensors like Ctrl+Sky of Advanced Protection Systems [3] and Boreades of CS [4].

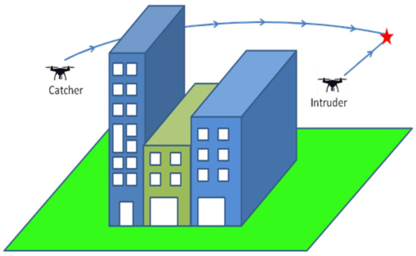

Fig. 1: Representation of the use case for physical neutralization in constrained environment

With respect to the neutralization of drones, there are also many developments that have been emerging in recent years. The technique of jamming of communications is the one that presents greatest robustness, for example the Scrambler 1000 of MC2 [5], but they usually cannot provoke the interruption of the flight. The work shown in this paper focuses on the physical neutralization of dangerous drones, so that they are intercepted and captured to prevent them from continuing with the threat and to minimize collateral damage. There are developments made by many companies since this field arouses much interest especially among the states security agencies. Within the state of the art, it can be highlighted the ONERA drone with a net launcher in [6] to capture intruder drones and another hunter drone from Purdue University with a hanging net in [7].

The work presented here focuses on the scenario of the physical interception of the intruder drone by means of a mechanism (for example a net) driven by an approaching drone. Hence, the intruder drone must be in the range of action of the interception system of the captive drone. The main interest is improving the capabilities of interception systems by increasing the automation of the physical interception operations and improving the efficiency of the approach trajectories to the intruder drone. The promptness in this operation is an important factor due to the criticality and dangerousness of the flight of a rogue drone. The time of exposure to risk due to the presence of a malicious drone must be minimized so that the damage caused is as small as possible. Hence, the optimization of the approach trajectory of the interceptor drone to capture the malicious aircraft is considered a key factor in this paper. Only multirotors will be considered in this work since this kind of drones is the most widespread today

Furthermore, threats with drones will be more worrying in urban environments, where there is a high population density. Given the number of buildings, towers and other obstacles that are usually present in these environments, a reactive algorithm to avoid these obstacles is required. In this way, the optimization of the approach trajectory is conditioned by the local deviations produced by the proposed obstacle avoidance algorithm to keep the catcher drone clear of collisions with obstacles.

2 Interception capability with obstacles

The first part of this work is focused on the generation of optimized trajectories so that the grabber drone can reach the suspicious drone in a fast and efficient manner. For this purpose, the location data of the suspicious drone which must be tracked is assumed to be an input from an external detection and localization system. Some systems such as the Boreades have integrated a multisensory platform (radar, infrared cameras, optronic cameras, etc.) which provides a localization solution in terms of local position of the intruder drone. Moreover, the trajectory of the intruder drone is unforeseeable since, as discussed above, the type of drone considered in this work is the multirotor. This adds complexity to the problem given the ability of this type of drones to execute aggressive and unpredictable maneuvers.

The problem can be formulated as an interception problem between two bodies which is quite common in physics and engineering field. Missile guidance is a widely studied field from which this study starts. Standard guidance laws like Proportional Navigation (PN) and Pure Pursuit (PP) are quite extended for interception problems and can be adapted to this scenario. Many works are available in using these guidance algorithms but mostly for fixed wing drones and for the purpose of tracking ground targets. In [8], Tan performs in his master thesis an adaptation of PN for multirotors tracking ground targets. Adaptation of PP to multirotors has also been studied in [9], where it is used for path following combining it with virtual target concept. Additionally, there are other approaches for interception problems such as the proposed in [10] with drones optimizing the time to rest after the capture.

Regarding obstacle avoidance, this is a field of great interest in aerial robotics and drones traffic management. The obstacle avoidance algorithms for drones are usually very local and reactive, executing in real time so that the drone can re-plan its trajectory to reach the objective, ensuring a certain distance from the encountered obstacles. Many approaches are available for this purpose, such as: graph search algorithms [11], methods of potential fields [12], rapidly exploring random trees [13], etc. In this work, a strategy based on the evaluation of a cost function in the future positions of the drone taking into account the approach trajectory to the intersection point based on the optimization algorithm is used.

