bachelor's thesis

Integration of relative visual localization into the system of stabilization of swarms of autonomous helicopters

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BACHELOR PROJECT ASSIGNMENT

Student: **Jan Valeš**

Study programme: Cybernetics and Robotics
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Title of Bachelor Project: **Integration of relative visual localization into the system of stabilization of swarms of autonomous helicopters**

Guidelines:

The aim of this thesis is to integrate constraints given by the relative visual localization [2] and by mutual influence of helicopters into an method of swarm stabilization and analyze influence of these constraints on the compactness of the group. Work plan:
1. To design and implement a method, which ensures that the constraints given by the relative visual localization and by mutual influence of helicopters will be ensured during the swarm motion
2. To integrate the designed method into the algorithm [1,4]
3. To verify the implemented system in a simulator of university of UPENN and to analyze constraints, in which the splitting of the swarm into small groups may occur

Bibliography/Sources:

[1] Min, Hongkyu; Wang, Zhidong; , "Design and analysis of Group Escape Behavior for distributed autonomous mobile robots," Robotics and Automation (ICRA), 2011 IEEE International Conference on , vol., no., pp.6128-6135, 9-13 May 2011
[2] Faigl, J. - Krajník, T. - Chudoba, J. - Přeučil, L. - Saska, M.: Low-Cost Embedded System for Relative Localization in Robotic Swarms, Proc. of IEEE International Conference on Robotics and Automation (ICRA), 2013
[3] Taeyoung Lee; Leoky, M.; McClamroch, N.H.; , "Geometric tracking control of a quadrotor UAV on SE(3)," Decision and Control (CDC), 2010 49th IEEE Conference on , vol., no., pp.5420-5425, 15-17 Dec. 2010
[4] Martin Saska, Jan Vakula, and Libor Preucil. Swarms of micro aerial vehicles stabilized under a visual relative localization. Accepted for IEEE ICRA, 2014.

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Prague, February 18, 2014

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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 23.5.2014

Abstract

Tato bakalářská práce se zabývá návrhem, implementací a ověření funčnosti metod, které v roji bezpilotních helikoptér zajistí omezení daná relativní vizuální lokalizací a vzájemným působením bezpilotních helikoptér. Navržené metody mají za úkol zabránit nebezpečným kolizím mezi helikoptérami a působení proudu vzduchu vytvořeného rotorem helikoptéry na ostatní helikoptéry v roji. Navržené metody jsou implementovány do algoritmu únikového chování pro roje bezpilotních čtyř-rotorových helikoptér. Funkčnost navržených metod je ověřena simulacemi. Do simulace algoritmu únikového chování jsou implementovány složitější překážky, které napodubují překážky reálného světa. Pro ověření funkčnosti metod a analýzy chování roje bezpilotních helikoptér jsou použity simulace v programu Matlab.

Klíčová slova

Bezpilotní helikoptéry, autonomní roje, relativní vizuální lokalizace

Abstract

This bachelor thesis deals with design, implementation and verification methods, that ensure constraints given by the relative visual localization and by mutual influence of unmanned helicopters in a swarm. The designed methods are tasked to prevent dangerous collisions between helicopters and acting of air flow induced by rotor of helicopter to other helicopters from the swarm. The designed methods are implemented to the algorithm of escape behaviour of swarm of unnamed four-rotor helicopters. The functionality of the methods are verified by simulation. More complex obstacles are implemented to the simulation of the algorithm of escape behaviour. These obstacles mimic obstacles from the real world. Simulation in the program Matlab are used to the verify the functionality of methods and analysis of behaviour of the swarm of unnamed helicopters.

Keywords

Micro aerial vehicles, robotic swarms, relative visual localization

Contents

1 Introduction

The main objective of this Bachelor thesis is to design, implement and verify the algorithm, which ensure the limitations given by the relative visual localization and by mutual influence of helicopters in the swarm. The algorithm will be integrated into the algorithm of escape behaviour, implemented and described by Jan Vakula in his bachelor thesis *Escape behaviour in swarms of unmanned helicopters* [10].

The given task is design, implement and verify the restrictions given by the relative visual localization and by mutual influence of helicopters into the algorithm of escape behaviour of swarm of unnamed helicopters. If a helicopter approach to another helicopter, collision may occur. Two possibilities of collision are solved in this thesis:

- Collision of frames of the helicopters
- Collision of a helicopter with an air flow induced by rotor of another helicopter

The functionality of designed algorithm will be verified by simulations in program Matlab using a swarm of quad-rotor.

Next task is to analyse the behaviour of the swarm of helicopter on the obstacles and to analyse constraints, in which the splitting of the swarm into small groups may occur.

A dynamic model of quad-rotor is described in chapter 2. There are described equations of motion of the model of quad-rotor, which are used in simulations. The equations of motion described in article *Geometric Tracking Control of a Quadrotor UAV on SE(3)* [8] were chosen. The algorithm of escape behaviour is described in chapter 3. There are described the origin equations described in *Design and Analysis of Group Escape Behavior for Distributed Autonomous Mobile Robots* [7] for 2D and the equations for 3D designed by Jan Vakula [10]. The equations of escape behaviour for 3D are used in simulation for motion of swarm.

The solutions of the main objective are described in chapter **5 Attractive and repulsive forces** and chapter **6 Air flow induced by rotor**. There are described the designed methods to ensure the limitations given by relative visual localization and by mutual influence of quad-rotor. Simulations of behaviour and verifications of designed method are described in chapters 7,8 and 9.

1.1 Micro aerial vehicle

The algorithm, which enables to integrate constraints given by the relative visual localization is primarily intended for the micro aerial vehicles.

A micro aerial vehicle (MAV) is an unmanned vehicle with a size restriction. The advantage of MAVs is capability of flying in small spaces outdoor or indoor. MAVs can be used for research, commercial and military purpose.

The simulations in Matlab imitates the behavior of swarm of autonomous quadrotors.

2 quad-rotor

A mathematical model of quad-rotor is described in this chapter. The model of quad-rotor is described in the article *Geometric Tracking Control of a quad-rotor UAV on SE(3)* [8]. The article describes a global dynamic model for a quad-copter and a geometric tracking controller. The geometric tracking controller is used for tracking the desired trajectory of the center of mass and the desired direction of the first body-fixed axis. Equations described in article are used in simulations for motion of quad-rotor.

A quad-rotor or quad-copter is type of helicopter with four propellers, located at the corners of square construction. The quad-rotors can fly vertically like the conventional helicopters. Due to its properties, quad-rotors have a variety of uses. Unnamed quad-rotors are popular and used for research purposes. A photo of quad-copter Parot AR.Dron is shown at the figure 1.

Figure 1 Illustration of the quad-rotor [2].

2.1 Dynamics model of quad-rotor

The model of the quad-rotor is a system of four identical propellers located in a square in the same plane. The each rotor with the propeller generates a torque and thrust normal to the plane. The mathematical model of quad-copter is shown at the figure 2.

The body-fixed frame lies in an inertial reference frame $\{\overrightarrow{i}_1, \overrightarrow{i}_2, \overrightarrow{i}_3\}$ The origin of the body-fixed frame $\{\overrightarrow{b}_1, \overrightarrow{b}_2, \overrightarrow{b}_3\}$ is placed at the center of mass of the model. The thrusts $\mathbf{f}_i$, where index i is $i = 1, 2, 3, 4$, generated by the each of the propellers have a direction along the axis $-\overrightarrow{b}_3$. The axes $\overrightarrow{b}_1$ and $\overrightarrow{b}_2$ are located in the plane of the rotors. It is assumed that the thrust of propellers is directly controlled and the torque

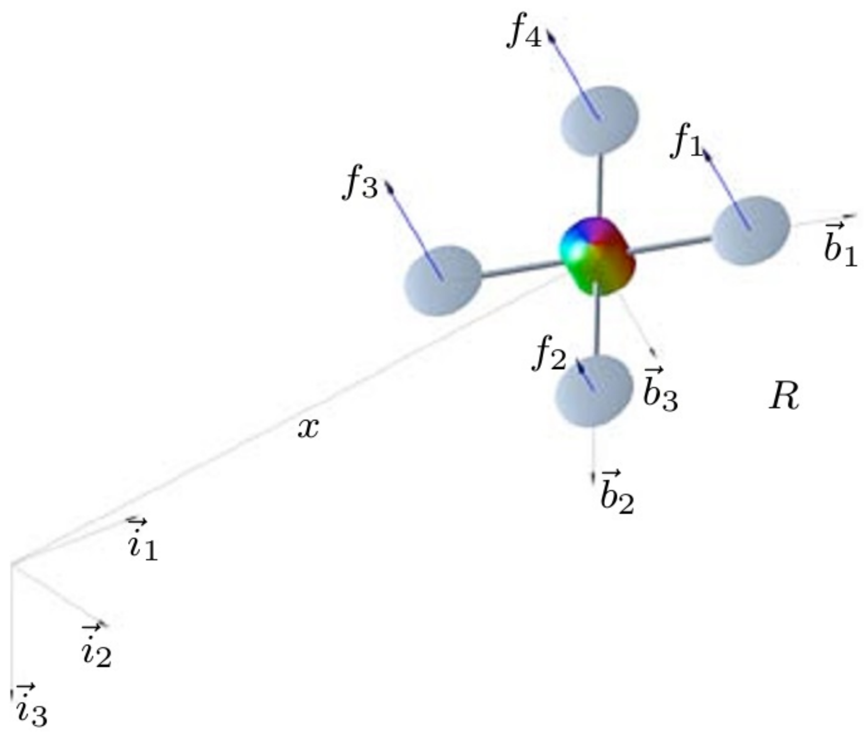

Figure 2 Illustration of the mathematical model of the quad-rotor [8]

is directly proportional to its thrust. Symbols $\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3$ are the columns of the identity matrix.

The equations of motion of the model of quad-rotor can by written as

$$\dot{\mathbf{x}} = \mathbf{v}, \tag{1}$$

$$m\dot{\mathbf{v}} = mg\mathbf{e}_3 - f\mathbf{R}\mathbf{e_3}, \tag{2}$$

$$\dot{\mathbf{R}} = \mathbf{R}\hat{\mathbf{\Omega}}, \tag{3}$$

$$\mathbf{J}\dot{\mathbf{\Omega}} + \mathbf{\Omega} \times \mathbf{J}\mathbf{\Omega} = \mathbf{M}. \tag{4}$$

The meaning of symbols used in the equations of motion of the quad-rotor is shown in table 1. The constants used in the simulation have the following values. The inertia matrix J is

$$\mathbf{J} = \begin{pmatrix} 0.082 & 0 & 0 \\ 0 & 0.0845 & 0 \\ 0 & 0 & 0.1377 \end{pmatrix} kg \cdot m^2. \tag{5}$$

The gravitational acceleration is $g = 9.81ms^{-2}$ and the total mass of quad-copter model is $m = 4.34kg$.

