Bachelor Thesis

Active and passive escape behavior designed for groups of autonomous helicopters in dynamic environment

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May 2014

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BACHELOR PROJECT ASSIGNMENT

Student: Jan B u l u š e k

Study programme: Cybernetics and Robotics

Specialisation: Robotics

Title of Bachelor Project: Active and Passive Escape Behavior Designed for Groups of Autonomous Helicopters in Dynamic Environment

Guidelines:

The aim of this thesis is to design, implement and compare different mutations of an algorithm for MAV swarm stabilization, which is able to respond to movement of dynamic obstacles.
Work plan:

- To design and implement an extension of a bio-inspired method „Escape behavior“ [1,2] for utilization with different control inputs gained from onboard sensors of MAVs.
- To integrate the implemented system into the virtual robot experimentation platform (V-REP), which enables to realistically simulate movement of swarm of MAVs.
- To verify functionality of the algorithm modifications in the V-REP simulator and to analyze responses of the MAV swarm to motion of several dynamic obstacles (predators simultaneously “attacking” the swarm).

Bibliography/Sources:

[1] H. Min, Z. Wang: Design and analysis of Group Escape Behavior for distributed autonomous mobile robots. IEEE International Conference on Robotics and Automation (ICRA), 2011.
[2] M. Saska, J. Vakula, and L. Preucil: Swarms of micro aerial vehicles stabilized under a visual relative localization. Accepted for IEEE ICRA, 2014.
[3] T. Lee, M. Leok, N.H. McClamroch: Geometric tracking control of a quadrotor UAV on SE(3). IEEE Conference on Decision and Control (CDC), 2010.

Bachelor Project Supervisor: Ing. Martin Saska, Dr. rer. nat.

Valid until: the end of the summer semester of academic year 2014/2015

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Prague, January 10, 2014

České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra kybernetiky

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: Jan B u l u š e k

Studijní program: Kybernetika a robotika (bakalářský)

Obor: Robotika

Název tématu: Aktivní a pasivní únikové chování skupiny autonomních helikoptér v dynamickém prostředí

Pokyny pro vypracování:

Student v bakalářské práci navrhne, implementuje a porovná různé varianty algoritmu skupinového chování MAV roje reagujícího na pohyb dynamických překážek.
Plán prací:

- Navrhnout a implementovat rozšíření přírodou inspirované metody „Escape behavior“ [1,2] pro použití s různými řídícími vstupy z palubních senzorů helikoptér.
- Integrovat implementovaný systém do simulačního prostředí V-REP, které umožňuje realisticky simulovat let roje.
- Ověřit a porovnat funkci jednotlivých variant algoritmu v simulátoru V-REP a analyzovat reakce roje na pohyb několika dynamických překážek (predátorů současně „útočících“ na roj).

Seznam odborné literatury:

[1] H. Min, Z. Wang: Design and analysis of Group Escape Behavior for distributed autonomous mobile robots. IEEE International Conference on Robotics and Automation (ICRA), 2011.
[2] M. Saska, J. Vakula, and L. Preucil: Swarms of micro aerial vehicles stabilized under a visual relative localization. Accepted for IEEE ICRA, 2014.
[3] T. Lee, M. Leok, N.H. McClamroch: Geometric tracking control of a quadrotor UAV on SE(3). IEEE Conference on Decision and Control (CDC), 2010.

Vedoucí bakalářské práce: Ing. Martin Saska, Dr. rer. nat.

Platnost zadání: do konce letního semestru 2014/2015

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V Praze dne 10. 1. 2014

Acknowledgement

I would like to thank all the people who helped me with my bachelor thesis in any way. Special thanks to my family for support and encouraging and to my thesis supervisor Dr. Saska for leading me.

Declaration

I declare that I worked out the presented thesis independently and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic thesis.

In Prague on May 22, 2014 ....

Abstract

Tento dokument se zabývá návrhem, implementací, testováním a porovnáním algoritmů únikového chování navržených pro roje MAV (Micro Aerial Vehicle) — bezpilotních helikoptér. Tento algoritmus snižuje nebezpečí kolizí roje s dynamickými překážkami. Algoritmus únikového chování uvedený v [1], navržený pro pozemní roboty, je zde analyzován a upraven pro použití v MAV a je dále upraven podle druhu a dosahu palubních senzorů helikoptér. Funkčnost algoritmu a jeho připravenost pro reálné použití je ověřena simulací v robotické platformě V-REP, která umožňuje simulaci realistických letových podmínek. Výsledky simulací jsou porovnány a dále analyzovány.

Klíčová slova

Autonomní helikoptéry; metody inspirované přírodou; roje

Abstract

This document deals with the design, implementation, testing and comparing the escape behavior algorithms designed for swarms of MAVs (Micro Aerial Vehicles) — unmanned helicopters. This algorithm decreases the possibility of collision of a swarm with dynamic obstacles. Escape behavior algorithm presented in [1] designed for ground robots is analyzed and the algorithm is modified for use in MAVs with further modifications depending on type and range of onboard sensors of MAVs. The proper functionality and readiness for real use of designed algorithms is verified by simulations in V-REP robotic platform, which enables to simulate realistic flight conditions. Simulation results are further analyzed and compared.

Keywords

Micro aerial vehicles (MAV); bio-inspired methods; swarms

Contents

1. Introduction

The main goal of this Bachelor thesis is to design, implement and compare different mutations of an algorithm for MAV (Micro aerial vehicle) swarm stabilization — algorithm of escape behavior, which is able to respond to movement of dynamic obstacles. The algorithm is later tested on virtual robot experimentation platform (V-REP) to verify its proper functionality.

The motivation of this thesis is to control a group of MAVs in a similar way to natural behavior of groups of animals like fishes or birds, to make their movement natural and thus most efficient so far. If one of MAVs discovers potentially dangerous object (a „predator"), the swarm as a whole has to fly away into safe distance and regroup there.

In this chapter, I am going to introduce the basic concepts and objects of this thesis. The second chapter describes and explains the escape behavior algorithm as presented in [1]. The third chapter shows the modifications made on that algorithm in order to adjust it for use in MAVs as well as multiple approaches designed for various onboard sensors of MAV that were created for this thesis. The fourth chapter presents the experimental results and their further analysis.

1.1. MAV

Figure 1. Parrot AR.Drone 2.0

MAV abbreviation stands for „Micro Aerial Vehicle", which is a subclass of UAVs (Unmanned Aerial Vehicles). As the name suggests, it is an aircraft limited in its size controlled by human remotely or with a certain autonomy.

MAVs can be of various forms and construction, but the best for our purposes is a type called quadcopter or quadrotor as shown in Figure 1. It is a multicopter that uses four rotors placed in vertexes of an imaginary square, two of them rotating clockwise and the other two counter-clockwise. The motion control is achieved via controlling the rotation speed and thus the thrust generated by each of the rotors.

The major advantages of quadrotor over the 'regular' aircraft are these:

- Lacking of linkages and small parts necessary to adjust the rotor blade pitch angle, which are common for regular helicopters. Quadrotor uses all four rotors pitch-fixed; this renders the construction and maintenance of the aircraft easier.
- In the opposite of comparably-scaled helicopters, the quadrotors are equipped with rotors with smaller diameter. As a result these rotors possess less kinetic energy further resulting in reducing the possible damage caused by them hitting any other objects.
- It is capable of VTOL (Vertical Take-Off and Landing).
- Quadrotors are relatively easy to stabilize and control.

1.2. Escape behavior

The designed algorithm for MAVs control is based on flocking behavior. This control algorithm is inspired by behavior of individuals in large animal groups like insect swarms or fish/bird flocks. Every individual in such group is a separate, independent entity, who acts upon its own intentions, and yet the group of such individuals with decentralized control laws appears to move like a greater organism with centralized control.

By the term of 'Escape behavior' of a swarm we understand its reaction to the presence of a predator. When one swarm member discovers a predator, it starts its escape behavior, which affects other members in a way that the information about the dangerous object spreads quickly across the entire swarm. As a result the escape behavior affects the swarm as a whole and this transformation is significantly faster than 'ordinary' behavior of the swarm, regardless of its size.

As [1] suggests, to mimic that kind of behavior we will allow the individual to transit between the following three states:

- **Active mode** — an individual has strong reaction to the presence of a predator and suppresses his relations to the other individuals.
- **Passive mode** — an individual does not detect a predator directly, but detects uncommon movement of his neighbors, and adjusts his behavior accordingly.
- **Normal mode** — an individual does not detect anything unusual.

If successful, this algorithm enables to achieve real-time control without the need for any precalculations; it also does not require any form of central control, since every individual „thinks“ for himself. The main problem of creating such an algorithm is the relative difficulty of balancing it correctly.

1.3. V-REP

The algorithm developed in this thesis will be verified in V-REP (Virtual robot experimentation platform), a simulator developed by Coppelia Robotics, which provides an advanced testing environment. The V-REP environment has built-in models of various robots with possibility to create your own, as well as functions for measuring various attributes of these robots. V-REP environment also takes in account certain physical laws like gravity, inertia or friction, which enables to truthfully verify applicability for deployment of MAVs in the real world.

2. Escape behavior in 2D

In this section the control equations for the flock and escape behavior designed for UGVs (Unmanned ground vehicles), presented in [1] are described and explained. The Flocking behavior itself is not part of work presented in this thesis, but its understanding is essential for further explanation of escape behavior mechanism.

2.1. Flocking behavior equations

The following Newton-Euler dynamic equations describe the mechanism of the flocking behavior for i-th individual as follows:

$$m_i \frac{d\vec{v_i}}{dt} = \vec{F_P} + \sum_{j(j \neq i)} e_{ij} \vec{F_{KH_{ij}}} - \gamma \vec{v_i}; \tag{1}$$

$$I_i \frac{d^2 \alpha_i}{dt^2} = \sum_{j(j \neq i)} (e_{c\_ij} M_{c\_ij} + e_{ij} M_{d\_ij}) + M_{rb\_i} - D_m \frac{d\alpha_i}{dt}. \tag{2}$$

The Newton equation (1) describes a motion effect of the sum of forces on the right side of equation on i-th individual of the swarm, while the Euler equation (2) describes a rotation effect of the sum of moments on the right side. The quantities m_i, I_i, $\vec{v_i}$ and α_i denote the mass, inertia, velocity and the angle of heading direction of the i-th individual; the forces and moments on the right side are the result of interactions between the individuals. Specifically:

- $\vec{F_P}$ denotes the heading direction component of the force created by the relative positions and headings of other individuals in the swarm;
- $\vec{F_{KH_{ij}}}$ denotes the heading direction component of the repulsive force of nearby individuals in the swarm in order to maintain a secure distance between them.

The vertical direction components of forces mentioned above are transformed into moments:

- M_{c_ij} denotes the moment created by heading directions of nearby individuals in the swarm;
- M_{d_ij} denotes the moment created by the repulsive force of nearby individuals in the swarm.

The moment M_{rb_i} is not derived from the forces above. It denotes the moment created by the repulsive force of detected obstacle.

Coefficients e_{ij} and e_{c_ij} are distance functions, which represent the sensory range limitations of an individual. γ and D_m denote the viscous coefficients of the environment in which the swarm is placed.

2.2. Escape behavior equations

In order to make the flocking behavior more dynamic, the Newton-Euler equations presented in (1), (2) are modified in this way:

$$m_i \frac{d\vec{v_i}}{dt} = \vec{F_P} + \vec{F_e} + \sum_{j(j \neq i)} e_{ij} F_{\vec{KH_{ij}}} - \gamma \vec{v}; \tag{3}$$

$$I_i \frac{d^2\alpha_i}{dt^2} = \sum_{j(j \neq i)} (e_{c\_ij}(M_{c\_ij} + M_{ecp\_ij}) + e_{ij} M_{d\_ij}) + M_{rb\_i} + M_{re\_i} - D_m \frac{d\alpha_i}{dt}. \tag{4}$$

There are new elements in these equations:

- $\vec{F_e}$ denotes the extra propulsion force, which appears in case the predator is discovered;
- M_{ecp_ij} denotes the moment as a product of a stronger interaction force;
- M_{re_i}, which denotes the moment created by the presence of the predator.

The M_{ecp_ij} moment can be further described as

$$M_{ecp\_ij} = K_e \alpha_{ji} + C_e \frac{d\alpha_{ji}}{dt}. \tag{5}$$

This formula is basically the same as for the normal interaction force, but the spring and damper coefficients K_e, C_e are greater than K_c, C_c used to generate M_{c_ij}. This difference enables the individual in case of emergency to react more intensively and faster to movement of the other individuals. This is important because of the swarm „inertia“. The regular interaction force is too weak to handle significant velocity changes, which, without the aid of the secondary moment, would result in a slow and weak reaction. In the case of an emergency it would be highly undesirable.

The moment M_{re_i} can be prescribed as follows:

$$M_{re\_i} = sgn(\psi_i) F_m \cos(\psi_i/2). \tag{6}$$

In this equation, ψ_i denotes the angle between the moving direction of an individual and the line connecting the individual with the predator. F_m represents the repulsion force. Cosine function used in this equation renders the moment zero in case the individual is heading directly away from the predator and maximizes it in case it is heading directly towards it.