3 Optimization strategy

The fundamental objective is to minimize the time of arrival to the interception by the capturing drone. Successive modifications to the traditional Pure Pursuit have been made to study the improvements they produce. Several criteria have been decisive in order to minimize the interception time through the estimation of the point of interception based on the trajectory followed by the intruder drone:

- Analyze the trajectory followed by the intruder drone to predict its movements or destination
- Estimate the time to interception and optimize the approach trajectory in order to minimize the time of exposure of the threat
- Anticipate the positions to which the intruder drone is expected to move based on previous analysis

As previously stated, the position of the intruder drone is assumed to be an input, which should be given by an external system. This position is referred to the same coordinate frame as the catcher drone. The key idea behind the optimization algorithm is to take advantage of the information of the trajectory followed by the intruder drone to foresee their intentions: changes in course, speed, etc. A strategy of intelligent approach to the intruder drone is proposed. For that purpose, it is assumed a trajectory model of both drones, the intruder and the catcher, governed by the following equations:

$$\frac{dx}{dt} = v * \cos(\gamma) * \cos(\varphi)$$
$$\frac{dy}{dt} = v * \cos(\gamma) * \sin(\varphi) \qquad (1)$$
$$\frac{dz}{dt} = v * \sin(\gamma)$$

Subscript "i" will refer to the intruder drone and subscript "c" will refer to the catcher drone. The positions of the drones in a world frame are defined as $[x_i y_i z_i]$ and $[x_c y_c z_c]$ respectively. The velocity of the drones is denoted as *v*. Finally, the climb angle and the course angle of the trajectory for each drone are defined as γ and φ respectively. All these state variables can be particularized for both drones with the specific subscript.

The control of the drones will be based on position commands. Most drones autopilots currently support commands in position. The optimization comes from an adaptation of the pure pursuit methodology for tracking a target by means of the command to the drone captor of the current position of the intruder drone with a higher cruising speed of the estimated v_i in order to reach it (Equation 2), so that it always goes towards it.

$$[x_c, y_c, z_c]_{cmd} = [x_i, y_i, z_i] \qquad (2)$$

The distance between the two drones *dist(t)* can be calculated as a function of time based on the position of both drones. This distance is calculated for the successive positions of both drones assuming constant heading and climb angles for the two drones in the next moments (integrating Equation 1 for both drones). The moment in which this distance is minimum is identified as candidate to be the point where the interception will take place. Apart from that, it gives an estimation of the time required for the interception t_{int} (Equation 3).

$$dist(t) = f\left(x_i(t), y_i(t), z_i(t), x_c(t), y_c(t), z_c(t)\right)$$
$$\frac{d(dist(t))}{dt} = 0 \;\; ==> t_{int} \qquad (3)$$

In a similar way to the "Deviated pursuit guidance" methodology [14], it is proposed to command the catcher drone with the anticipated interception position taking into account the calculated time t_{int} and using the current velocity, heading and climb angle of the intruder drone. Then, the position command to the catcher drone would be estimated interception point based on the time calculated for interception:

$$[x_c y_c z_c]_{cmd} = [x_i(t_{int}) y_i(t_{int}) z_i(t_{int})] \quad (4)$$

Directing the catcher drone towards the predicted interception point with the target is called Constant Bearing (CB) Guidance in missiles field, since the interceptor trajectory must be straight (see Fig. 2). This will mean a reduction in the time needed for the interception, as well as a reduction in the distance traveled by the malicious drone, and therefore its possibility of reaching its target and causing the damage. The difference between Pure Pursuit strategy (Equation 2) and Constant Bearing (Equation 4) can also be explained with the Line Of Sight (LOS) which joins both drones. In the Constant Bearing case, the LOS is maintained parallel during the persecution and in the nominal PP it is rotating.