Table 1 Table of symbols used at equations.

Symbol	Description
x	the position of the center of mass in the inertial frame
v	the velocity of the center of mass
m	the total mass of the quad-rotor
g	the gravitational acceleration
f	the total thrust generated by propellers
R	the rotation matrix from the body-fixed frame to the inertial frame
Ω	the angular velocity in the body-fixed frame
J	the inertia matrix from the body-fixed frame
M	the total moment in the body-fixed frame

3 Group escape behaviour

The group escape behaviour is a algorithm inspired by behaviour of swarms of animals (bird flocks or fish schools) being observed when a predator is approaching to the swarm. The algorithm is adapted to control of a swarm of robots. This behaviour of the swarm of animals is imitated for the purpose of the swarm of robots.

The swarm of robots keeps the formation till a robot detects a possibly dangerous object. Then the robot starts turning away to escape into a more safety place. Other robots from swarm detect such motion, which influences their own behaviour. This collective motion of the robots in the swarm ensures their safe movement and an active dangerous object avoidance.

This behaviour is expressed for unnamed ground vehicle by the flocking equations in *Design and Analysis of Group Escape Behaviour for Distributed Autonomous Mobile Robots* [7].

3.1 Flocking equations in 2D

The flocking control equations (6) and (7) describe the dynamics of the swarm of robots. The first equation (6) is Newton's second law of motion. This equation describes the dynamics of the i-th robot on the left side and sum of all forces action on the i-th robot. The second equation (7) is Euler's second law. This equation describes the dynamic of rotation of the i-th robot.

The flocking equations are

$$m_i \frac{d\mathbf{v}_i}{dt} = F_p \mathbf{H}_i + \sum_{j,j\neq i} e_{ij} \mathbf{F}_{KH_i} - \gamma \mathbf{v}, \tag{6}$$

$$I_i \frac{d^2\alpha_i}{dt^2} = \sum_{j,j\neq i} (e_{c\_ij} M_{c\_ij} + e_{ij} M_{d\_ij}) + M_{re\_i} - D_m \frac{d\alpha_i}{dt}, \tag{7}$$

where indexes $j, i = 1, 2, ..., N$ and the other symbols are described in the table 2.

The interaction moment M_{c_ij} is designed as

$$M_{c\_ij} = K_t \alpha_{ji} + C_t \frac{d\alpha_i}{dt}. \tag{8}$$

If the swarm is in danger caused by obstacle or predator the interaction moment M_{c_ij} is not suitable. The stronger interaction moment M_{ecp_ij} is used instead of M_{c_ij}. The stronger interaction moment M_{ecp_ij} is defined as

$$M_{ecp\_ij} = K_e \alpha_{ji} + C_e \frac{d\alpha_i}{dt}. \tag{9}$$

The interaction moment M_{ecp_ij} is similar to non-alignment spring-damper model as the normal interaction moment M_{c_ij}. The difference is that the spring constant K_e and damper constant C_e are more valuable than constants K_t and C_t.

The interactive force $\mathbf{F}_{K_ji}$ provides cohesion and separation of robots. This force is designed as a spring-damper model. The interactive force $\mathbf{F}_{K_ji}$ ensures that the

Table 2 Table of symbols used in equations.

Symbol	Description
m	mass of robot
v	velocity
t	time
F	force
R	the position vector in world coordinates
H	the unit vector
e	the distance function
α	the angle of heading direction vector
I	moment of inertia of a robot
M	the rotational moment
a,b,c	constants for set distance functions e_{ij} and e_{c_ij}
L_{ji}	relative position vector from jth robot to ith robot
L_d	constant determining the required distance between robots
K, C	constants, set the speed of reaction when $\alpha_{ji} \neq 0$
D	constant, set speed of reaction for robots divert from their optimal relative distance

distance between robots $\mathbf{L}_j i = \mathbf{R}_j - \mathbf{R}_i$ is a constant. The constant of distance between robots is marked as L_d. The interactive force $\mathbf{F}_{K_j i}$ is defined as

$$\parallel \mathbf{F}_{K_j i} \parallel = K_d(L_{d_i} - \parallel \mathbf{L}_{ji} \parallel) + D_d \frac{d\mathbf{L}_{ji}}{dt}. \tag{10}$$

The force $\mathbf{F}_{K_j i}$ has two components:

$$\mathbf{F}_{K_j i} = \mathbf{F}_{KH_ij} + \mathbf{F}_{K\perp ij} \tag{11}$$

The first component $\mathbf{F}_{KH_ij}$ is heading direction component. The second component $\mathbf{F}_{K\perp ij}$ is vertical direction component. Symbols used in equations (8, 9, 10) are described in the table 2.

The sensors of robots have limited range. Hence, the forces acting between robots are restricted by their range. The sensor range is provided by functions e_{ij} and e_{c_ij} in the equations (6) and (7). The functions e_{ij} and e_{c_ij} are defined as

$$e_{c\_ij} = \frac{1}{e^{aL_{ji}-b} + c}, \tag{12}$$

$$e_{ij} = \frac{1}{e^{aL_{ji}-b} + c} + \frac{1}{e^{\frac{1}{2}aL_{ji}-b} + c}, \tag{13}$$

where $e_{ij} > e_{c\_ij}$.

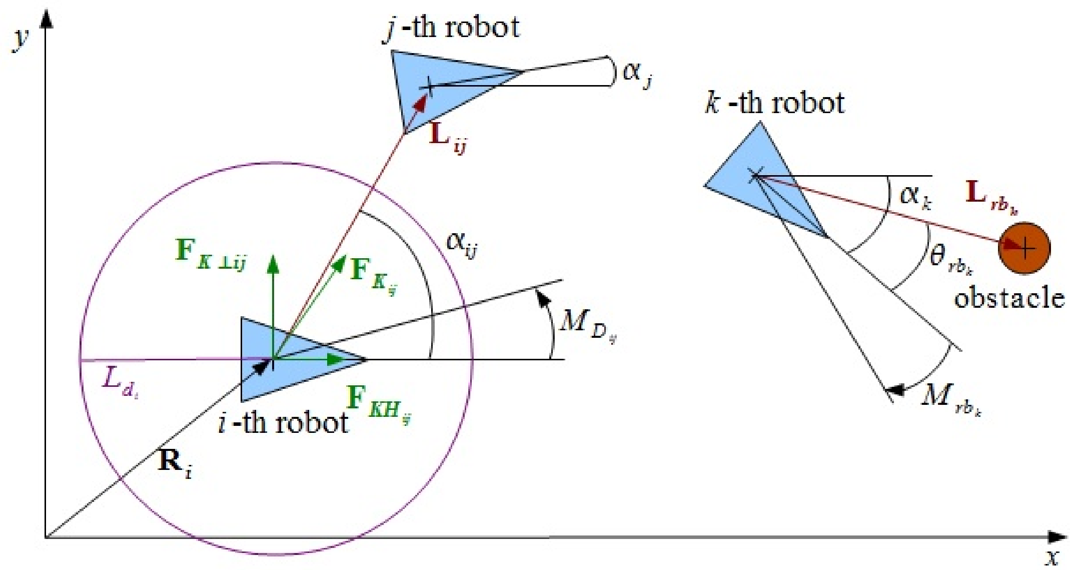

Figure 3 Schematically illustrated forces and moments acting on robots [10]

4 Flocking equations for swarm of quad-rotors

The flocking equations for quad-rotors are described in this chapter. These flocking equations are derived from the equations described in the previous chapter Escape behaviour. The equations are used for calculating the forces acting on quad-copter in the swarm. The acting forces are summed and then the required position is calculated. All three forces and the total force is calculated for each individual in the swarm. The equations described in this chapter are used for simulation of swarm in Matlab. The flocking equations for quad-rotors are designed and implemented by Jan Vakula [10].

4.1 The acting forces

Three types of forces are acting on the quad-rotor. The first type is $\mathbf{F}_{ind_i}$ acting on other individuals in the swarm of robots. The second type is force $\mathbf{F}_{obs_i}$ to the obstacles and the last type is $\mathbf{F}_{goal_i}$ force to the goal.

The total force $\mathbf{F}_i$ acting on the i-th quad-copter in the swarm is calculated by the weighted sum

$$\mathbf{F}_i = W_{ind} \cdot \mathbf{F}_{ind_i} + W_{obs} \cdot \mathbf{F}_{obs_i} + W_{goal} \cdot \mathbf{F}_{goal_i}, \tag{14}$$

where constants W_{ind}, W_{obs} and W_{goal} indicate the value of weighted sum.

The required position $\mathbf{X}_{g_i}$ of the ith quad-rotor is calculated from the total force $\mathbf{F}_i$ and the actual position $\mathbf{X}_i$ as

$$\mathbf{X}_{g_i} = \mathbf{X}_i + C_{FtoD} \cdot \mathbf{F}_i \tag{15}$$

where C_{FtoD} is a constant to transforms the total force acting at the robot $\mathbf{F}_i$ to the position vector.

4.2 Force to other individuals

The force to other individuals $\mathbf{F}_{ind_i}$ acts between the $i-$th quad-rotor and other quad-rotor in the swarm. This force provides cohesion and separation of robots in the swarm.

The interactive force $\mathbf{F}_{ind_{ij}}$ to a other individual is defined as

$$\mathbf{F}_{ind_{ij}} = K_d(\parallel \mathbf{L}_{ij} \parallel - L_r) \parallel \mathbf{L}_{ij} \parallel + D_d \frac{d\mathbf{L}_{ij}}{dt}. \tag{16}$$

The force $\mathbf{F}_{ind_{ij}}$ is designed as a spring-damper model with required distance L_r.

The total force to other individuals $\mathbf{F}_{ind_i}$ is calculated by

$$\mathbf{F}_{ind_i} = \sum_{j, j \neq i}^{N} e_{ij} \cdot \mathbf{F}_{ind_{ij}}, \tag{17}$$

where e_{ij} is the distance function. The distance function e_{ij} expresses distance between ith quad-rotor and jth quad-rotor.