In order to make the escape from a predator succesful, we have to redistribute these elements for all three states of the individual behavior mentioned before. The states are listed in Table 1.

	Active mode	Passive mode	Normal mode
M_{c_ij}	0	0	$K_t\alpha_{ji} + C_t\frac{d\alpha_{ji}}{dt}$
M_{d_ij}	0	0	$sgn(\alpha_i - \phi_i)k_{F-M}F_{K\perp_{ij}}$
M_{ecp_ij}	0	$K_e\alpha_{ji} + C_e\frac{d\alpha_{ji}}{dt}$	0
M_{re_i}	$sgn(\psi_i)F_m\cos(\psi_i/2)$	0	0
$\vec{F_e}$	F_e	0	0

Table 1. States description.

The individual controlled in the Active mode carries the information about the observed predator, therefore it is allowed to move independently on the other individuals. The additional force $\vec{F_e}$ also allows this individual to move faster, since we want to get away from the predator as quickly as possible.

The individuals in Passive mode, with their enhanced interaction force, are meant to follow the other individuals closely, including the fast-moving one in Active mode. This is the key element of the desired swarm escape behavior. The entire group should follow the active swarm member away from the predator. If the Passive mode is spread quickly enough throughout the swarm, the whole swarm changes its position remarkably faster than in Normal mode.

Swarm members in Normal mode are simply maintaining their standard flocking behavior as described before.

The important aspect to mention is the mechanism of transitions between these modes. As presented in [1], one of the possibilities for the i-th individual is to measure the angular velocity ($\dot{\alpha_j}$) of all other individuals:

if *individual is in Normal mode* **then**
  for j = *all other individuals indexes* **do**
    if $|\dot{\alpha_j}| > \dot{\alpha_t}$ *and* $|\dot{\alpha_j}| > |\dot{\alpha_i}|$ **then**
      switch to Passive mode;
    end
    if $|\dot{\alpha_j}| > \dot{\alpha_t}$ *and* $|\dot{\alpha_j}| < |\dot{\alpha_i}|$ **then**
      switch to Active mode;
    end
  end
else
  $t_{delay} = t_{delay} + 1$;
  possibility_to_change = 1;
  for j = *all other individuals indexes* **do**
    if $|\dot{\alpha_j} - \dot{\alpha_i}| > \dot{\alpha_{t\_s}}$ *or* $t_{delay} < T_{delay-max}$ **then**
      possibility_to_change = 0;
    end
  end
  if *possibility_to_change == 1* **then**
    switch to Normal mode;
  end
end

Algorithm 1: State behavior transitions mechanism.

There are the following elements in Algorithm 1:

- $\dot{\alpha_t}$ denotes a threshold value of an angular velocity greater than angular velocities possibly reached in a normal mode;
- $\alpha\dot{t\_s}$ denotes a threshold value of maximal angular velocities difference between two individuals;
- t_{delay} is a counting time which counts time since the mode change;
- $T_{delay-max}$ is a minimal threshold value for t_{delay}.

In other words, if an individual detects that anyone in the swarm changes its direction too quickly than it is allowed in Normal mode, the escape mode is triggered. The exact type of escape mode depends on who is making such a movement — if it is the individual itself, then it is likely to be affected by predatory repulsive forces and triggers an Active mode. If it is someone else, then it gets on higher alert by triggering a Passive mode. These modes are clearly triggered simultaneously in all the individuals, and they are stopped simultaneously after a certain time has left and the swarm members no longer produce any rash movement.

3. Escape Behavior in 3D

In this chapter, the escape behavior algorithm designed for MAVs is described. It is based on the algorithm described in chapter 2 presented in details in [1]. In this chapter we focus on major changes made in order to make the algorithm suitable for 3D environment. To achieve this goal, multiple approaches not included in [1] had to be made, including the Passive mode specifications and the state transition mechanism.

The algorithm presented in [1] and described in previous chapter has to be rewritten for the 3D environment, which presents certain distinctions. An object placed in such an environment gains six degrees of freedom instead of three in 2D. Apart from the third dimension it also gains the ability to rotate around two additional axes, which makes certain calculations relatively more difficult.

There should be also emphasized the distinctions in movement between UGVs, which the algorithm in [1] was originally developed for, and MAVs that are used in the proposed method. While UGV can move in its heading direction only, quadrotor does not suffer from the same limitations. It does not need to change its heading direction in order to move along a different path. In effect, we have to modify some of the previous calculations accordingly.

First of all, since the continuous controlling system is not possible to fully transfer into its digital form, it was transformed into a discrete one. At the beginning of each time step the values of position, velocity, angular velocity etc. of each quadrotor and obstacle are saved and stored. Then every individual takes the calculations based on these values to determine his desired position, velocity, angular velocity etc. for the next time step. This desired position is determined by:

- Relative positions of the other individuals;
- Relative positions of obstacles;
- Movement patterns of the other individuals;
- Relative positions of predators.

This desired position creates an attractive force for a quadrotor, which is further transformed into moments generated by rotor velocities by inner regulator. This regulator should have been designed upon the [2].

3.1. Normal mode

The 3D flocking algorithm, which acts as the Normal mode, was presented in [3]. In this section it is briefly described and explained similarly to the previous chapter.

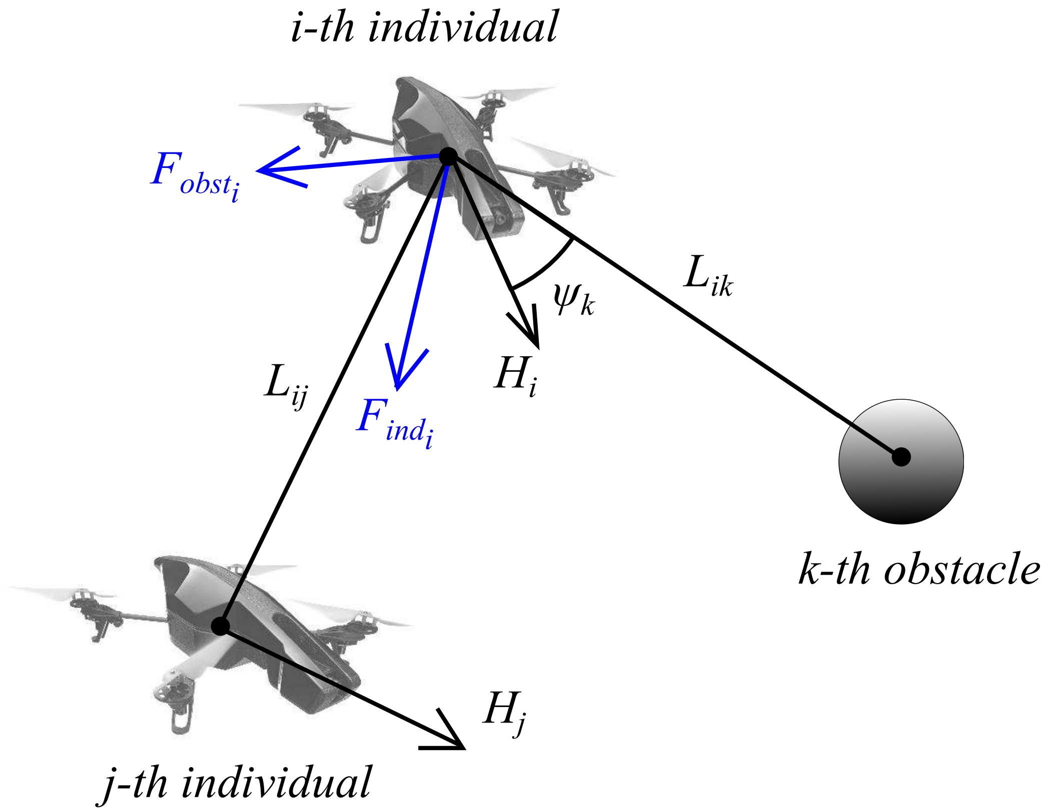

Figure 2. Interactions in the Normal mode.

3.1.1. Other individuals interaction

In order to maintain distances between the individuals and the swarm coherence, we transform the force $\vec{F_{KH_{ij}}}$ mentioned in (1) into the summation:

$$\vec{F_{ind_i}} = \sum_{j(j \neq i)} e_{ij} \vec{F_{ind_{ij}}}, \tag{7}$$

where e_{ij} denotes the distance function which can be described as

$$e_{ij} = \frac{1}{e^{a|\vec{L_{ij}}|-b} + c} + \frac{1}{e^{0.5a|\vec{L_{ij}}|-b} + c}. \tag{8}$$

In this function, $\vec{L_{ij}}$ denotes the distance between i-th and j-th individual; a, b and c are constants that are experimentally determined as shown in chapter 4.

$\vec{F_{ind_{ij}}}$ denotes the interactive force between i-th and j-th individual and can be described as

$$\vec{F_{ind_{ij}}} = K_d(|\vec{L_{ij}}| - L_d)\vec{L_{ij}} + D_d \frac{d\vec{L_{ij}}}{dt}, \tag{9}$$

which is a spring-damper model designed to maintain the desired distance L_d.

3.1.2. Obstacle interaction

Obstacle interaction is presented in (2) and (4) via the moment M_{rb_i}. As stated in the beginning of this chapter, this moment was transformed into force prescribed as follows:

$$\vec{F_{obst_i}} = \sum_k W_d \cdot \delta \cdot b_o \cdot e^{a_o |\vec{L_{ik}}|} \cdot \vec{F_{obst_k}} \tag{10}$$

This force is applied to i-th individual and it is computed from the positions of obstacles indexed with k. W_d, a_o and b_o are experimentally determined constants, $|\vec{L_{ik}}|$ denotes the distance vector between i-th individual and k-th obstacle. δ presents the dependence function designed as

$$\delta = 1 + d_o \cos(\Psi_k). \tag{11}$$

In this function, d_o denotes a constant and Ψ_k an angle between the movement direction of a quadrotor and the line connecting the center of MAV with the k-th obstacle.

The element $\vec{F_{obst_k}}$ in (10) denotes the normalized vector perpendicular to the current individual's movement direction and heading away from the obstacle. The perpendicularity is ensured by crossproducts:

$$\vec{F'_{obst_k}} = (\vec{H_i} \times \vec{L_{ik}}) \times \vec{H_i}, \tag{12}$$

$$\vec{F_{obst_k}} = \frac{\vec{F'_{obst_k}}}{|\vec{F'_{obst_k}}|}, \tag{13}$$

where $\vec{H_i}$ denotes the heading direction of i-th individual.

3.2. Active mode

The predatory repulsive force as described was altered due its transformation into third dimension. The main forces operating are these:

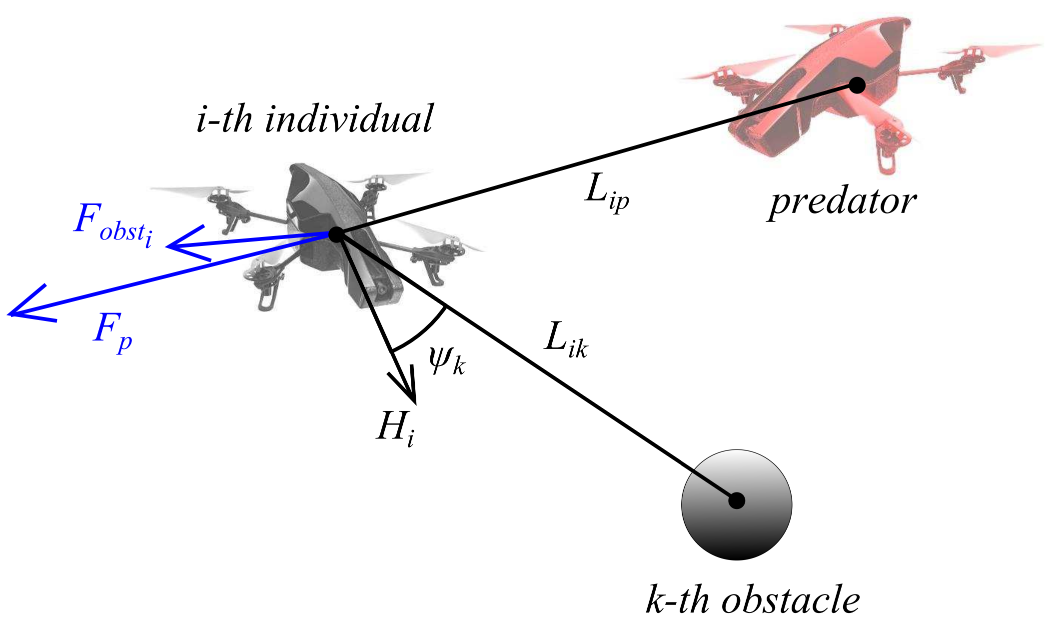

Figure 3. Interactions in the Active mode.

Naturally, it is not desirable to let the individual maneuvering around the predator. Each MAV should simply move away from it; the equation (6) is then simplified into

$$\vec{F_p} = \frac{1}{e^{a|\vec{L_{ip}}|+b} + c} \cdot \frac{|\vec{L_{ip}}|}{|\vec{L_{ip}}|}, \tag{14}$$

where $\vec{L_{ip}}$ represents the vector from the predator to an individual and a, b, c denote experimentally determined constant values to scale the function.