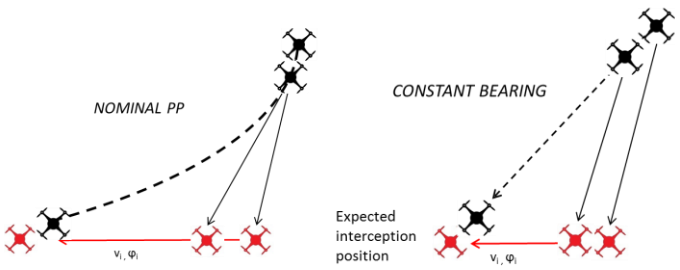

Fig. 2: Comparison between nominal approach (direct command of the target position) and the implementation of the Constant Bearing (CB)

In case of variations of course or height, the estimation of interception position is updated in real time (@ freq=100Hz which is the frequency of the controller) but there may be high deviations if these changes are abrupt. A parameter is defined to measure the abruptness of the trajectory changes of the intruder drone "*var*", during the recent previous instants. This parameter is based on the rate of change of climb and course angles in the previous moments. When this parameter is high, it is representative of significant changes in the intruder drone direction of movement, so there is high uncertainty in its destination. In this case, logical actions are considered in order to adapt the guidance strategy to the trajectory that the intruder drone is performing. These logical actions consist of commanding an estimation of the average position of the intruder drone in the previous moments. The time considered to compute this average position t_{av} depends on the amplitude of the orientation change and the proximity to the target.

$$var = f\left(\frac{\Delta\varphi_i}{\Delta t}, \frac{\Delta\gamma_i}{\Delta t}\right), \quad t_{av} = f(var, dist(t)) \quad (5)$$

Then, when the value of *var* is bigger than a threshold parameter *k,* the position command to the catcher drone is given by Equation 6. This parameter *k* is defined as maximum climb and course angle rate average in the last 5 seconds.

$$[x_c(t)]_{cmd} = \frac{\sum_{n=0}^{t_{av}*f} x_i(t - n/f)}{t_{av}}$$

$$[y_c(t)]_{cmd} = \frac{\sum_{n=0}^{t_{av}*f} y_i(t - n/f)}{t_{av}} \qquad (6)$$

$$[z_c(t)]_{cmd} = \frac{\sum_{n=0}^{t_{av}*f} z_i(t - n/f)}{t_{av}}$$

The position commanded to the catcher drone $[x_c(t), y_c(t), z_c(t)]_{cmd}$ is based on navigation NWU frame, parallel to Earth axis. In order to impose the commanded velocity to the catcher drone $v_{c,cmd}$, it is necessary to decompose the velocity vector, which joins the current position of the catcher drone to its commanded position, and impose rate of changes in each axis. In this way, using Equation 1, it is also possible to obtain the commanded climb and course angle: $\varphi_{c,cmd}$ and $\gamma_{c,cmd}$.

4 Obstacle avoidance

The algorithm described above has as output a position commanded to the capturing drone to approach and intercept the intruder drone. This position is calculated in real time and assuming that there are no obstacles in the environment, so that the drone executes the corresponding actions to move towards the commanded position at every moment. In the presence of obstacles, it is necessary to locally modify the trajectory in order to avoid interferences with them. For this purpose, a cost function (*cost(t)*) is defined (Equation 7) that takes into account the distance to the target (*dist*) and the proximity of the catcher drone d_{obs} to the obstacles. The evaluation of this function has a high computational cost, so the refresh rate is 10Hz. Through this evaluation, it will be possible to locally change the course of the catcher drone in order to avoid the present obstacles although the target position remains the same.

$$cost(t) = f\left(dist(t, t + \Delta t, \dots), d_{obs}(t, t + \Delta t, \dots)\right) \qquad (7)$$

The strategy to avoid obstacles considers a range of commanded course $\Delta\varphi_{c,cmd}$ and climb angles $\Delta\gamma_{c,cmd}$, taking the commanded $\varphi_{c,cmd}$ and $\gamma_{c,cmd}$ as references:

$$\begin{aligned} \Delta\varphi_{c,cmd} &= \varphi_{c,cmd} + \Delta\varphi \\ \Delta\gamma_{c,cmd} &= \gamma_{c,cmd} + \Delta\gamma \end{aligned} \qquad (8)$$

The projection of the future positions of the capturing drone is calculated considering the sweep in previous angles. Hence, in each iteration, this cost function *cost(t)* is evaluated taking into account the current position of both drones and the projection of said positions in the successive instants in a certain range of orientations with respect to the current course (Equation 8). Fig. 3 shows the situation of the catcher drone (in black) in front of an obstacle that must be avoided with the objective of following the intruder drone (in red) and for this it evaluates the cost function for a range of courses. The course to follow is chosen in such a way that the cost function has the lowest value (Equation 8).