4.3 Force to obstacles

Force to obstacles $\mathbf{F}_{obs_i}$ ensures that the quad-rotor avoids the obstacles. The avoidance of obstacles is ensured by the equation

$$\mathbf{F}_{obs_i} = \delta \cdot e_{oi} \cdot \frac{\mathbf{H}_{oi}}{\parallel \mathbf{H}_{oi} \parallel}, \tag{18}$$

where δ is dependence function and e_{oi} is distance function.

The direction vector $\mathbf{H}_{oi}$ is perpendicular to heading direction vector and this vector is oriented from the obstacle. The direction vector $\mathbf{H}_{oi}$ is designed as

$$\mathbf{H}_{oi} = (\mathbf{H}_i \times \mathbf{F}_{oi}) \times \mathbf{H}_i, \tag{19}$$

where the force $\mathbf{F}_{oi}$ is designed as

$$\mathbf{F}_{oi} = K_o \cdot \mathbf{L}_{oi} + D_o \frac{d\mathbf{L}_{oi}}{dt}. \tag{20}$$

The distance function e_{oi} is designed as

$$e_{oi} = b_o e^{a_o \|\mathbf{L}_{oi}\|} \tag{21}$$

and the dependence function δ is designed as

$$\delta = d_o \cdot cos(\Psi_{oi}) + 1. \tag{22}$$

The angle Ψ_{oi} is the angle between the head direction vector $\mathbf{H}_i$ and vector to obstacle $\mathbf{L}_{oi}$.

4.4 Force to goal

The force to goal $\mathbf{F}_{goal_i}$ ensure that the swarm of quad-rotor will fly to the specified location.

The interaction force to goal is defined as

$$\mathbf{F}_{goal_i} = K_g \cdot \mathbf{L}_{g_i} + D_g \frac{d\mathbf{L}_{g_i}}{dt}, \tag{23}$$

where $\mathbf{L}_{g_i}$ is the vector to goal and K_g and D_g are constants.

If the $i-$th helicopter is far from the goal, the force has large magnitude. The magnitude of force $\mathbf{F}_{goal_i}$ is set as the constant vector to the goal

$$\mathbf{F}_{goal_i} = W_g \frac{\mathbf{L}_{g_i}}{\parallel \mathbf{L}_{g_i} \parallel}. \tag{24}$$

Table 3 Table of symbols used in equations.

Symbol	Description
F	force acting to the quad-rotor
L	the position vector from quad-rotor
R	the position vector in world coordinates
H	direction vector
X	position vector of quad-rotor
δ	dependence function
e_{oi}	distance function
$W_{ind}, W_{obs}, W_{goal}$	constants for weighted sum
C_{FtoD}	constant to transform the force to the position vector
L_r	constant, determines the required distance between quad-rotors
K_d, D_d	constants for set the force to other individuals
K_o, D_o	constants for set the force to obstacles
K_g, D_g	constants for set the force to goal
W_g	constant for set the magnitude of force to goal
d	constant, set the magnitude of dependence function δ
Ψ	angle between the head direction vector $\mathbf{H}_i$ and vector to obstacle $\mathbf{L}_{oi}$
a,b,c	constants for set the distance function

5 Attractive and repulsive forces

The collision of two (or more) quad-rotors in the swarm may occur with high probability. The risk of the collision increases with the number of members in the swarm. On the other hand, a member of swarm can gets too far apart and separates from the swarm. This could cause a loss of communication with others quad-rotors.

The similar problems arises between atoms (or molecules). Hence, the proposed work was inspired by attractive and repulsive forces between atoms.

5.1 Van der Waals forces

Van der Waals forces between particles are attraction and repulsion forces between two nearby atoms or molecules. The value of Van der Waals force depends on the distance between atoms.

When the atoms are closer to each other they attract slightly at the beginning. This attractive force increases with decreasing distance between the atoms, until their electrons begin to repel one other electrostatically. This repulsive force rapidly increases with decreasing distance. The attractive force goes to zero with increasing distance between the atoms. This causes that the atoms can not to collide or separate from each other without the contribution of the other forces.

The curve of the attractive and repulsive forces is shown at the Fig. 4.

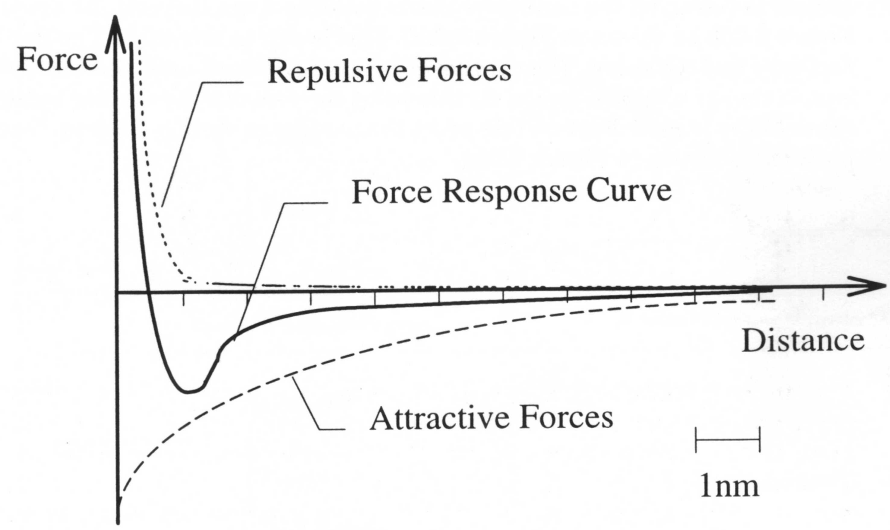

Figure 4 Attractive and repulsive forces between atoms. [1]

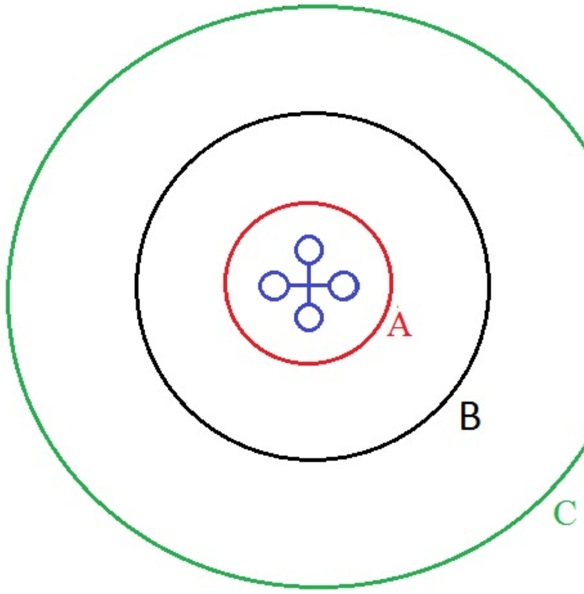

Figure 5 Distribution of zones.

5.2 Distribution of zones

The curve of the attractive and repulsive forces of two atoms is not entirely satisfactory for the purpose of the developing swarm based control approach. The quad-rotor can be separated from the swarm by acting of an external force. The force from obstacles is an example of these forces, which can separate the swarm. There is no force to attract the quad-rotors together until the quad-rotors get closer to each other again. The quad-rotors will attract even at a longer distance in designed algorithm.

Another difference is that the value of the force between robots will depend on the number of neighbours of a quad-rotor. For each quad-rotor, a required number of neighbours which are in range of relative localization system is specified. If the quad-rotor will have less neighbours in the distance that enables the relative localization than is the specified number of neighbours, the quad-rotor will be attracted to the nearby quad-rotor.

The area around a quad-rotor is divided to four zones depending on the distance between two quad-rotors. Each zone has different value of the weight function. The first zone is between the quad-rotor and the *close distance*. There is a strong repulsive force, which keeps the quad-rotor in safe distance from each other. In the next zone, between the *close distance* and the *mean distance*, the value of function is zero. Most of the neighbours of the quad-rotor will be in this area. The next zone is between *mean distance* and *far distance*. There is a low attractive force. The value of weight function is the same for all neighbours in the previous zones.

Two possibilities of the value of the weight function are behind the far distance. That depends on the number of neighbouring quad-rotors in the previous zones. If there is a predetermined number of quad-rotors (or more), the value of weight function will be zero. If there are not enough quad-rotors, the force will be strongly attractive. So this ensures that a quad-rotor has enough neighbouring quad-rotors.

The distribution of zones is shown at Fig. 5.

5.3 Weight function

The weight function expresses the magnitude of the force between two quad-rotors depending on their distance. The function must respect the distribution of zones and ensure two other important distances. The distance of the maximum allowable approach of quad-rotors is located between the quad-rotor and close distance. The neighbouring quad-rotor must not exceed this distance. This is to ensure the rapid growth of mutually repulsive forces. The second important distance is distance of the maximum allowable delay. This distance determines how far the neighbouring quad-rotor can be from the closest quad-rotor. It is located to the twice the far distance.

The mathematical expression of the designed weight function is

$$wf(x) = \frac{a}{x - \frac{cd}{2}} - b^{x-md} + \frac{c}{x - 2fd}. \tag{25}$$

The meaning of the symbols used in the formula is shown in the table 4.

Table 4 Table of symbols used at equation.

Symbol	Description
wf	weight function
x	distance between quad-rotors
cd	close distance
md	mean distance
fd	far distance
a	constant determining the slope of the weight function between close and mean distance
b	constant determining the slope of the weight function between mean and far distance
c	constant determining the slope of the weight function behind far distance

The mathematical expression of the designed weight function has one point of failure. The function *wf(x)* can't ensure precise value between close and mean distances, where the magnitude of the weight function is zero. For the reason the actual implementation of the weight function in the algorithm is

$$wf(x) = \frac{a}{x - \frac{cd}{2}},\ \text{if x} < \text{close distance} \tag{26}$$

$$wf(x) = 0,\ \text{if close distance} < \text{x} < \text{mean distance} \tag{27}$$

$$wf(x) = -b^{x-md},\ \text{if mean distance} < \text{x} < \text{far distance} \tag{28}$$

$$wf(x) = \frac{c}{x - 2fd},\ \text{if x} > \text{far distance.} \tag{29}$$

This implementation of the weight function ensures compliance with borders of zones and the required value in each zone.