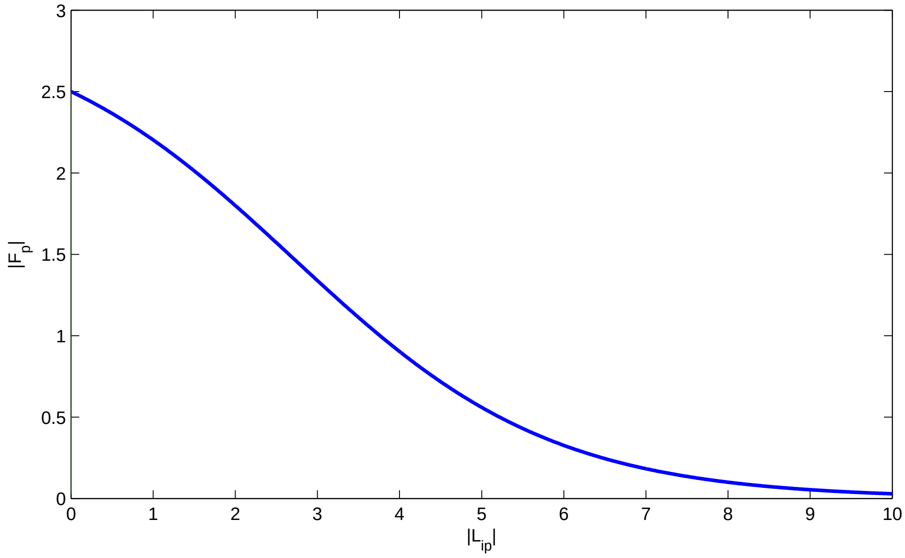

Figure 4. Predatory repulsion force for $a = 0,6330$; $b = -2,7935$; $c = 0,3389$.

If we assume that the quadrotor carries sensors being able of detecting the predator everywhere in the workplace, the repulsive force could be evaluated during the whole Active mode. If we assume however that the sensory range is limited, then the equation (14) serves merely to set the initial state when the individual reaches the detection distance. Outside the range, the repulsive force is computed as follows:

$$\vec{F_{p_t}} = (1 - 0,9\frac{t_s}{T_{delay-max}})\vec{F_{p_{t-1}}}, \tag{15}$$

where t_s denotes the length of time step. F_{p_t} and $F_{p_{t-1}}$ represent the repulsive force calculated in this and previous time step respectively. Meaning of the $T_{delay-max}$ is tightly connected to states transitions section (3.4).

In order to maximize the escaping effect, it is necessary to surpass the relations to other individuals completely. Thus the force mentioned in (7) is set to zero for an individual in Active mode.

The obstacle interaction described by (10) remains untouched in the proposed Active mode. However, it is reasonable to make this interaction stronger if we expect the traveling speed of escaping individuals too high to avoid the obstacles otherwise.

3.3. Passive mode

In order to reduce the inertia of a swarm, it is necessary to strengthen the relations between the individuals in a way that they would react more intensively to the movement of nearby individuals.

The force displayed by equation (7), which describes the force generated by positions and movement of nearby individuals, is not sufficient for our case. The distance function of its components described in (8) renders the resulting force rather repulsive than attracting. To solve this issue, two new prescriptions of the individual interaction force were created for this thesis.

However, we can assume that the individuals that reach this state would be moving considerably faster than in Normal mode. In order to prevent the collisions in that speed it is reasonable to make this repulsive force greater than in Normal mode by properly adjusting K_d and D_d constants in (9).

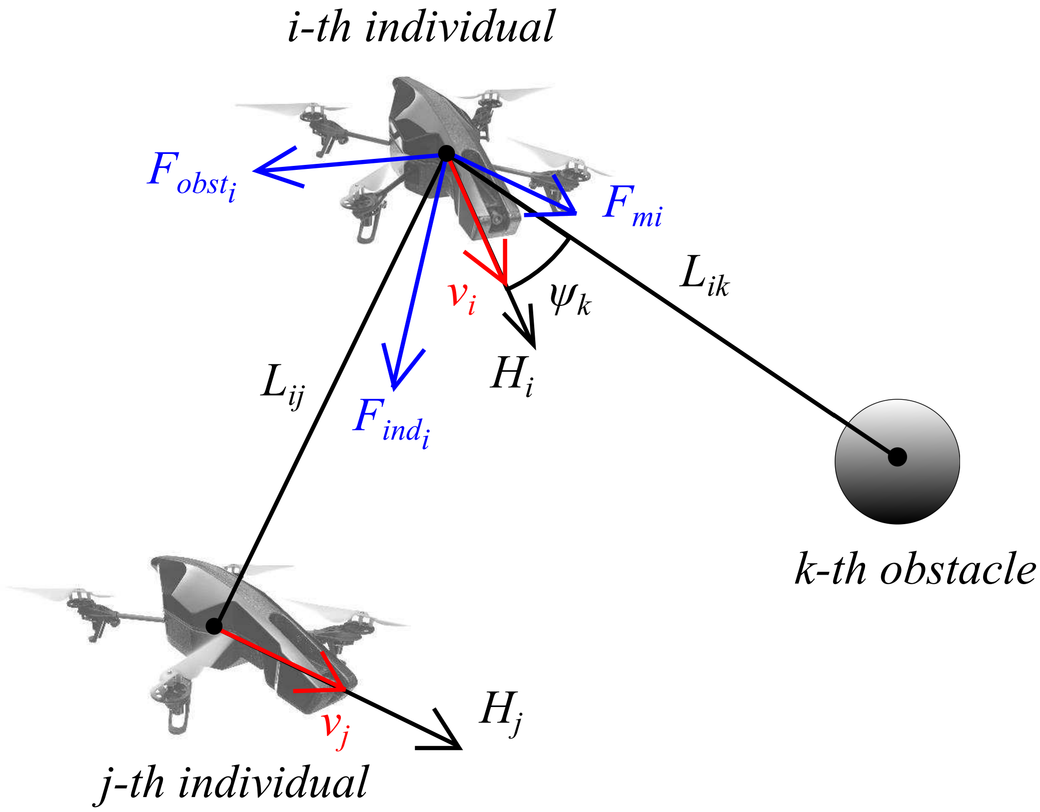

Figure 5. Interactions in the Passive mode.

3.3.1. Mimicking nearby movement patterns

To generate necessary attracting force, this new element is added into (7):

$$\vec{F_{ind_i}} = \sum_{j(j \neq i)} (e_{ij}\vec{F_{ind_{ij}}} + e_{c\_ij}\vec{F_{mi}}), \tag{16}$$

where $\vec{F_{ind_{ij}}}$ represents the stronger individual repulsive force with K_d, D_d coefficients and $\vec{F_{mi}}$ denoted the neighbor velocity mimicking force:

$$\vec{F_{mi}} = K_m\vec{v_j} + C_m\frac{d\vec{v_j}}{dt}. \tag{17}$$

K_m, C_m are constants of spring-damper. e_{c_ij} coefficient represents another distance function prescribed this way:

$$e_{c\_ij} = \frac{1}{e^{a|\vec{L_{ij}}|-b} + c}. \tag{18}$$

Purpose of this distance function is not only to simulate the sensory range of quadrotor, but also to restrict the effect of the mimicking force F_{mi}. For this reason it was decided to set the constants a, b, c in the way the e_{c_ij} function would have the following process:

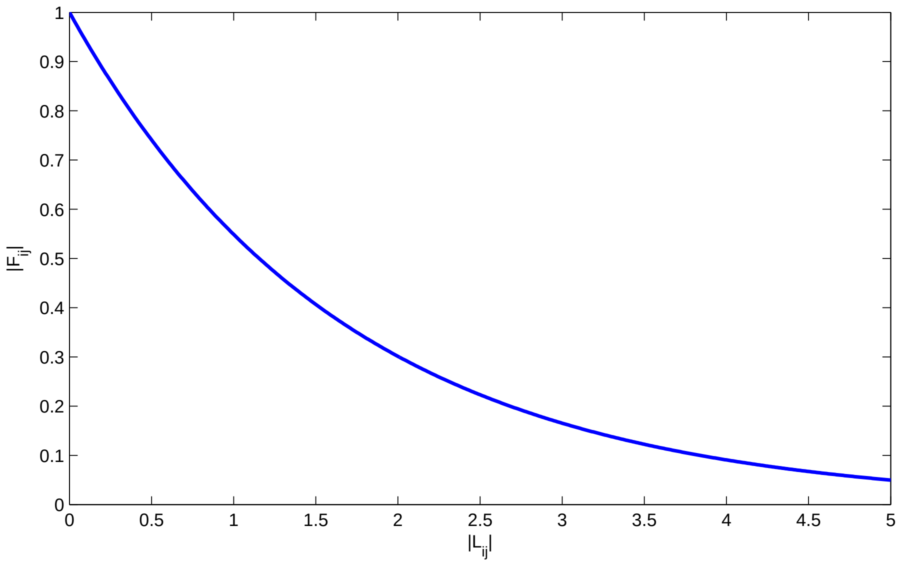

Figure 6. Mimicking force intensity for $a = 0,6$; $b = 0$; $c = 0$.

This mimicking force is sufficient to enhance the attraction to the other individuals in swarm. The biggest disadvantage of this method is the cumulation of MAVs and subsequently multiplying the requested velocity leading the swarm into disarray (similar to a tube effect of a fluid flowing through the smaller space). Because of this instability, a new approach has been made.

3.3.2. Mimicking strongest movement patterns

The whole approach is based on the fact that during the escape maneuvers the swarm temporarily transforms into leader-follower system with the individual(s) in the Active mode in the role of leader(s) and everyone else as followers. This leads us to an idea of surpassing the initiative of the individuals in Passive mode; none of them shall move at greater speed than the individual in the Active mode.

Also, it is necessary for each individual to memorize the MAV that had caused their state transition into the Passive mode and try to mimic solely its movement patterns (this memorized MAV is not necessarily in the Active mode). Very important aspect is that there should be limitations of the follower's velocity, so that they can never move faster than their leader. This leads into tree-like structure with the fastest-moving individual in the Active mode as a root.

If the MAV the individual is locked onto reaches out of its sensory range, the fastest moving one is chosen as the next one to follow. As the fastest one it is most probable to be in the Active or Passive mode.

After picking the leader, the individual interaction is calculated upon these equations:

$$\vec{F_{ind_i}} = \sum_{j(j \neq i)} e_{ij} \vec{F_{ind_{ij}}} + \vec{F_{mi}}, \tag{19}$$

$$\vec{F_{mi}} = K_m \vec{v_k} + C_m \frac{d\vec{v_k}}{dt}. \tag{20}$$

In the opposite to (16), we do not need any distance function like e_{c_ij} since we want to mimic the movement of k-th individual precisely (k denotes the index of the individual we are currently locked onto).

IF-ELSE structure bellow this computation ensures that if the resulting force proves to be greater than leader's, it is further reduced. It also ensures that in case the leader leaves individual's sensory range, the individual continues on its current course while slowing down.

3.4. State transitions

As mentioned in the previous chapter, there are certain distinctions between the movement of UGVs used in [1] and the movement of MAVs which are used in this thesis. The decision tree presented in Algorithm 1 is based on angular velocity calculations. On the contrary to 2D, the angular velocity measured in 3D is a vector instead of scalar. In addition, angular velocity of a quadrotor and does not show only the moving direction change, but also its velocity change. Furthermore, it is not required for quadrotor to face the moving direction at all.

Based on these facts it is no longer possible to distribute the states in a way suggested in Algorithm 1. To solve this issue, the following distribution methods were developed for this thesis.

3.4.1. Normal to active mode transition

If we assume that an individual can detect the predator in arbitrary distance, we should set up the critical distance we allow the predator to move in. If $|\vec{L_{ip}}|$ is shorter than the required distance L_s, we start computing and applying the force described in (14).

If we take the more realistic assumption that there is a limited range of sensors carried by quadrotor, the detection range is set as the critical distance in which the predator is allowed to move. The force (14) is being evaluated only in case the distance L_{ip} is lesser than the required detection distance L_s. If an individual reaches out of the detection distance, the lowered value of this force from the previous time step is used instead as mentioned in (15).

It is also natural to assume that if an individual is able to adjust its movement by presence of a predator, it is also able to detect and thus recognize it. If so, there is no need to measure angular velocities to determine which individual is the one spreading the information about the dangerous object. If an individual detects the predator directly, we trigger his Active mode immediately. We also start counting the time as suggested in (Algorithm 1).

3.4.2. Normal to passive mode transition

Since measuring the angular velocities no longer provides us with the information about the change of movement direction of an individual as stated in the beginning of this section, the new methods had to be developed.

The angular velocity measurement is still possible, but the information we get from it is different — since the quadrotor does not change its facing direction, angular velocity can be taken as tilt intensity of quadrotor's body. This can be interpreted as a sudden change in quadrotor's movement, either its velocity or direction change, or possibly both. Active mode patterns we are looking for include apart from sudden direction change, as mentioned in [1] considerably greater velocity than it is common in the Normal mode. Thus, we can use the angular velocity measurement to detect this uncommon behavior, but in slightly different way than suggested.