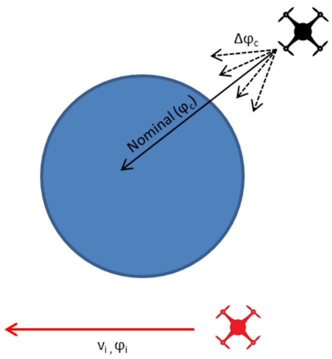

Fig. 3: Exploring different orientations to avoid obstacles

$$\varphi_{c,obs} \,/\quad \min cost(t) \quad \forall\, \varphi \in (\varphi(t) + \Delta\varphi) \tag{8}$$

As explained in section 3, where the $\varphi_{c,cmd}$ and $\gamma_{c,cmd}$ are computed, the variation of the commanded position in all its axes is limited by decomposing the maximum commanded speed according to the course and the climb angle of the aircraft and the target point. In the presence of obstacles, the computed angle $\varphi_{c,obs}$ replace $\varphi_{c,cmd}$, so the catcher drone moves according to this new angle in order to avoid the obstacles. Hence, the avoidance algorithm works by commanding changes in the course of the multirotor, but not in the position command based on the optimization strategy explained in section 3. The design and development of the presented algorithms has been validated through simulations of different scenarios and trajectories. The tool used for this purpose is Matlab-Simulink. The module architecture of the developed algorithms in the Guidance block includes the approach trajectory optimization and the obstacle avoidance strategy. The modular architecture is shown in Fig. 4.

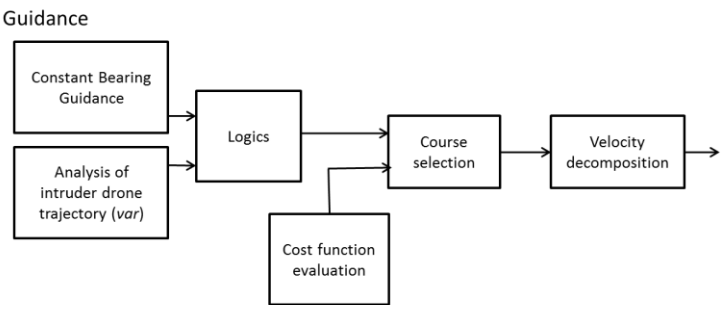

Fig. 4: Modular architecture of the algorithm

5 Results

The analysis will be centered for a random path of the intruder drone in which there are multiple changes of orientations. Then, the previous scenario will be combined with an obstacle map to evaluate the capabilities of the algorithm developed in the required environment. For the simplicity of the analysis, constant speeds for both drones will be considered and will be maintained in all simulations. The intruder drone will fly with a speed of 5 m/s and for the capturing drone to reach it, a higher speed is needed: 8 m/s. The analysis will be made according to the time required to carry out the interception. As the objective of this work is to optimize the approach path to the point of interception, this will be defined as the moment when the distance between both drones is less than a distance of 5 m.

1. Random non-straight trajectory

A random trajectory is established in left part of Fig. 5 for the intruder drone so that it changes its course without any predefined criteria. The interception time with the nominal strategy is 235,12s. On the other hand, if the optimization strategies and the logic for intelligent guidance are used, the required time for the interception is 195,26s, so there is a reduction of 16,95%.