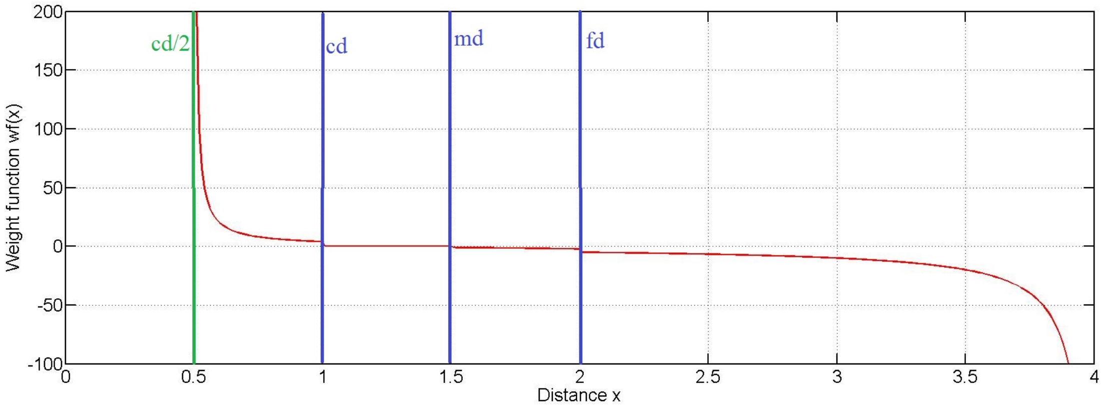

Figure 6 Example of the weight function.

An example of the weight function is shown at the figure Fig. 6.

The figure Fig. 6 shows the borders between zones. The mathematical expression of the function is

$$wf(x) = \frac{2}{x - \frac{1}{2}} - 5^{x-1.5} + \frac{10}{x - 2 \cdot 2}. \tag{30}$$

6 Air flow induced by rotor

A helicopter induces the airflow by rotation of the propeller. If the helicopter hovers, the direction of the airflow is perpendicular to the rotor disc. The air flow under the helicopter has high velocity, depending on the weight of helicopter and the size of the rotor.

The airflow induced by the hovering helicopter is shown at the figure 7. There is shown the direction of the air flow .

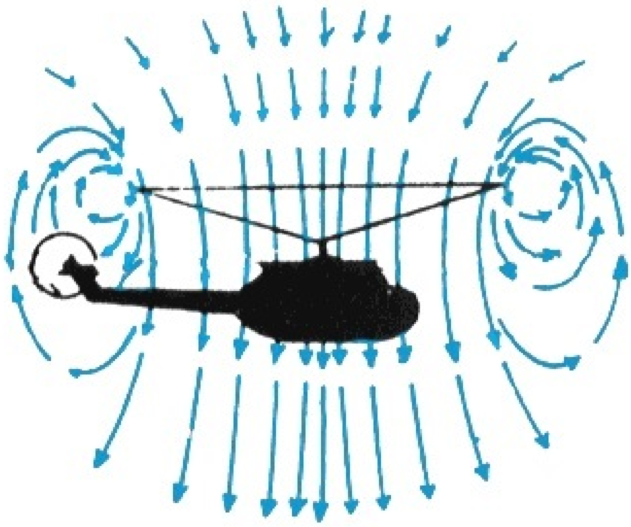

Figure 7 The airflow induced by helicopter [4].

The effect of the airflow induced by rotor can be seen on the water surface. The airflow acting on the surface of the water is shown at the figure 8.

The induced airflow can be dangerous for a helicopter in the swarm flying under another helicopter. The lower helicopter gets under the other helicopter, the airflow induced by the upper helicopter can blow away the lower helicopter.

6.1 Extension of z coordinate of zones

The velocity and pressure of the induced airflow below a helicopter decreases with the distance from the helicopter. The danger distance of the airflow from the helicopter is represented by constant h. The constant h is dependent on the weight of helicopter and the size of the rotor. The constant h is used to calculate the relative position vector $\mathbf{L}_{ji}$ between the $i-$th quad-rotor and the $j-$th quad-rotor. The relative position vector

Figure 8 The airflow acting on the surface of the water [3].

$\mathbf{L}_{ji}$ is calculated as

$$\mathbf{L}_{ji} = \mathbf{R}_j - \mathbf{R}_i, \tag{31}$$

where $\mathbf{R}_j = (x_j, y_j, z_j)$ and $\mathbf{R}_i = (x_i, y_i, z_i)$ are position vectors of quad-rotors in world coordinate. The position vector of the bottom of the airflow of jth quad-rotor is $(x_j, y_j, z_j - h)$.

If the $i-$th quarotor is upper than the $j-$th quad-rotor, the vector $\mathbf{L}_{ji}$ is computed directly from the vectors $\mathbf{R}_j$ and $\mathbf{R}_i$. If the height of the $i-$th quad-rotor is between the height of the $j-$th quad-rotor and bottom of airflow of the $j-$th quad-rotor, the vector $\mathbf{L}_{ji}$ is computed form the $i-$th quad-rotor to point between $j-$th quad-rotor and its bottom of the airflow. If the $i-$th quad-rotor is lower than the bottom of the airflow of $j-$th helicopter, the vector $\mathbf{L}_{ji}$ is computed from the point of the bottom of airflow to the $i-$th quad-rotor. This is described by equations

$$\mathbf{L}_{ji} = (x_j, y_j, z_j) - (x_i, y_i, z_i), \text{ if } z_j < z_i, \tag{32}$$

$$\mathbf{L}_{ji} = (x_j, y_j, z_j - h) - (x_i, y_i, z_i), \text{ if } z_j - h > z_i, \tag{33}$$

$$\mathbf{L}_{ji} = (x_j, y_j, z_i) - (x_i, y_i, z_i), \text{ if } z_j - h > z_i > z_j. \tag{34}$$

This shift of point for calculation of vector $\mathbf{L}_{ji}$ extends the zones in z coordinate. If a quad-rotor approaches from below to other quad-rotor, the distance between quad-rotors will be calculated shorter than it actually is. This prevents that a quad-rotor in the swarm flies under other quad-rotor.

The extension of zones in z coordinate is shown at the figure 9. There are shown the distribution of zones in 3D. A quad-rotor is located to the upper part of the cylinder. The height of the cylinder is height of the induced airflow of a quad-rotor.

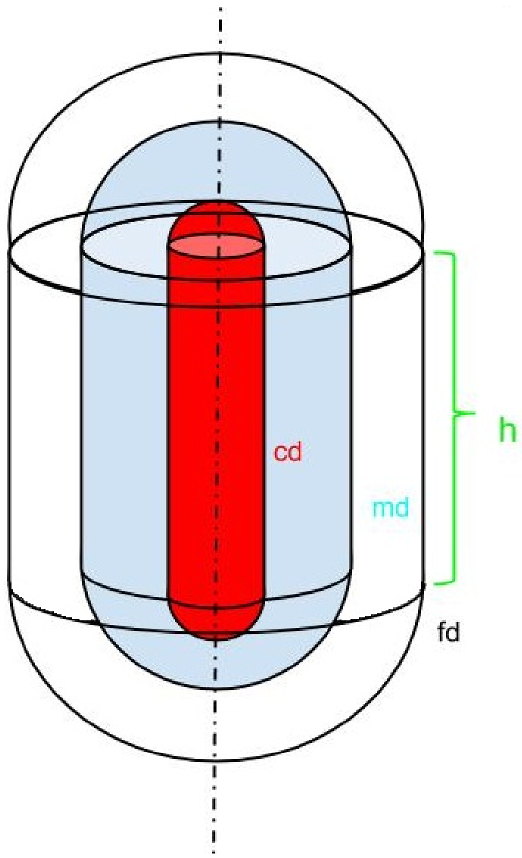

Figure 9 Extension of the z coordinate of zones. h is height of the airflow, cd is close distance, md is meam distance and fd is far distance.

7 Behaviour of the swarm with simple obstacles

Simulations and experiments of the swarm behaviour are shown in this chapter. Experiments are aimed to verify the functionality of the attractive and repulsive forces and restriction of the flight of a quad-rotor under another helicopter (which are described in previous two chapters).

Experiments are conducted of the swarm of quad-rotors in an environment with simple obstacles. The obstacles are implemented as lines to which the quad-rotors must not approach. The experiments are conducted as a simulations in program Matlab.

The initial placement of quad-rotors and obstacles is identical for all simulations. The initial placement is shown at the figure 10. quad-rotors are placed so that the shortest distance between quad-rotors is $D = 2$. The distances of quad-rotors in simulations and at graphs are listed in map units.

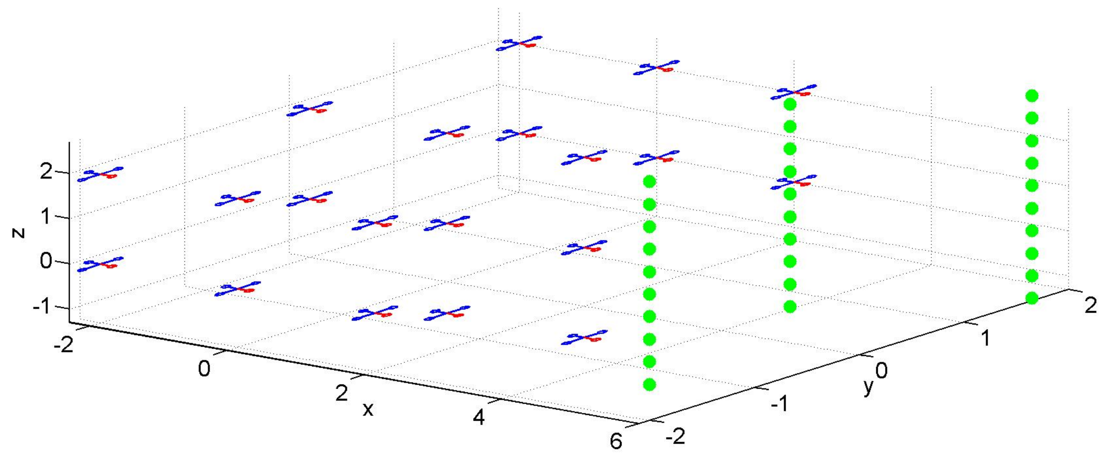

Figure 10 Initial placement of quad-rotors and obstacles. The 20 quad-rotors are placed around position $[0, 0, 1]$ with distance to each other 2. The green points are obstacles which are implemented as vertical line. The goal for the swarm is located in point $[10, 0, 1]$.

7.1 Number of neighbours and required distances

Effect of number of neighbouring quad-rotors N at behaviour of swarm is shown in this section. Experiments differ in the setting of number of neighbours.

A The required distances between quad-rotors for these experiments are $cd = 1, md = 2$ and $fd = 2.5$, where cd is *close distance*, md is *mean distance* and fd is *far distance*. A quad-rotor should not exceed the minimum required distance $cd/2 = 0.5$ and maximum required distance $2 \cdot fd = 5$. The setting for this simulation is set in program on CD.