To detect this kind of behavior, we simply compare the norm of angular velocity vector of a neighbor individual within the sensory range to a predefined threshold value. If that vector exceeds this threshold, the Passive mode is triggered in the individual taking the measurement.

Another way to determine the Passive escape mode trigger would be to **analyze velocity vectors in the following time steps**.

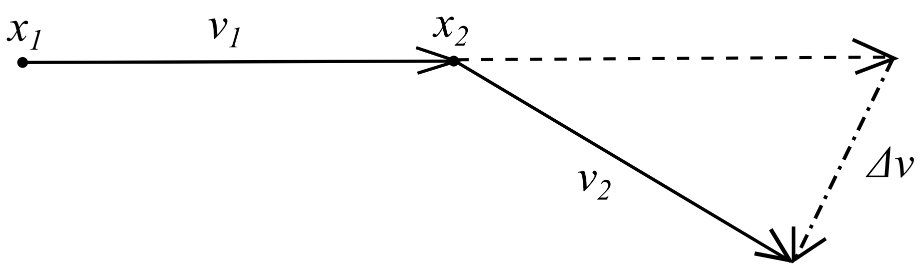

Figure 7. Velocity vector analysis

In Figure 7 x_1 and v_1 represent the position and velocity of an individual in first time step, while x_2, v_2 show the respective parameters in the next time step. Δv represents the variance from the original course and apparently it is a key to evaluate the movement change of an individual. The following function was designed to evaluate this variance:

$$\delta = \frac{|\vec{\Delta v_1}|}{max(|\vec{v_1}|,\ |\vec{v_2}|)} = \frac{|\vec{v_2} - \vec{v_1}|}{max(|\vec{v_1}|,\ |\vec{v_2}|)} \tag{21}$$

Term max in (21) means the greater value from the two enlisted possibilities. This function met the expectations only on a limited range, however and therefore a better prescription is needed. The following function was created to solve this problem:

$$\delta = \frac{|\vec{\Delta v_1}|}{|\vec{v_1}| + |\vec{v_2}|} = \frac{|\vec{v_2} - \vec{v_1}|}{|\vec{v_1}| + |\vec{v_2}|} \tag{22}$$

The value of δ ranges between zero and one (zero for minimal change, one for the maximal) depending on the velocity vector change — both direction change and accelerating/decelerating. It does not depend on the exact direction of the change (turning left or right) and on the order of $\vec{v_1}$, $\vec{v_2}$ vectors (acceleration and deceleration with the same ratio). It is also not affected by absolute values of velocity vectors (we get the same result if doubling the initial vector regardless of its size).

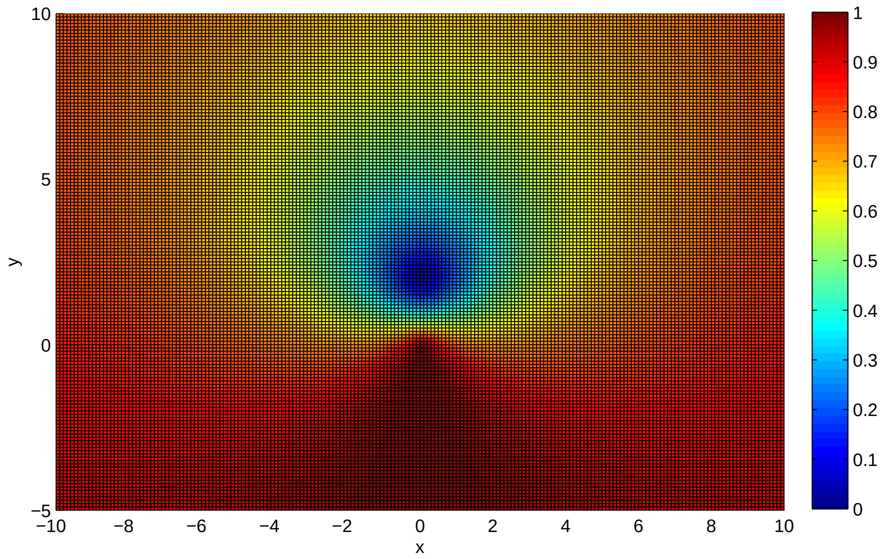

Figure 8. Delta function results for initial vector $\vec{v_1} = [0\ 2]'$.

Finally, to evaluate the activation of the Passive mode we set up a threshold value for this function. An individual evaluates this function for every neighbor in its sensory range. It compares the result with the predefined threshold value, and triggers the Passive mode in case the result is greater than the threshold.

The displayed method is more suitable for experiments with real quadrotors than the first one, because the measurement of angular velocity vector is more challenging than the measurement of moving velocity vector.

Both of these methods are capable of triggering the Passive mode even during the minor movement like stabilization process. Because of that, we need to create the velocity restriction — both of these methods would be evaluated only for the individuals moving faster than a predefined threshold value.

Regardless of the method we use to trigger the Passive mode, when this mode is activated, we also start counting the time as suggested in Algorithm 1.

3.4.3. Active and passive to normal mode transition

For the reasons mentioned before, we can not use the angular velocities difference to determine whether the swarm members are moving rashly or not, as suggested in Algorithm 1. In fact, it is difficult to determine this 'state' in any way. Because of that, it was decided to cross out this condition from the state transition mechanism. The Active and passive mode duration now depends on $T_{delay-max}$ constant only. After this predefined amount of time passes, an individual returns to the Normal mode, expecting the threat is over.

4. V-REP implementation and experimental results

In this chapter, the implementation details of developed methods and experimental results for each method are presented.

4.1. Implementation

The escape behavior algorithm was written in MATLAB. The source code of this algorithm is presented on the enclosed CD. The V-REP offers the use of the remote API interface, thus the simulation was taking place in V-REP while the MATLAB was computing the actions for each quadrotor based on the interactions displayed in the previous chapter.

For experiments in the V-REP simulator, it was decided to substitute the regulator presented in [2] by the one predefined in quadrotor model in V-REP. The V-REP model works without necessity to identifying parameters that are required by the low-level regulator in [2]. Also, the V-REP regulator appeared to be suitable with the proposed algorithms.

Constant	Appearance	Description	Value
a b c	(8)	Shaping the distance function.	6.5 3.9 0.6
K_d D_d	(9)	Spring-damper constants.	0.5 0.1
L_d	(9)	Desired distance between individuals.	1.3
W_d	(10)	Scale factor.	0.3
a_0 b_0	(10)	Shaping the distance function.	-3 100
d_0	(11)	Scaling the elevation.	1
a b c	(14)	Shaping the distance function.	0.6330 -2.7953 0.3389
$T_{delay-max}$	(15)	Amount of time necessary to exit the escape behavior.	3
K_m C_m	(17, 20)	Spring-damper constants.	0.4 0.01

Table 2. Constants description.

Various constants required for presented algorithms are presented in Table 2.

4.2. Experimental results

In each experiment, the experimental system consists of the objects shown in Figure 9. There is a swarm of 9 quadrotors in the 3 × 3 square formation, a predator approaching the swarm and several obstacles.

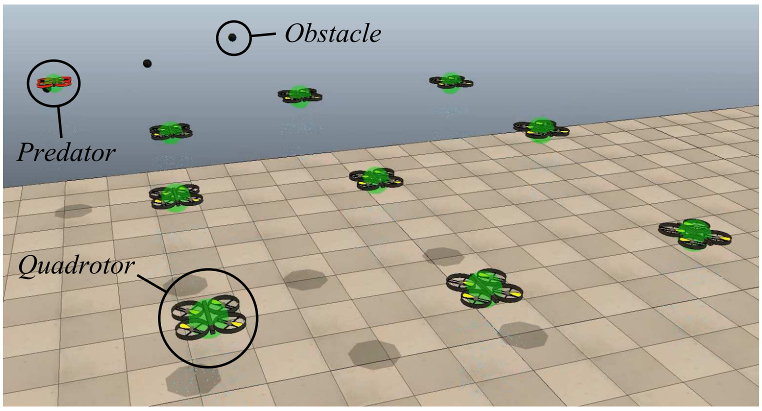

Figure 9. Experiment initial conditions.

In each experiment the two described methods of state transitions are compared: angular velocities vector analysis and velocity vector analysis. For further use, we tag the angular velocities vector analysis method displayed in 3.3.1 as **Method A**. Similarly, we tag the velocity vector analysis method displayed in 3.3.2 as **Method B**.

4.2.1. Experiment 1 — Infinite sensory range, without obstacles

In the first experiment, we let the sensory range of quadrotors to be infinite and we remove the obstacles from the path of swarm. In effect, the escape behavior is triggered simultaneously in the whole swarm and the escape maneuvers are conducted smoothly, regardless of the state transition methods as shown in Figure 10, Figure 11 and Figure 12.

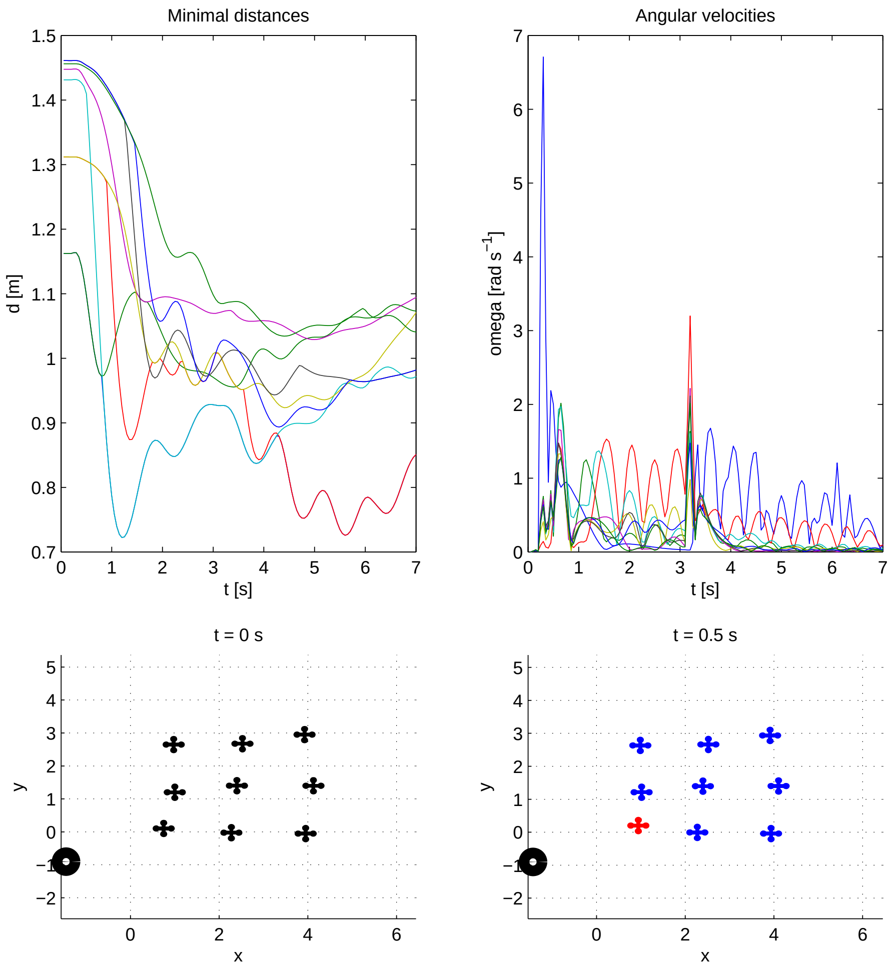

Figure 10. Experiment 1 (infinite sensory range, without obstacles), Method A: The graph in upper left shows minimal distances between quadrotors, the graph in upper right shows norms of angular velocities of each quadrotor used to decide states transitions. The figures below show the states distribution and positions in time, where the black cross represents an individual in the Normal mode, blue cross denotes an individual in the Passive mode and the red cross denotes an individual in the Active mode. The black circle denotes a predator.