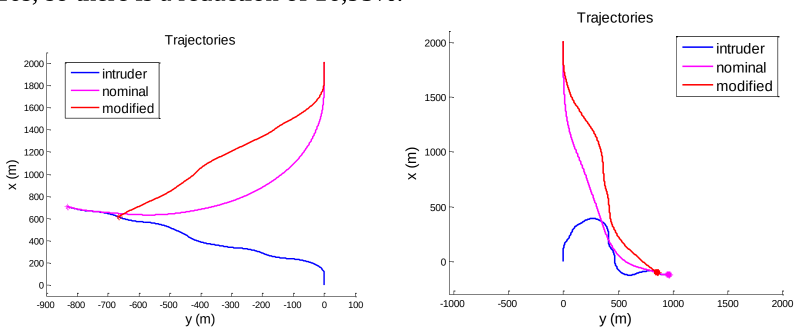

Fig. 5: Comparison between nominal and modified approach with non-straight trajectory of the intruder drone

It can be seen how the trajectory with the Constant Bearing strategy directs the capturing drone towards an estimated intercept position, shortening the trip to the encounter. The estimation of the meeting point is conditioned by the changes of orientation of the intruder drone. Another result can be shown in the right case of Fig. 5 in order to remark the difference between the considered two cases with a trajectory of the intruder drone which performs a more curvilinear trajectory. In this case the improvement in performance measured as the reduction of time needed for interception is 6,7%. From the right figure it can be extracted how the red trajectory reaches the target before the nominal case in pink.

2. Obstacles environment

In case there are obstacles in the environment where interception is desired, it will be necessary to modify the approach trajectory based on the algorithm in section 4. Below there is an example of the interception produced with the same trajectory for the intruder drone than in the previous case but with two circumferences which represent obstacles. Again, the capabilities of the two strategies analyzed in this study are compared. In the first nominal case there is a required time of interception of 225,37s, while with the Constant Bearing the time is reduced to 200,07s, so that the reduction of exposure time of the threat is 11,23%.

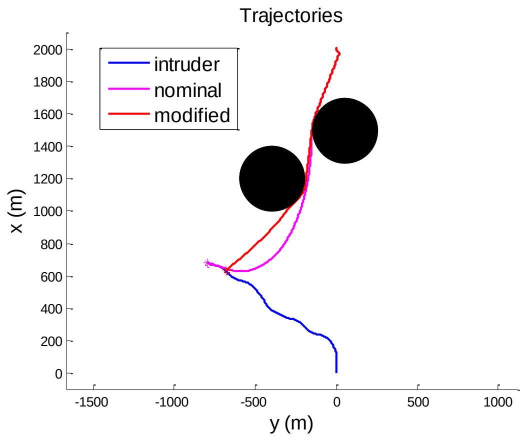

Fig. 6: Comparison between nominal and modified approach with non-straight trajectory of the intruder drone in an obstacle environment

The results shown in Fig. 6 are a specific sample of certain trajectories and environments. For the validation of the work carried out, up to 100 simulations with different trajectories for the intruder drone have been carried out and considering different obstacle maps with density similar to that shown in Fig. 6. In general, the results are satisfactory with an average reduction of exposure time in an unobstructed environment around 15%; and when there are obstacles, this improvement is reduced to roughly 10%. This is due to the fact that the replanning carried out for the avoidance of obstacles makes the optimizations of the Constant Bearing algorithm less efficient.

6 Conclusions

This paper analyzes a functionality that arouses much interest in the drone community, such as designing a guiding algorithm that allows other drones to intercept malicious drones in an environment with obstacles such as urban scenario. The main objective is to reduce the exposure time of the malicious drone and minimize the threat. The location of the rogue drone is assumed as an input from an external system.
Starting from the field of missiles guidance laws, algorithms such as “Pure pursuit” have been adapted and improved to the problem of interception of multirotors taking into account the particularities of the movement of this type of aircraft. Moreover, an obstacle environment has been considered since the case of interception of drones in urban environments is of special interest, where the danger of this threat is very significant due to the high population density. The results extracted from the simulations show the improvements produced by the proposed guidance strategies compared to traditional solutions in a scenario of aerial pursuit and interception between drones.

Next work will focus on increasing the capabilities of the algorithm presented here so that with a multitude of variable trajectory inputs of the intruder drone and maps of obstacles the time of interception is minimal. Additionally, deep work is required for the final stage of the approach trajectory in which the catcher drone must capture the intruder drone, when the relative distance is small. In addition, experimental tests are intended to have a practical validation of the results obtained in simulation. One of the proposed options is to use DJI drones, that are currently the most widespread, and to command the interception trajectories through the development kit SDK by DJI.

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