The number of neighbours is set to zero for the first experiment. This means that the strong attractive force behind the *far distance* is zero for each neighbouring quad-rotor. The samples of first experiment is shown at the figure 11 and graph of the shortest distances between quad-rotors is shown at the figure 12. A quad-rotor is separated from the swarm, because there are not acting attractive force at the quad-rotor.

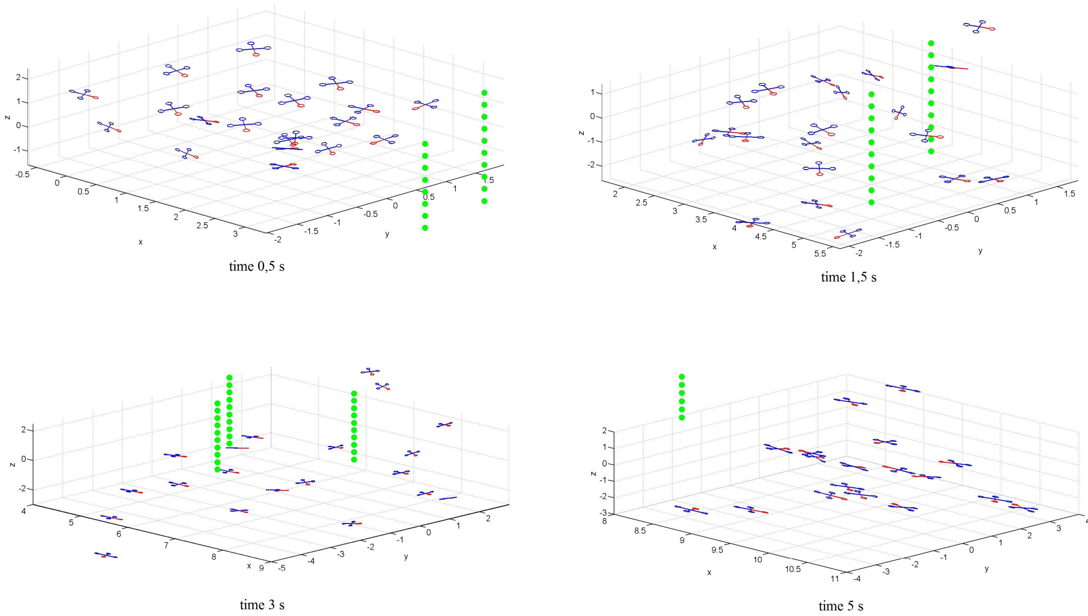

Figure 11 Sample of simulation. The number of neighbours is set N = 0.

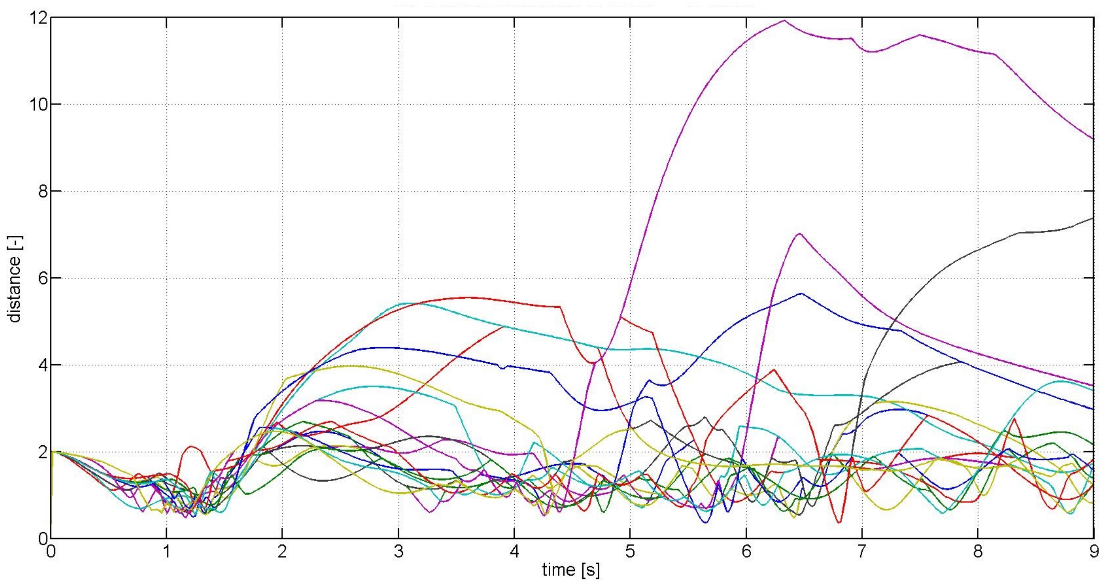

Figure 12 The shortest distances to other quad-rotor. The number of neighbours is set N = 0

The number of neighbours is set $N = 1$ for the second experiment. If a quad-rotor flies behind the *far distance*, the attractive force will act to the nearest quad-rotor. It ensures that a quad-rotor cannot separate too far from the swarm. The samples of second experiment for $N = 1$ is shown at the figure 13 and graph of the shortest distances between quad-rotors is shown at the figure 14. Comparison of graphs 11 and 13 shows that the setting of number of neighbours $N = 1$ reduced separating of swarm.

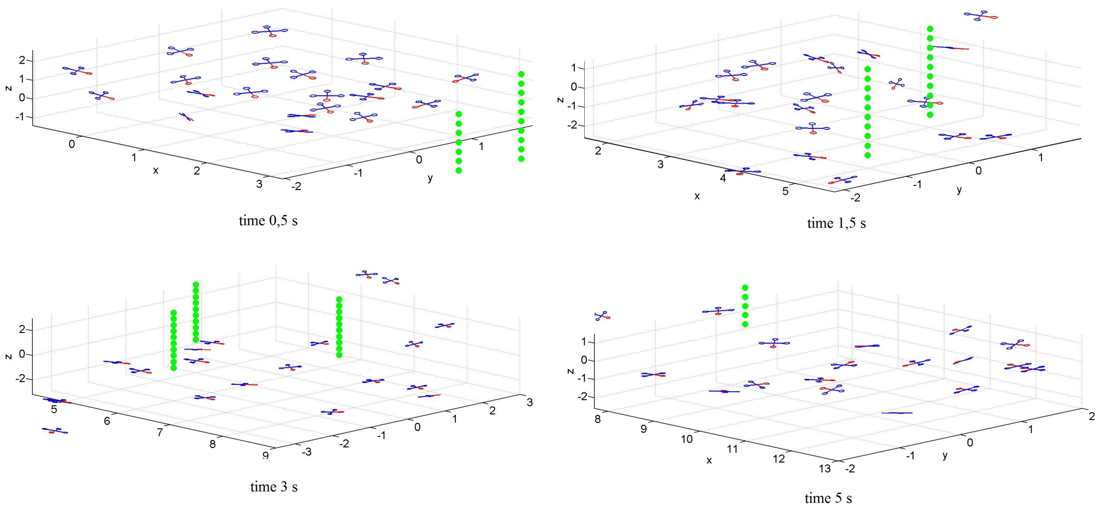

Figure 13 Sample of simulation. The number of neighbours is set N = 1

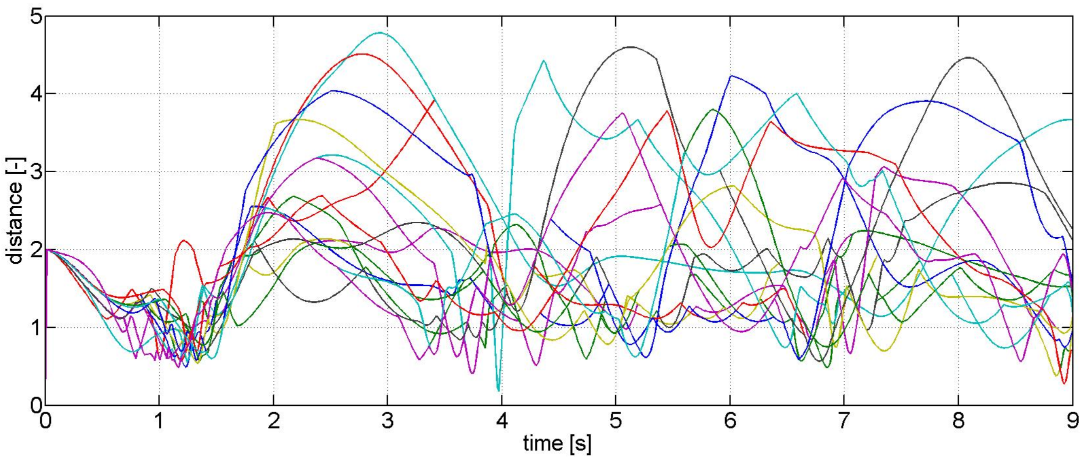

Figure 14 The shortest distances to other quad-rotor. The number of neighbours is set N = 1

The graph of the shortest distances to other quad-rotors for the number of neighbours $N = 2$ is shown at the figure 15. The distances between quad-rotors decreased again.

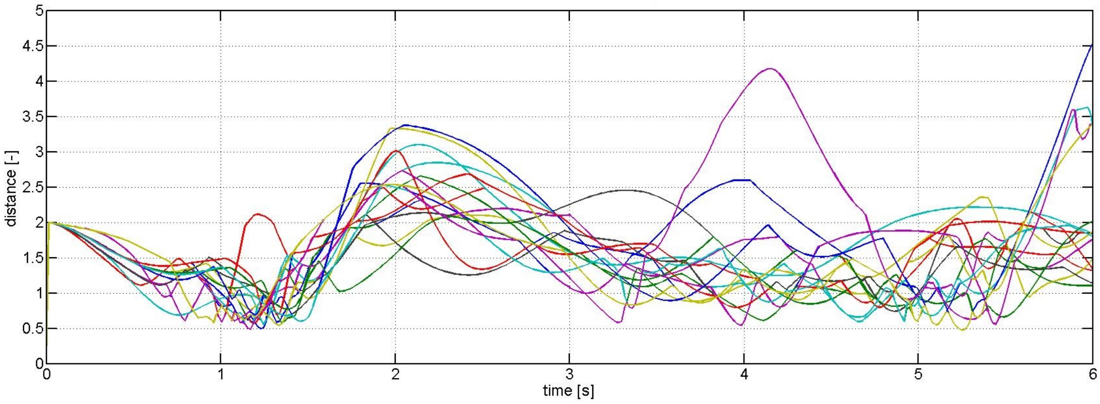

Figure 15 The shortest distances to other quad-rotor. The number of neighbours is set N = 2

The last experiment is with setting of number of neighbours $N = 3$. Graph for this setting is shown at the figure 16. There is no separation of a quad-rotor from the swarm in experiments with setting $N = 2$ and $N = 3$.