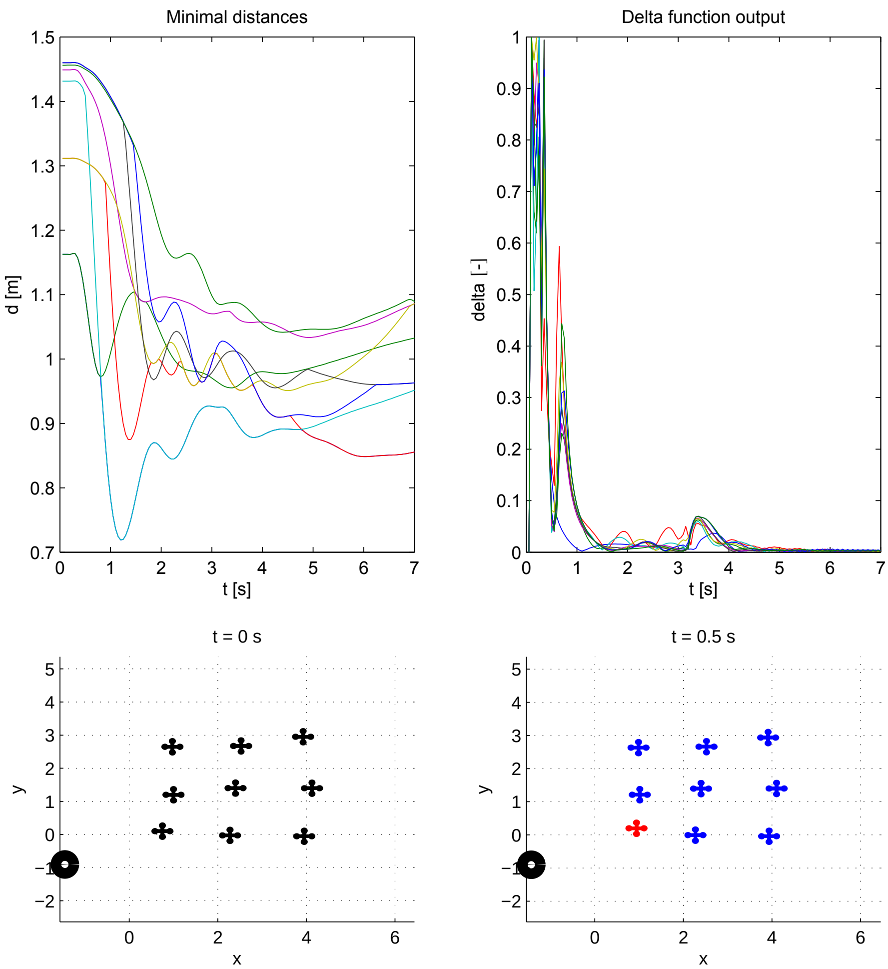

Figure 11. Experiment 1 (infinite sensory range, without obstacles), Method B: The graph in upper left shows minimal distances between quadrotors, the graph in upper right shows delta function output of each quadrotor used to decide states transitions. The figures below show the states distribution and positions in time, where the black cross represents an individual in the Normal mode, blue cross denotes an individual in the Passive mode and the red cross denotes an individual in the Active mode. The black circle denotes a predator.

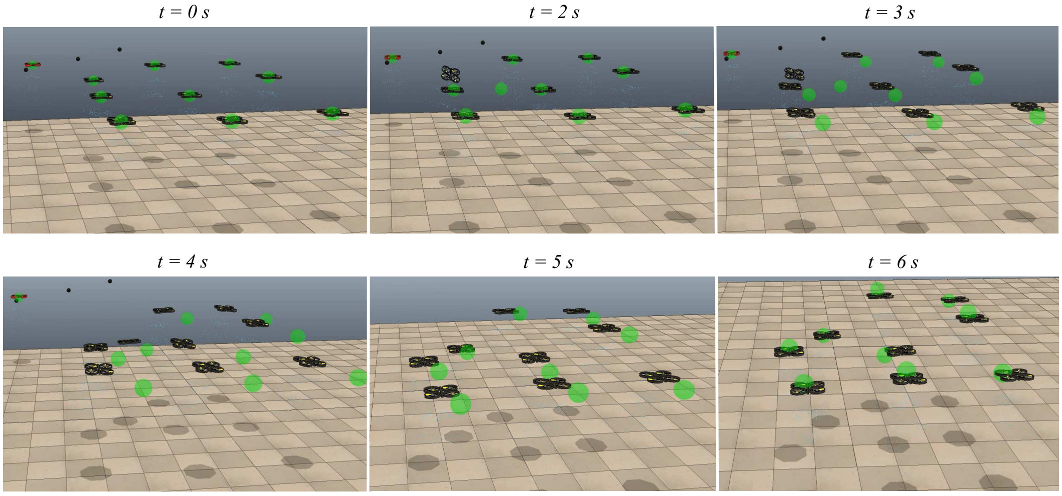

Figure 12. Sub-figures of Experiment 1 (infinite sensory range, without obstacles), Method B. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 2$ s, we can see the individual in the Active mode starting its escape behavior. At $t = 3$ s the rest of the swarm transit into the Passive mode until $t = 6$ s, when the Normal mode is set again.

4.2.2. Experiment 2 — Infinite sensory range, with obstacles

In the second experiment, the infinite sensory range was left, but an obstacle was placed in the expected path of swarm's movement. Similarly to the previous experiment, the escape behavior is triggered simultaneously in the whole swarm and the escape maneuvers are conducted smoothly, as shown in Figure 13, Figure 14, Figure 15 and Figure 16.

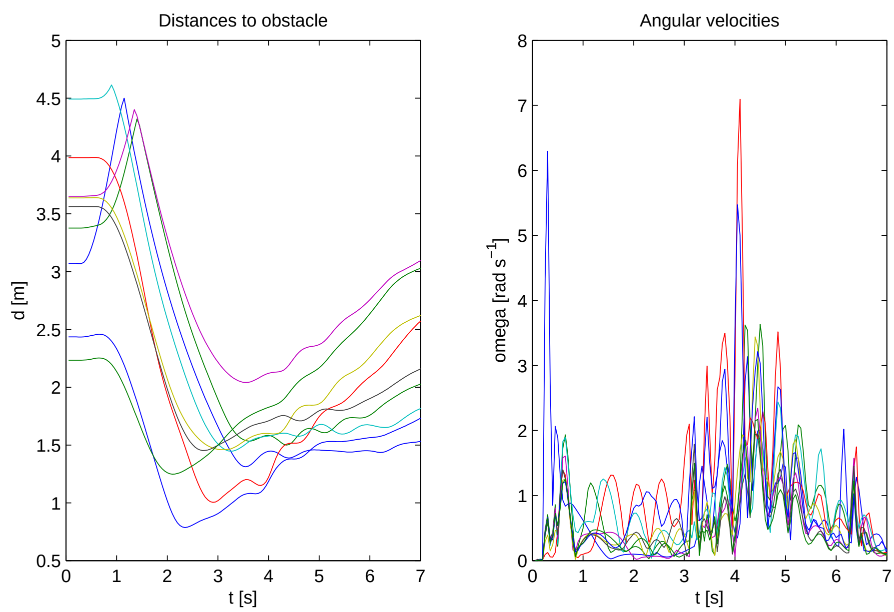

Figure 13. Experiment 2 (infinite sensory range, with obstacles), Method A: The graph on the left shows minimal distances between quadrotors and the obstacle, the graph on the right shows norms of angular velocities of each quadrotor used to decide states transitions.

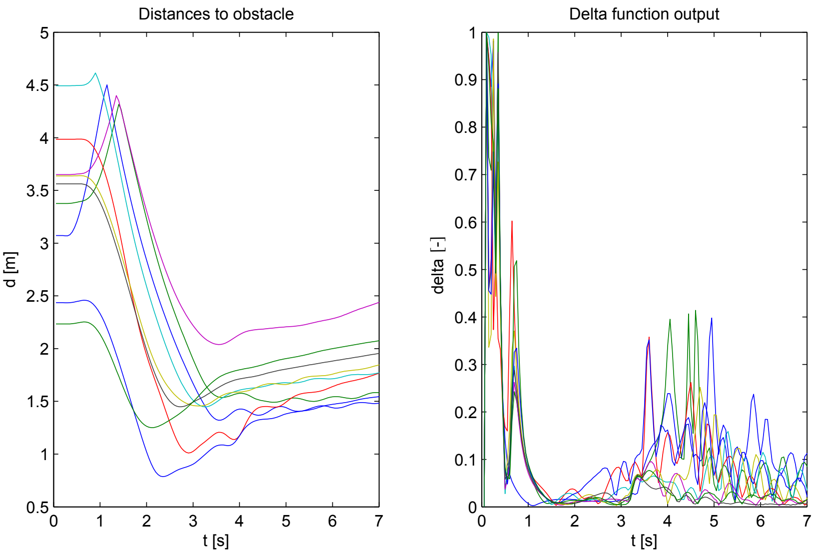

Figure 14. Experiment 2 (infinite sensory range, with obstacles), Method B: The graph on the left shows minimal distances between quadrotors and the obstacle, the graph on the right shows delta function output of each quadrotor used to decide states transitions.

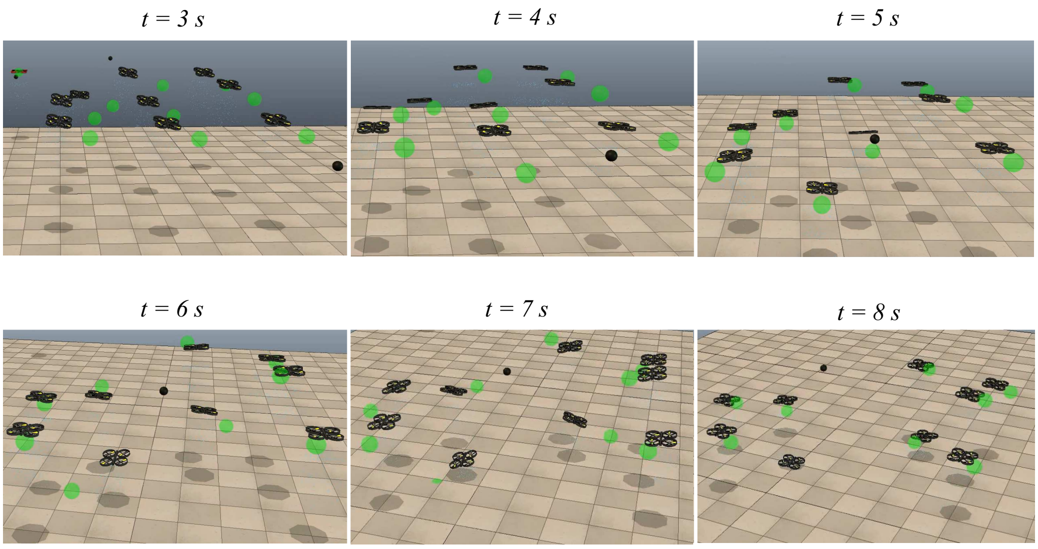

Figure 15. Sub-figures of Experiment 2 (infinite sensory range, with obstacles), Method A. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 3$ *s*, we can see that the escape behavior is triggered in the whole swarm. At $t = 4$ *s* and $t = 5$ *s*, the swarm is attempting to avoid the obstacle, while in $t = 6, 7, 8$ *s* the escape behavior is stopped and the swarm individuals are trying to maintain distances between them and their environment.

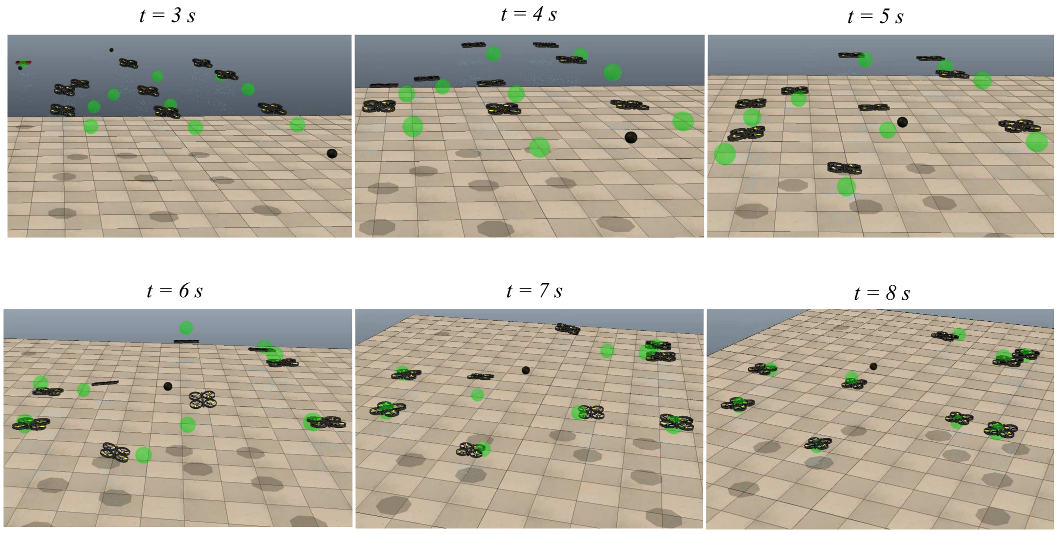

Figure 16. Sub-figures of Experiment 2 (infinite sensory range, with obstacles), Method B. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 3$ *s*, we can see that the escape behavior is triggered in the whole swarm. At $t = 4$ *s* and $t = 5$ *s*, the swarm is attempting to avoid the obstacle, while at $t = 6, 7, 8$ *s* the escape behavior is stopped and the swarm individuals are trying to maintain distances between them and their environment.

According to these figures, both of these methods are working as expected. However, the Figure 15 indicate that Method A is slightly more difficult to stabilize than the Method B. That is also shown in Figure 13, where norms of angular velocity vectors as the decision elements reach significantly higher levels than it is desirable.

4.2.3. Experiment 3 — Finite sensory range, without obstacles

In the third experiment, the sensory range is limited to 2.5 meters. The escape behavior is triggered in surrounding individuals only and these can subsequently pass the information about the predator further via their movement. The obstacle in their colliding path was removed in this experiment. The experimental results are shown in Figures 17-21.

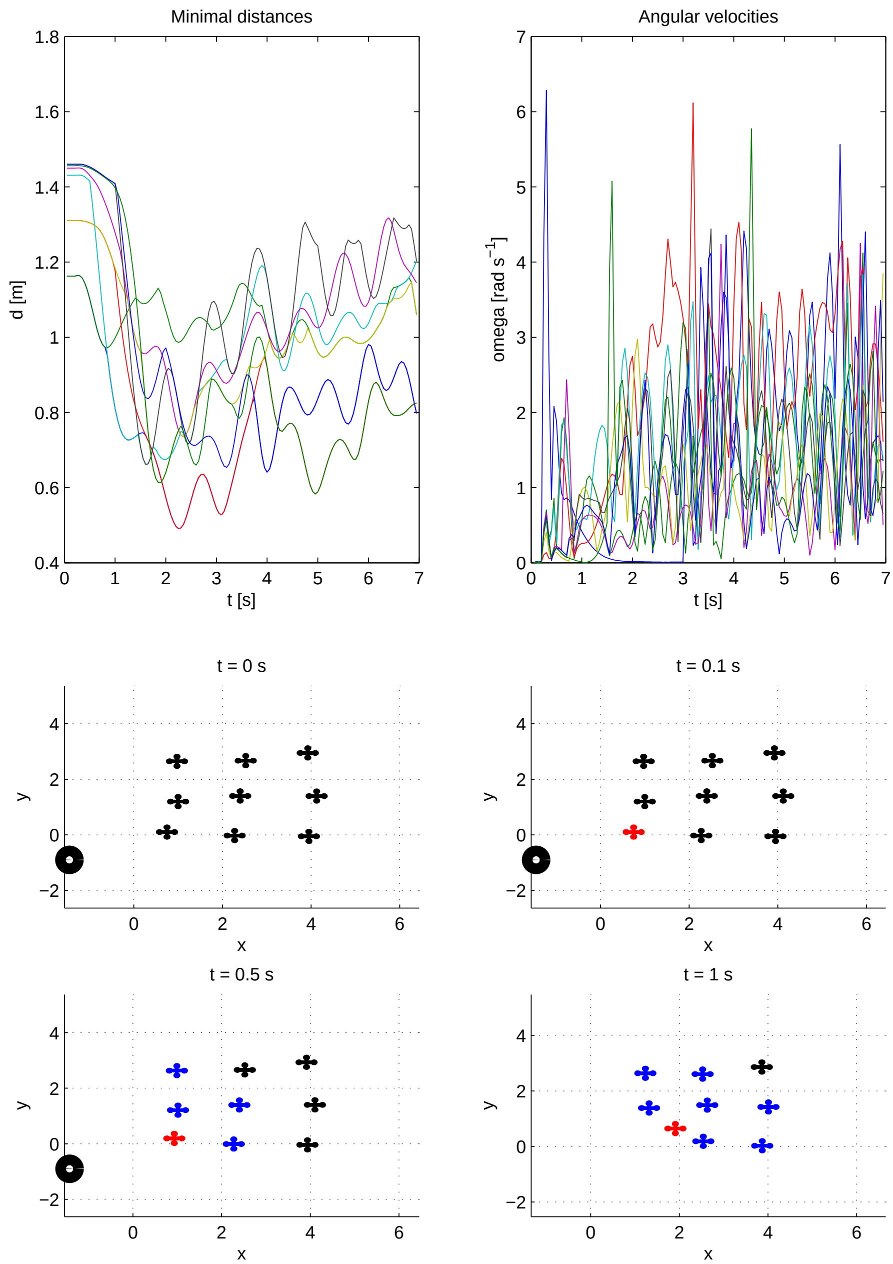

Figure 17. Experiment 3 (finite sensory range, without obstacles), Method A: The graph in upper left shows minimal distances between quadrotors, the graph in upper right shows norms of angular velocities of each quadrotor used to decide states transitions. The figures below show the states distribution and positions in time, where the black cross represents an individual in the Normal mode, blue cross denotes an individual in the Passive mode and the red cross denotes an individual in the Active mode. The black circle denotes a predator.

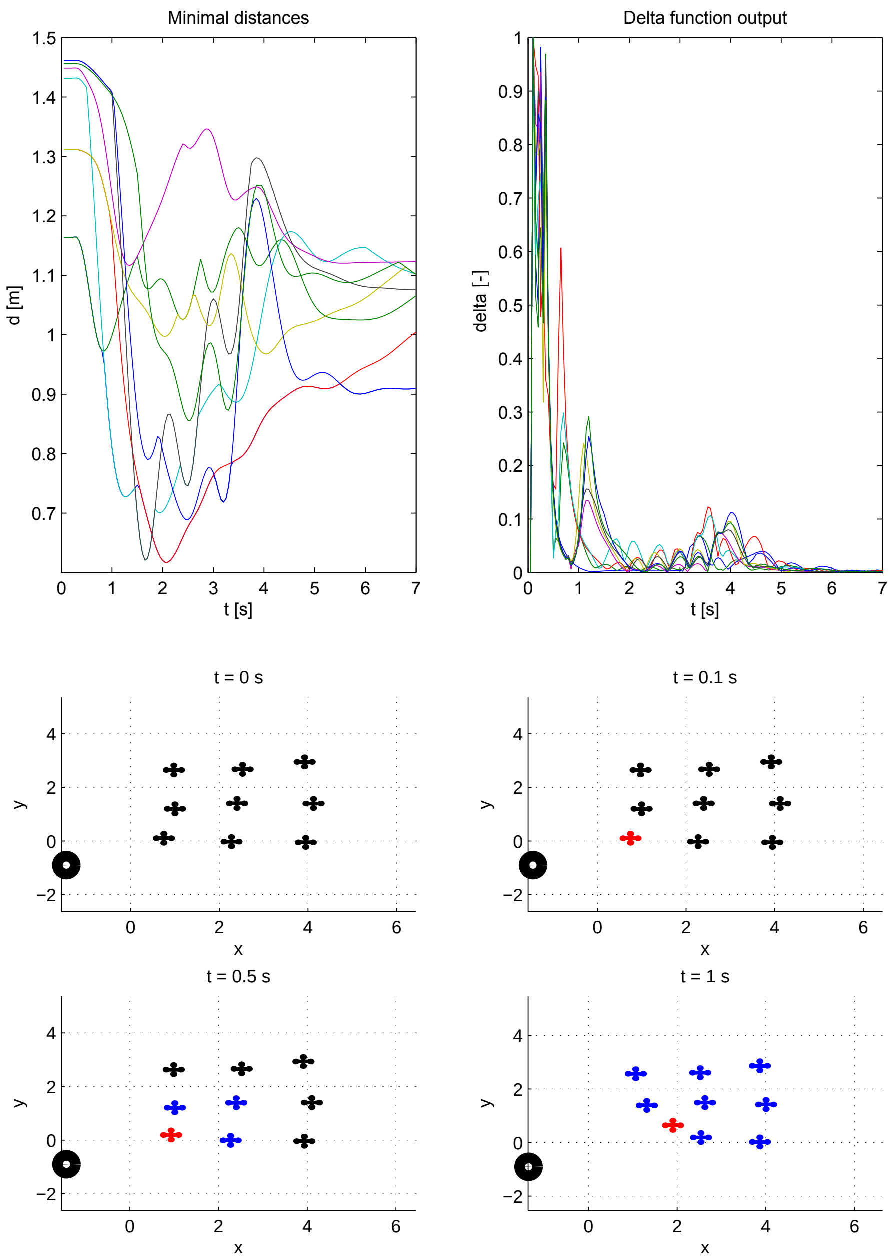

Figure 18. Experiment 3 (finite sensory range, without obstacles), Method B: The graph in upper left shows minimal distances between quadrotors, the graph in upper right shows delta function output of each quadrotor used to decide states transitions. The figures below show the states distribution and positions in time, where the black cross represents an individual in the Normal mode, blue cross denotes an individual in the Passive mode and the red cross denotes an individual in the Active mode. The black circle denotes a predator.

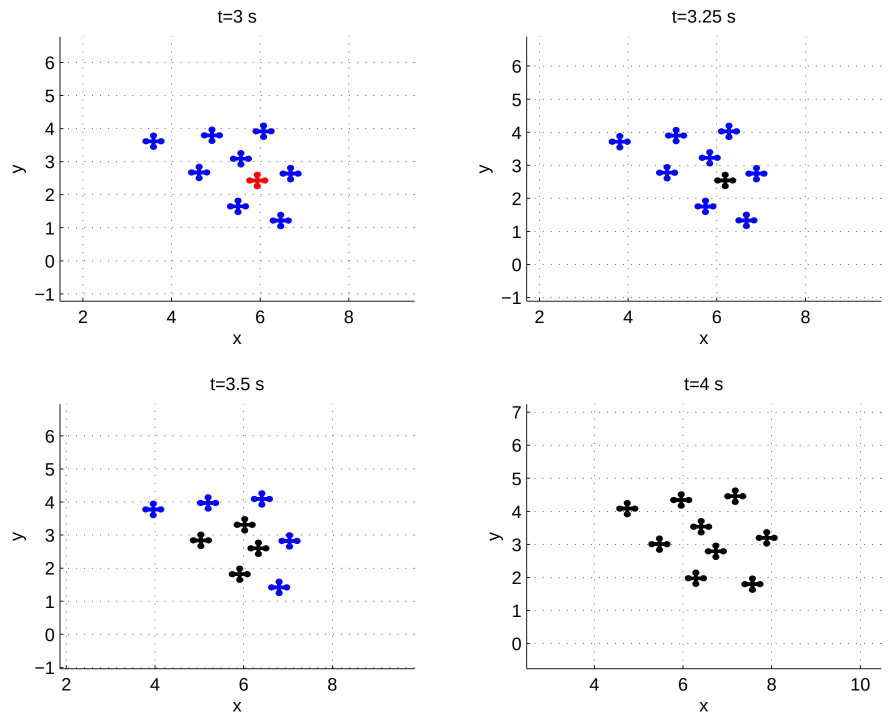

Figure 19. Experiment 3 (finite sensory range, without obstacles), Method B: Exiting escape behavior process. The black cross represents an individual in the Normal mode, blue cross denotes an individual in the Passive mode and the red cross denotes an individual in the Active mode.

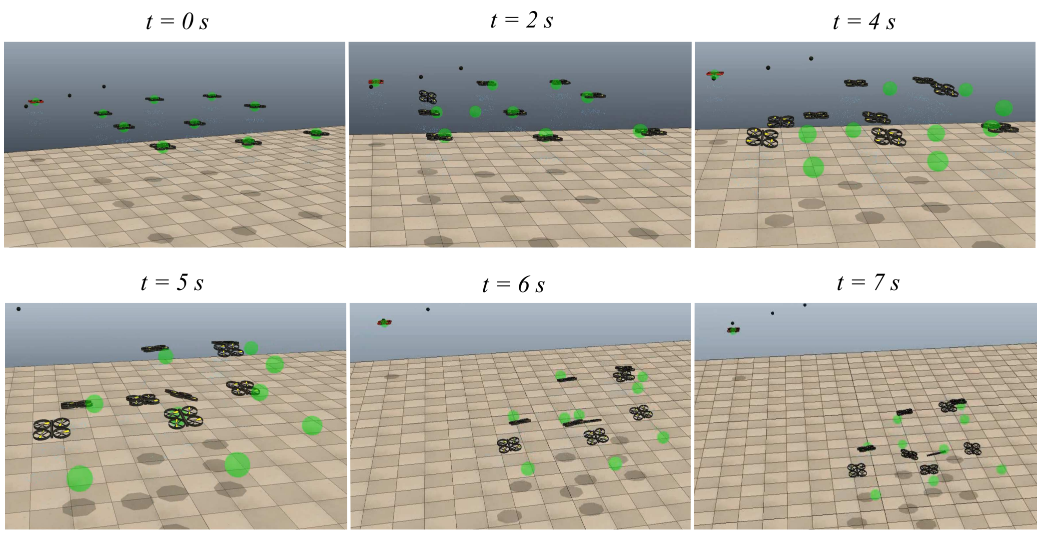

Figure 20. Sub-figures of Experiment 3 (finite sensory range, without obstacles), Method A. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 2$ *s*, we can see the individual in the Active mode starting its escape behavior. At $t = 4$ *s* the most of the swarm transit into the Passive mode; at $t = 5$ *s*, all the individuals reach the escape behavior. At $t = 6$ *s*, some of the individuals return to the Normal mode, but the rest of the swarm with their Passive mode still active trigger their Passive mode again as seen in $t = 7$ *s*.