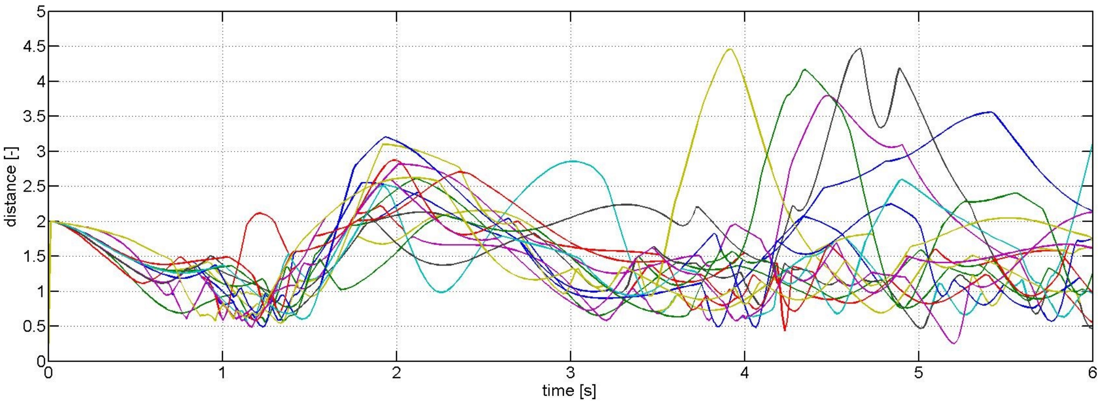

Figure 16 The shortest distances to other quad-rotor. The number of neighbours is set N = 3

B Next experiments show the behaviour of swarm with other parameters. The required distances between quad-rotors for these experiments are $cd = 1, md = 1.4$ and $fd = 2$, where cd is *close distance*, md is *mean distance* and fd is *far distance*. A quad-rotor should not exceed the minimum required distance $cd/2 = 0.5$ and maximum required distance $2 \cdot fd = 4$.

The simulations result is same as the result of simulations with the previous setting. If the number of neighbours is set $N = 0$, a quad-rotor separates from the swarm. If the number of neighbours is not set $N = 0$, no one quad-rotor exceeds the maximal required distance.

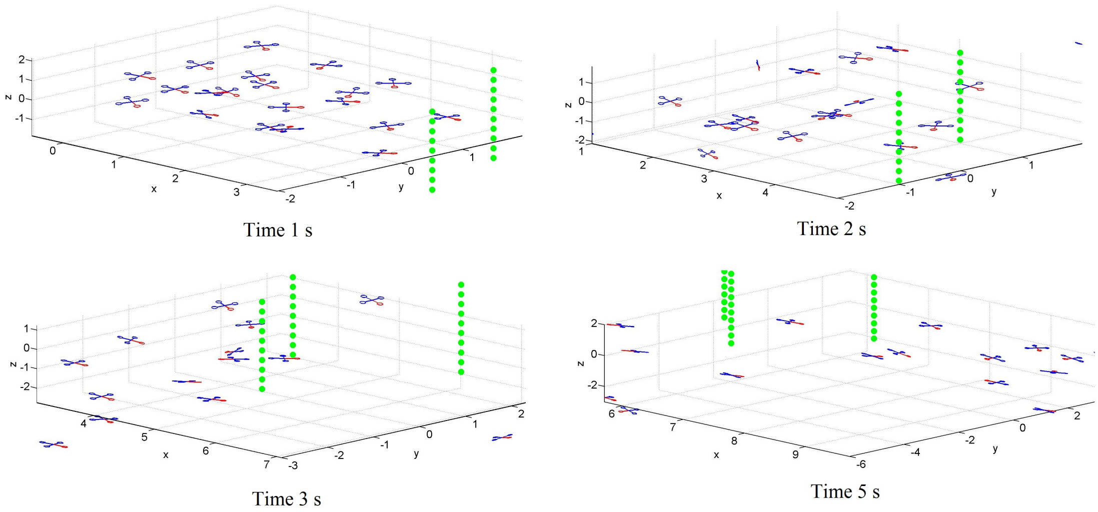

Figure 17 Sample of simulation. The number of neighbours is set N = 0. A quad-rotor separates from the other quad-rotors, because there is no attract force acting on long distance.

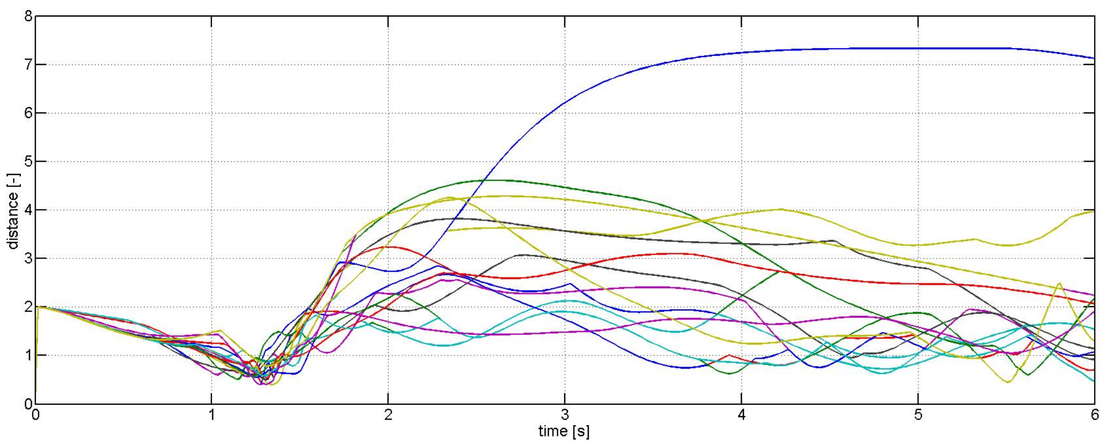

Figure 18 The shortest distances to other quad-rotor. The number of neighbours is set N = 0

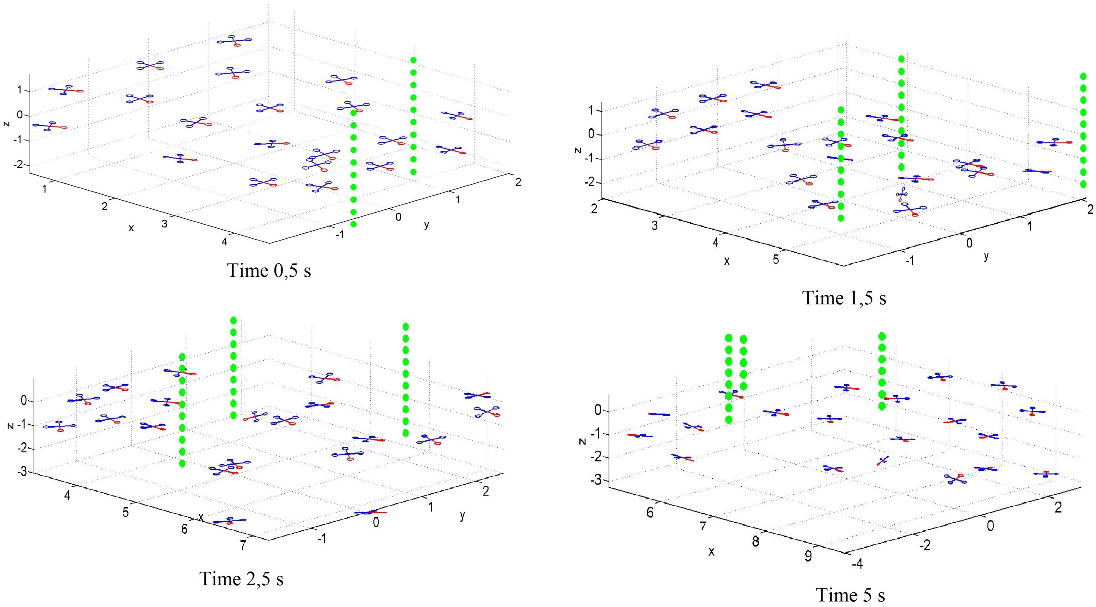

Figure 19 Sample of simulation. The number of neighbours is set N = 1.

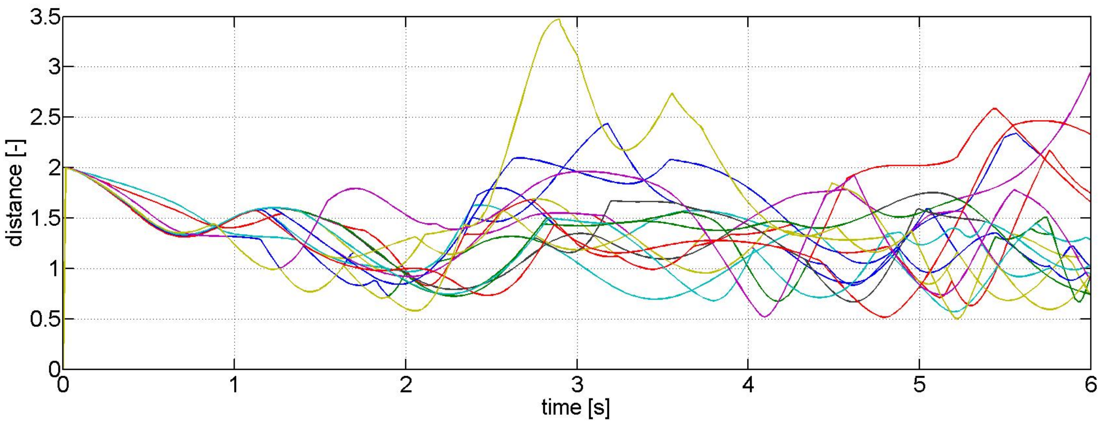

Figure 20 The shortest distances to other quad-rotor. The number of neighbours is set N = 1. No one quad-rotor separates from the swarm.

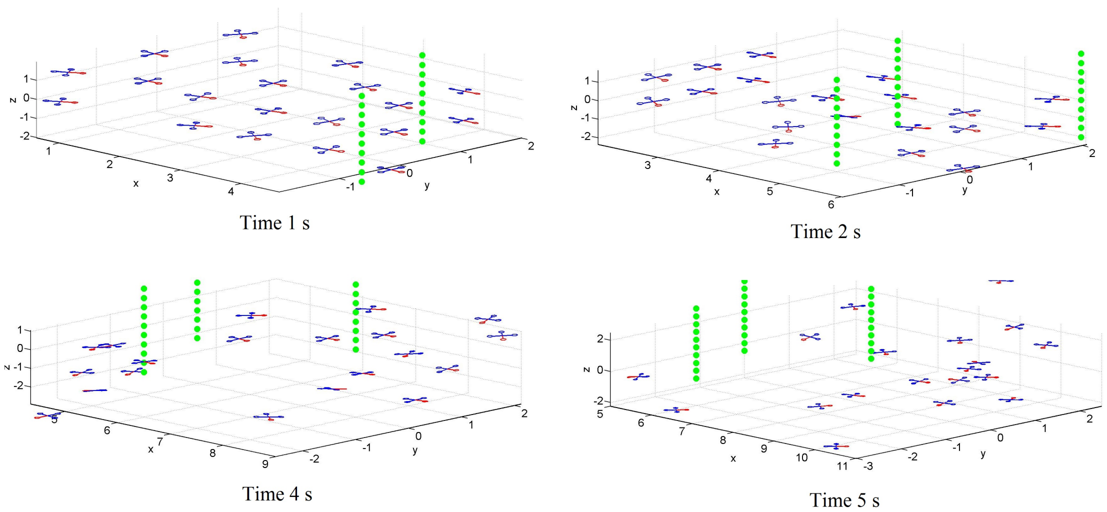

Figure 21 Sample of simulation. The number of neighbours is set N = 2

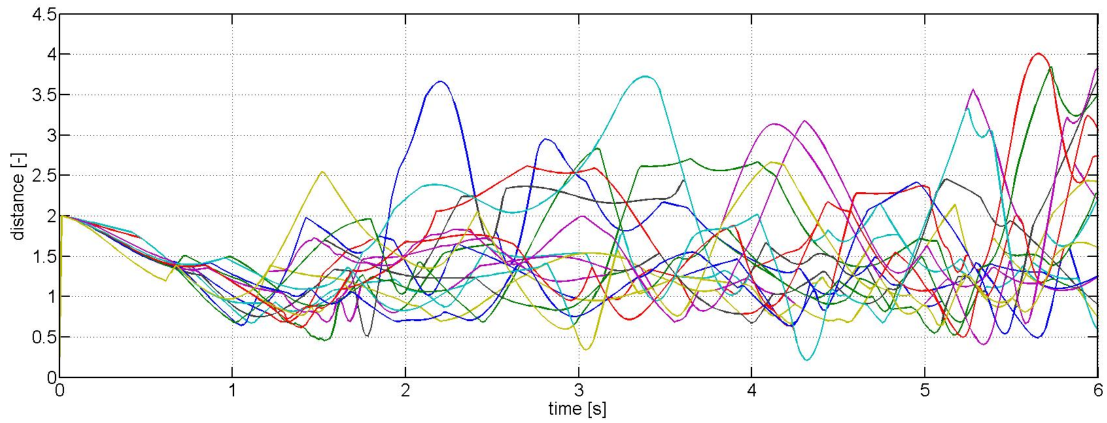

Figure 22 The shortest distances to other quad-rotor. The number of neighbours is set N = 2

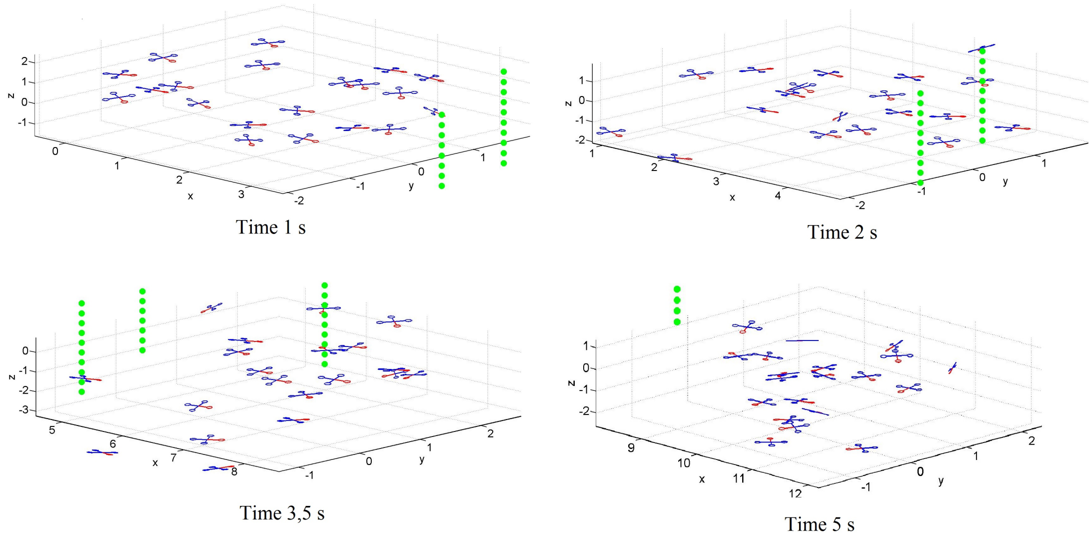

Figure 23 Sample of simulation. The number of neighbours is set N = 3

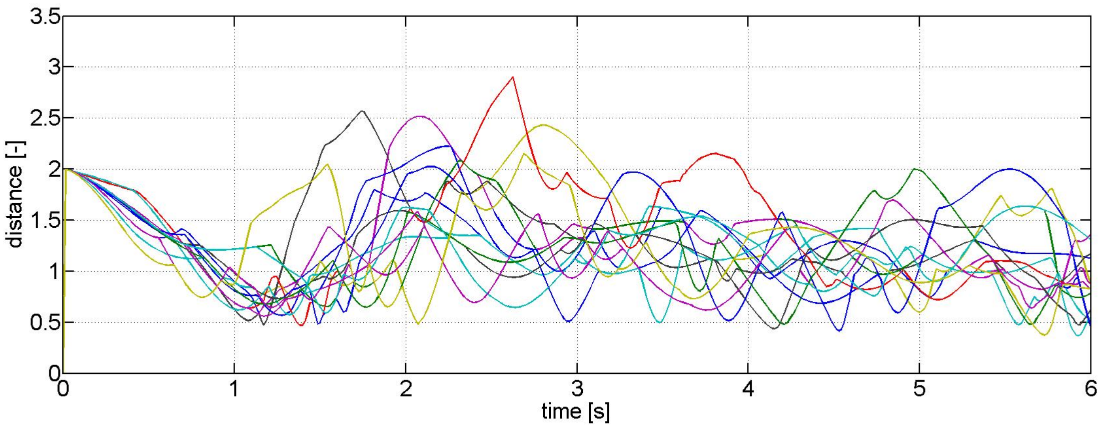

Figure 24 The shortest distances to other quad-rotor. The number of neighbours is set N = 3

7.2 Exceeding of limits of required distances

A quad-rotor exceeds the minimum or maximum required distances. It is shown at the figure 25, where the required distances are marked. The borders of zones are marked as blue lines and minimum and maximum required distances are marked as red lines.

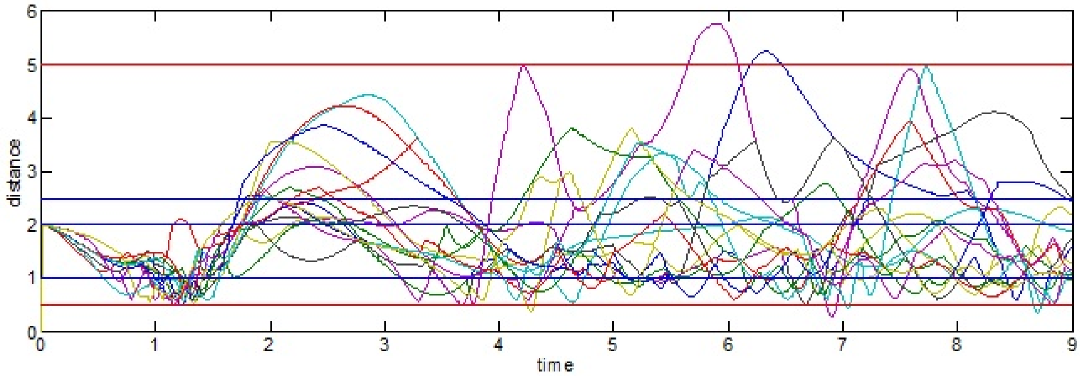

Figure 25 The shortest distances to other quad-rotor with marked required distances.The far distance is set $fd = 2.5$, the mean distance is $md = 2$ and the close distance is $cd = 1$. The maximal required distance is set $2 \cdot fd = 5$ and minimal required distance is $cd/2 = 0.5$.

The exceeding of minimal required distance is caused by pushing of a quad-rotor to another by two other quad-rotors. The composite repulsive force from two neighbouring quad-rotors push quad-rotor to another against its repulsive force. It can not be avoided even by increasing the repulsive force. The exceeding of maximal required distance can be avoided by increasing attractive force. It is shown at the figure 26.

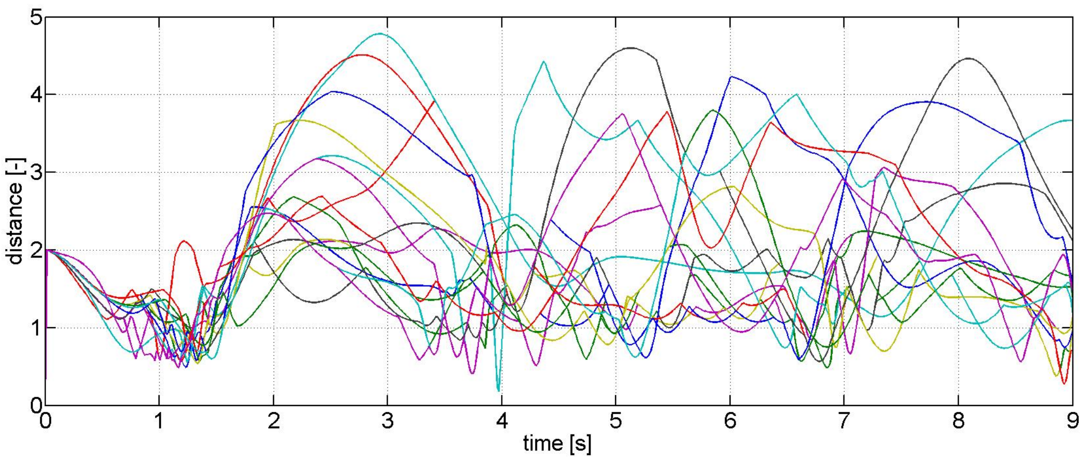

Figure 26 The shortest distances to other quad-rotor. The setting of distances is same as for graph at figure 25. The differences are the setting of values of weight function. The value of attractive force for long distance is higher than the value of the previous simulation.