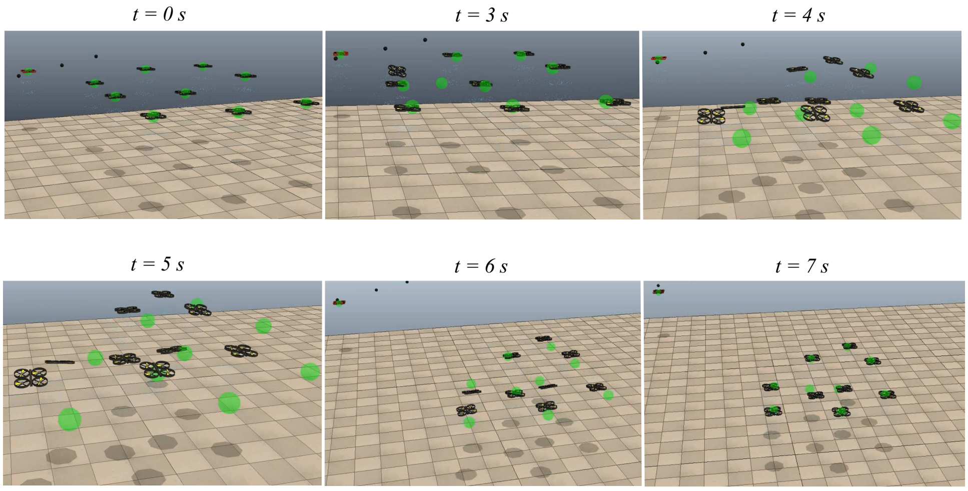

Figure 21. Sub-figures of Experiment 3 (finite sensory range, without obstacles), Method B. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 2$ *s*, we can see the individual in the Active mode starting its escape behavior. At $t = 4$ *s* the rest of the swarm transit into the Passive mode. At $t = 6$ *s*, some of the individuals return to the Normal mode, while the rest of the swarm exit their Passive mode at $t = 7$ *s*.

As seen in Figure 17 and Figure 18, both of these methods are effective in spreading the escape behavior properly. However, it is difficult to stabilize the swarm using Method A, since the swarm is not able to end its escape behavior, which is shown in Figure 20. As is shown in Figure 17, angular velocity measurement provides us with limited information only and thus renders Method A unstable.

The Method B effectively spreads the escape behavior and in comparison with Method A also provides us with successful exiting escape behavior process, as shown in Figure 19. According to Figure 18, its alerting potential is limited however due to the fact that delta function values are dropping down. This is caused by the velocity limitations mentioned in 3.3.2, which ensure that no individual in the Passive mode can move faster than the individual in the Active mode, and the fact that the individual in Active mode is slowing down according to equation (15).

4.2.4. Experiment 4 — Finite sensory range, with obstacles

In this experiment, the sensory range is limited to 2.5 meters similarly to Experiment 3. The escape behavior is triggered in surrounding individuals only and these can subsequently pass the information about the predator further via their movement. In addition, an obstacle was placed in the expected path of swarm's movement. The experiment results are shown in Figures 22-25.

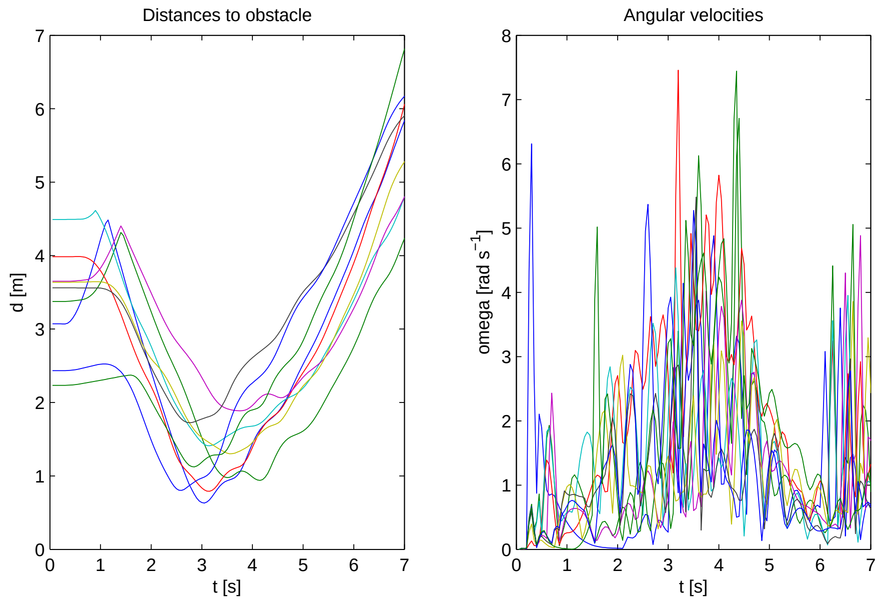

Figure 22. Experiment 4 (finite sensory range, with obstacles), Method A: The graph on the left shows minimal distances between quadrotors and the obstacle, the graph on the right shows norms of angular velocities of each quadrotor used to decide states transitions.

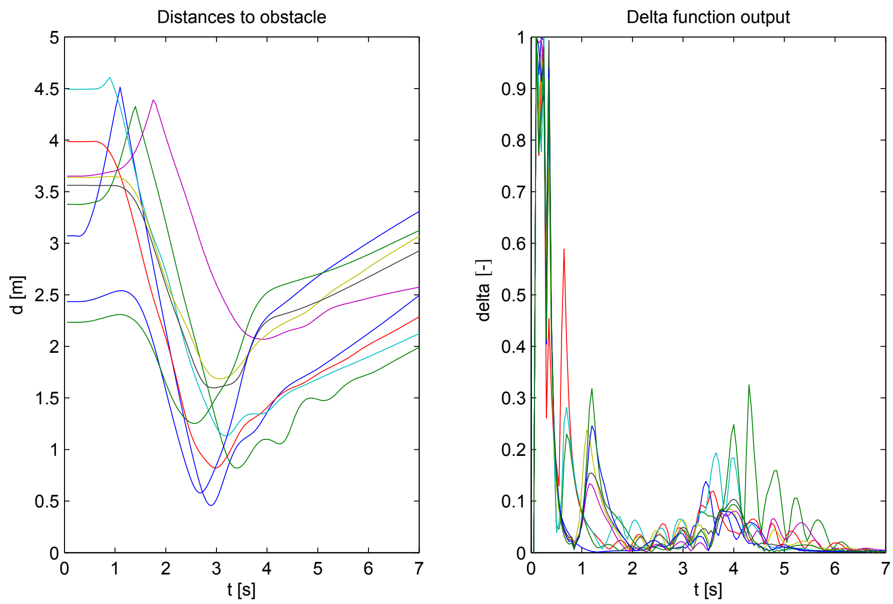

Figure 23. Experiment 4 (finite sensory range, with obstacles), Method B: The graph on the left shows minimal distances between quadrotors and the obstacle, the graph on the right shows delta function output of each quadrotor used to decide states transitions.

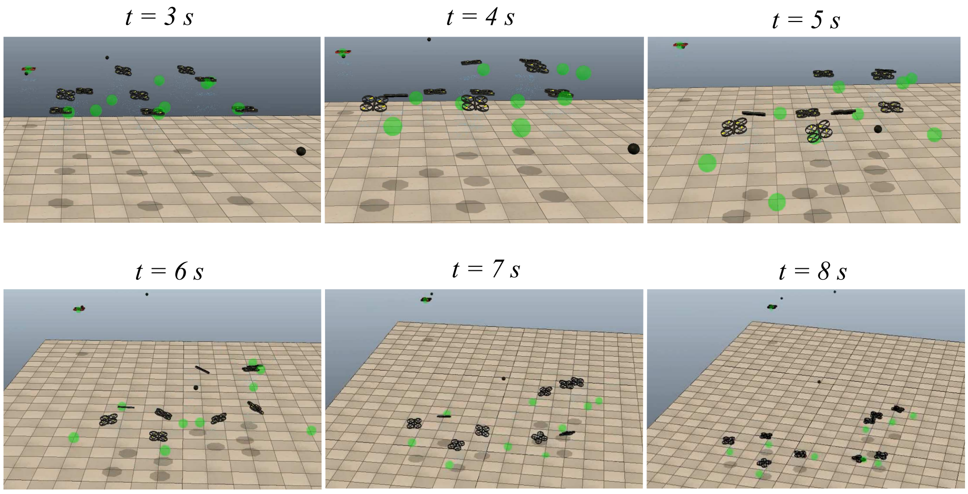

Figure 24. Sub-figures of Experiment 4 (finite sensory range, with obstacles), Method A. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 3$ s, we can see the most of the swarm transit into the Passive mode; at $t = 5$ s, all the individuals reach the escape behavior while attempting to avoid the obstacle. At $t = 6$ s, the obstacle is successfully avoided by most of the swarm individuals, but the evasive maneuvers trigger again the Passive mode for the individuals that had been transited into the Normal mode already. The escape behavior continues, as seen in $t = 7$ s and $t = 8$ s.

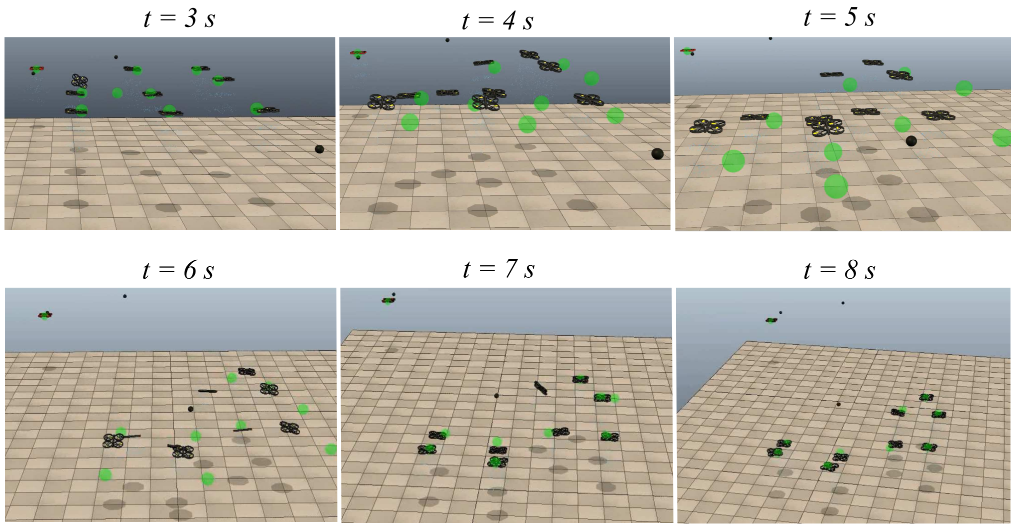

Figure 25. Sub-figures of Experiment 4 (finite sensory range, with obstacles), Method B. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 3$ s, an individual in the Active mode starts its escape behavior. At $t = 4$ s, the escape behavior is triggered in the whole swarm. At $t = 5$ s and $t = 6$ s, the swarm is attempting to avoid the obstacle, while at $t = 7, 8$ s the escape behavior is stopped and the swarm individuals are trying to maintain distances between them and their environment.

According to Figure 22 and Figure 24 the movement of each individual was irregular and unstable. We can also see that because of this the swarm using Method A was not stabilized and continued further in its motion.

On the contrary, Figures Figure 23 and Figure 25 show that the swarm controlled by Method B is able to avoid the obstacle and stabilize itself as well.

4.2.5. Experiment 5 — Finite sensory range, two predators

In this experiment, we put two predators in the workplace, moving towards the swarm from different directions. The obstacles are removed. Sensory range limitations are left to 2.5 meters.

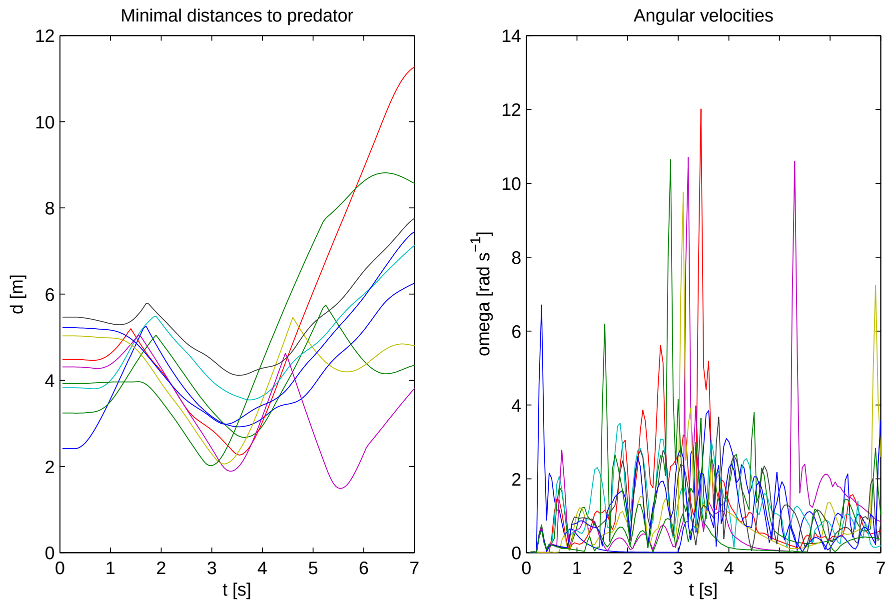

Figure 26. Experiment 5 (finite sensory range, two predators), Method A: The graph on the left shows minimal distances between quadrotors and one of the predators, the graph on the right shows norms of angular velocities of each quadrotor used to decide states transitions.

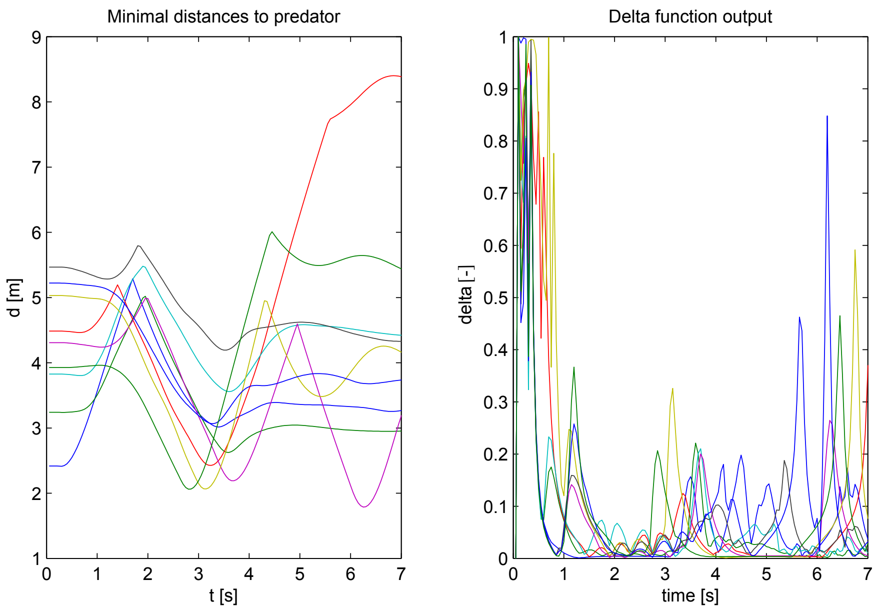

Figure 27. Experiment 5 (finite sensory range, two predators), Method B: The graph on the left shows minimal distances between quadrotors and one of the predators, the graph on the right shows delta function output of each quadrotor used to decide states transitions.

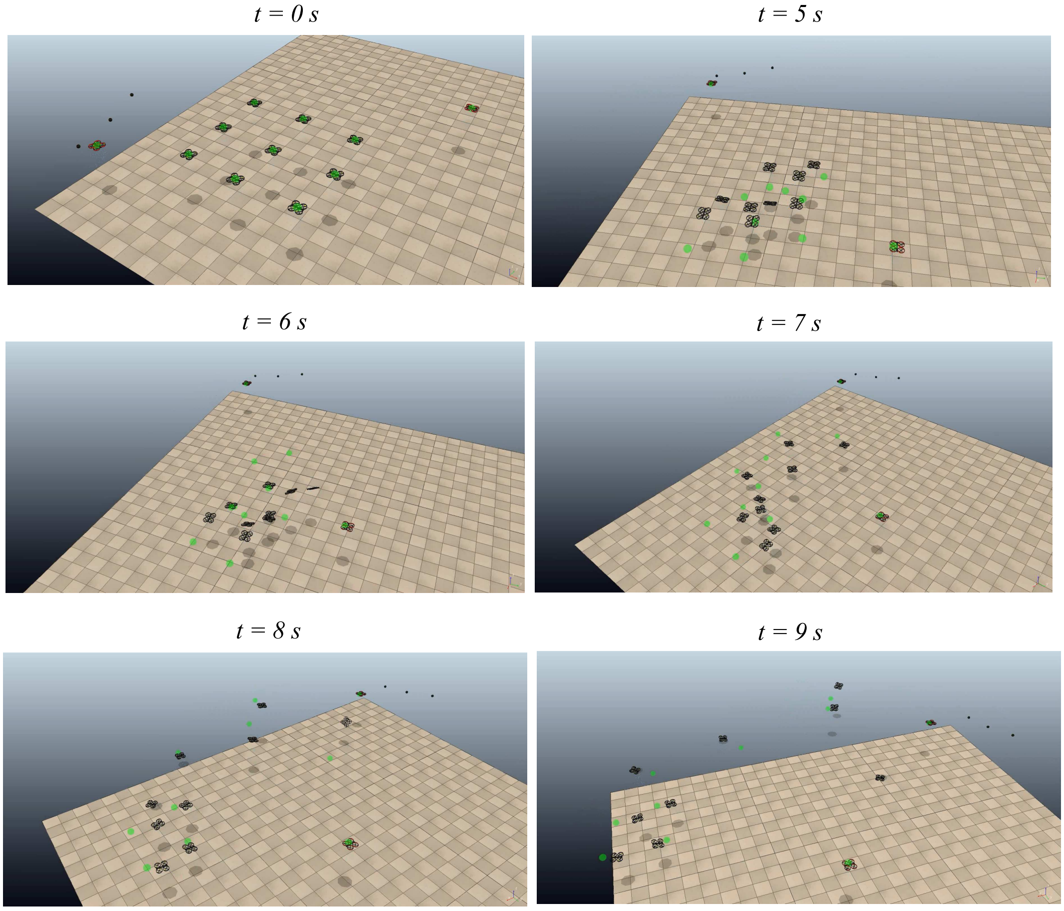

Figure 28. Sub-figures of Experiment 5 (finite sensory range, two predators), Method A. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At t = *0 s*, we can see the initial positions of scene objects. At t = *5 s* the swarm is performing the escape behavior. At t = *6 s* the swarm encounters the second predator, causing the transition to Active mode in some individuals. At t = *7, 8, 9* the swarm performs the escape behavior.

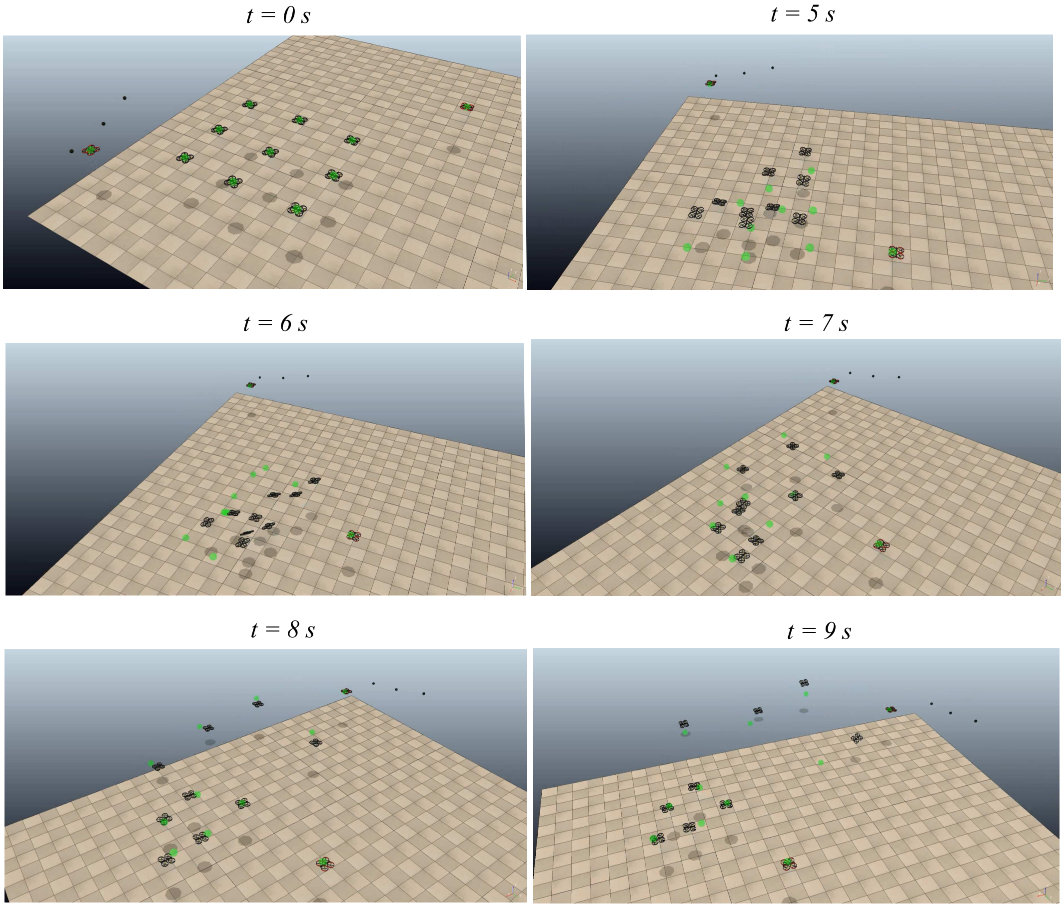

Figure 29. Sub-figures of Experiment 5 (finite sensory range, two predators), Method B. The green dots denote the desired position in current time step the quadrotor is attempting to reach. At $t = 0\ s$, we can see the initial positions of scene objects. At $t = 5\ s$ the swarm is performing the escape behavior. At $t = 6\ s$ the swarm encounters the second predator, causing the transition to Active mode in some individuals. At $t = 7, 8, 9$ the swarm performs the escape behavior.

Apart from stability issues of Method A, which was shown in previous experiments already, we can conclude that the presence of several predators sets more than one individual into the Active mode. Because of the Active mode conditions mentioned in 3.2, which include surpassing the relations to the other individuals, and the different trajectories these individuals in Active mode are taking, the ultimate result of this situation is the swarm separation. This separation is shown in figures 28 and 29.

5. Conclusion

The main objective of this thesis was to develop the escape behavior algorithm for group of unmanned quadrotors in multiple versions, based on basic flocking algorithm and MAV stabilization agorithm presented in [3, 4]. The idea of the escape behavior comes from [1]. This objective was successfully completed. Two swarming approaches were made and two controlling algorithms were created. These algorithms, differing by sensoric data required for their function, were successfully implemented into V-REP simulator and verified in several tests to prove their usefulness.

The results of experiments proved that the 3D environment is significantly different from 2D, for which the original algorithm [1] was designed. Unlike UGVs, quadrotor control is more complex, and its movement itself affects the measurement in such way that the original approach is not usable. The algorithm based directly on this method, tagged as the Method A, proved to be functional, yet unstable and very difficult to stabilize. In addition, the measurement of angular velocities with onboard sensors of real quadrotors would be difficult. To sum it up, the Method A is not recommended for use on real quadrotors.

The secondary approach developed for this thesis later referred to as Method B proved to be more promising, since the algorithm based on this method, though carrying the potential for further upgrades, fulfilled our expectations. The V-REP simulation success also suggests that this algorithm is suitable for testing on real quadrotors in real environment.

All the thesis objectives were successfully completed:

- An extension of bio-inspired method „Escape behavior“ was designed and implemented in chapter 3.
- The extension of escape behavior was integrated into V-REP simulator in section 4.1.
- The functionality of the algorithm modifications was verified in section 4.2.
- The response of MAV swarm to motion of several dynamic obstacles was analyzed in section 4.2.5.

All the simulation videos and source codes are provided on the enclosed CD.

Appendix A.

Contents of the enclosed CD

```
/
├── bachelor_thesis.pdf ............ this Thesis in PDF format
├── Scenes
│   ├── quadSim.ttt .............. V-REP scene with 1 predator without obstacles
│   ├── quadSim-obst.ttt ........... V-REP scene with 1 predator and 1 obstacle
│   └── quadSim-2pred.ttt ....................... V-REP scene with 2 predators
├── Simulator
│   ├── quadSim.m ........................... main m-file starting the simulation
│   ├── prep.m ........................ m-file containing the initialization function
│   ├── interForce.m ............. m-file computing the force between individuals
│   ├── obstacleForce.m ................. m-file computing the force to obstacles
│   ├── predForce.m ..................... m-file computing the force to predators
│   ├── suspB.m ......................... m-file determining the states transitions
│   ├── createQuadModel.m, drawQuad.m,
│   │   drawSimulation.m ........... supporting m-files for MATLAB visualization
│   ├── saveFlightParameters.m,
│   │   savePredParameters.m .............................. supporting m-files
│   └── extApi.c, extApi.h, extApiCustom.c,
│       extApiCustom.h, extApiInternal.h,
│       extApiPlatform.c, extApiPlatform.h,
│       remApi.m, remoteApi.dll,
│       remoteApi_thunk_pcwin64.dll,
│       remoteApi_thunk_pcwin64.exp,
│       remoteApi_thunk_pcwin64.lib,
│       remoteApi_thunk_pcwin64.obj,
│       remoteApiProto.m ................... supporting V-REP remote API files
└── Videos
    ├── infinite-a-0obst.avi,
    │   infinite-b-0obst.avi ........ videos from Experiment 1 described in 4.2.1
    ├── infinite-a-1obst.avi,
    │   infinite-b-1obst.avi ........ videos from Experiment 2 described in 4.2.2
    ├── finite-a-0obst.avi,
    │   finite-b-0obst.avi ......... videos from Experiment 3 described in 4.2.3
    ├── finite-a-1obst.avi,
    │   finite-b-1obst.avi ......... videos from Experiment 4 described in 4.2.4
    └── 2pred-a.avi, 2pred-b.avi ... videos from Experiment 5 described in 4.2.5
```

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