7.3 Comparing with the original algorithm

Comparing of implemented algorithm with the original algorithm is described in this section. The original algorithm is implemented by the flocking equations witch are described in the chapter 4. The required distance is set only by constant L_r. Graph of the shortest distances to other quad-rotor for $L_r = 1$ is shown at the figure 27, $L_r = 1.2$ is shown at the figure 28 and $L_r = 1.5$ is shown at the figure 29.

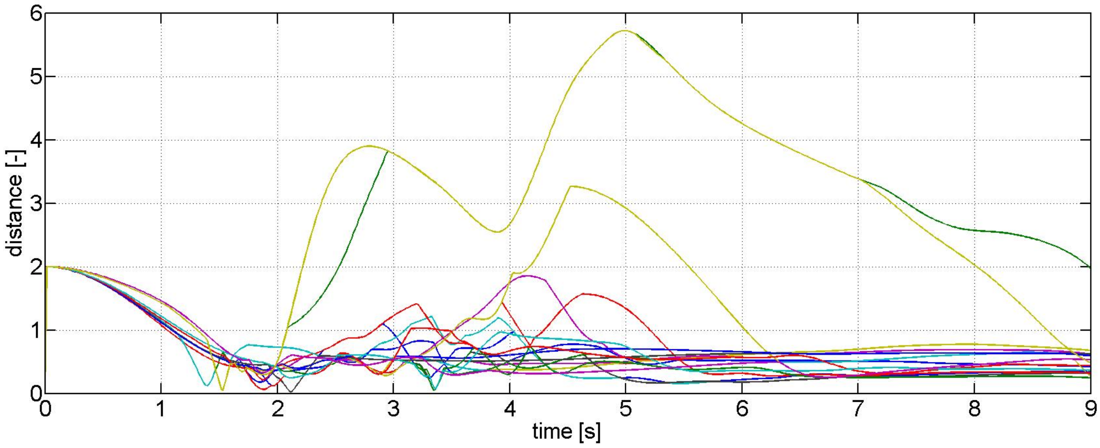

Figure 27 The shortest distances to other quad-rotor for $L_r = 1$

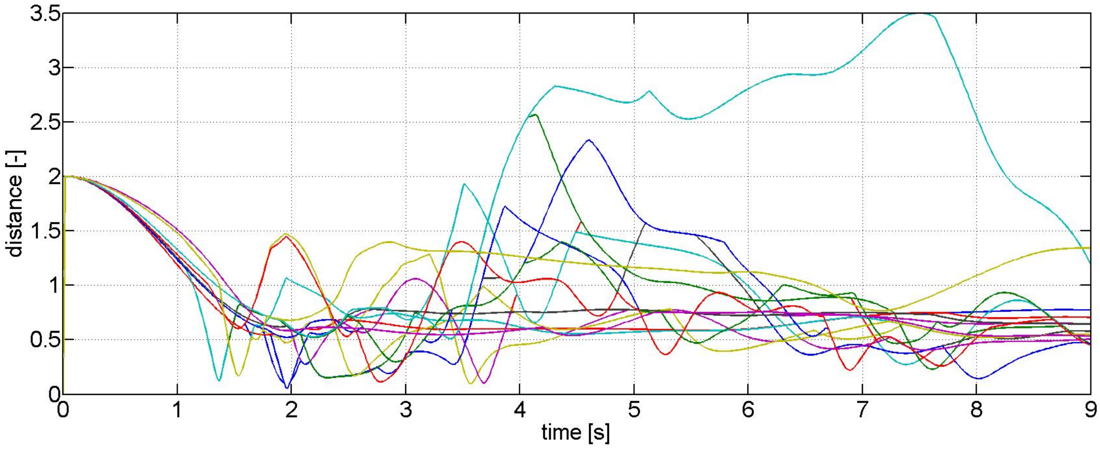

Figure 28 The shortest distances to other quad-rotor for $L_r = 1.2$

Some quad-rotors approached to each other, because there are not repulsive force. In this case can happen to crash. Some quad-rotors separated from the swarm at the graph 27. There is no attractive force, which attracts quad-rotors to each other on the longer distance.

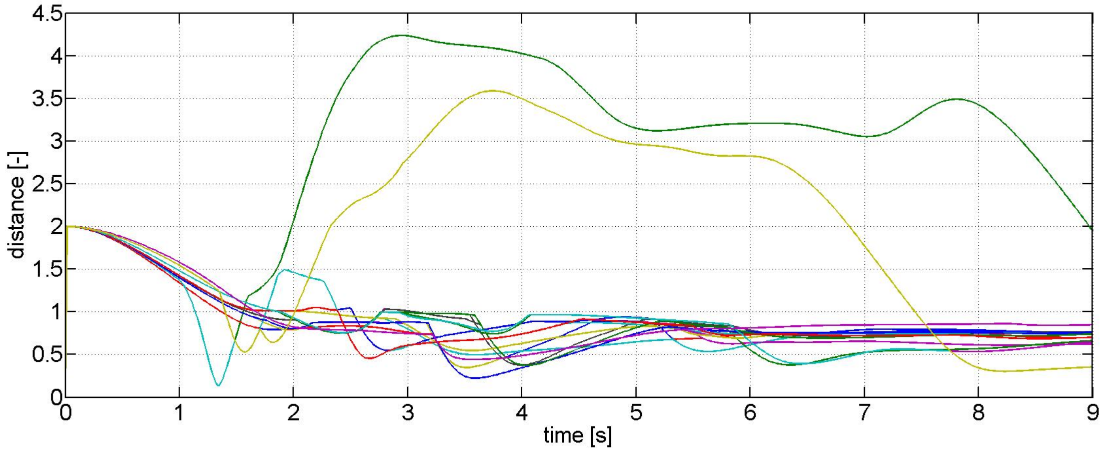

Figure 29 The shortest distances to other quad-rotor for $L_r = 1.5$

8 Splitting of the swarm

The swarm splits to several small groups sometimes. It is not exceeds of maximal required distance between quad-rotors, because each quad-rotor have enough neighbours in its area. It can be seen at the figure **??** in time 4 s. There is small group of quad-rotors, which separate from others. The group consists of eight quad-rotors. Analysis of the splitting is described in this chapter.

The splitting of the swarm depends on initial placement of quad-rotors, placement of obstacles and the setting of distances and forces between quad-rotors. quad-rotors have too large distances between them in the simulations in previous chapter to determine if the swarm splits to small groups. The simulations with smaller distances between quad-rotors is shown at the figures 31 and 33. The required distances between quad-rotors for these experiments are $cd = 0.6$, $md = 1$ and $fd = 1.5$, where cd is $close\ distance$, md is $mean\ distance$ and fd is $far\ distance$. A quad-rotor should not cross the minimum required distance $cd/2 = 0.3$ and maximum required distance $2 \cdot fd = 3$. The number of neighbouring quad-rotor N is set to $N = 1$ and $N = 3$. quad-rotors are close to each other so that a small group is more visible.

Splitting of the swarm to the four groups is shown at the figure 31 in time 3 s. This splitting of the swarm is caused by initial placement. quad-rotors attract so that quad-rotors formed three groups at the beginning of the simulation. This can be changed by placing quad-rotors closer or increase the number of required neighbours. The simulation with number neighbours $N = 3$ is shown at the figure 33. There is no splitting of the swarm, because the higher number of neighbours avoid to splitting.

If a swarm begins splitting to the groups, there is only small attractive force between mean distance and far distance to attract quad-rotors together. The effect of this force is shown at the figures 34 and 35. The attract force is not zero between mean distance and far distance for simulation in figure 34. The attract force is set zero for the second simulation in figure 35. A obstacle divides the swarm to the groups, if the force is zero between mean and far distances. If the attractive force is not zero, the swarm rejoins behind the obstacle. The goal is placed in the point [15,0,1] to minimize attract the groups to each other by force to goal.

The swarm splits to the groups, if a group of quad-rotors gets out of reach of the attractive force of the rest quad-rotors. Both groups must contain enough quad-rotors to satisfy the condition on the number of neighbour. If a group does not have enough members, the forces attract the groups together.

8.1 Value of force

The value of attractive and repulsive force is shown at the figure 36. The attractive force has negative values and the repulsive force has positive values. The shortest distance to other quad-rotor is shown at the figure 37. If a quad-rotor approaches to another, the force repels. The attractive force increases at the end of simulation, because a quad-rotor exceeds the far distance.

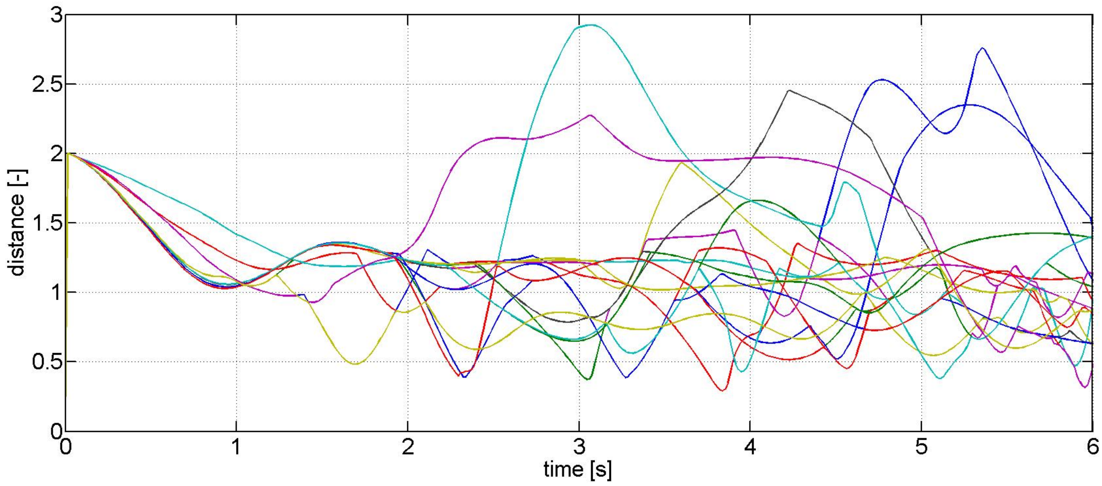

Figure 30 The shortest distances to other quad-rotor. The number of neighbours is set N = 1.

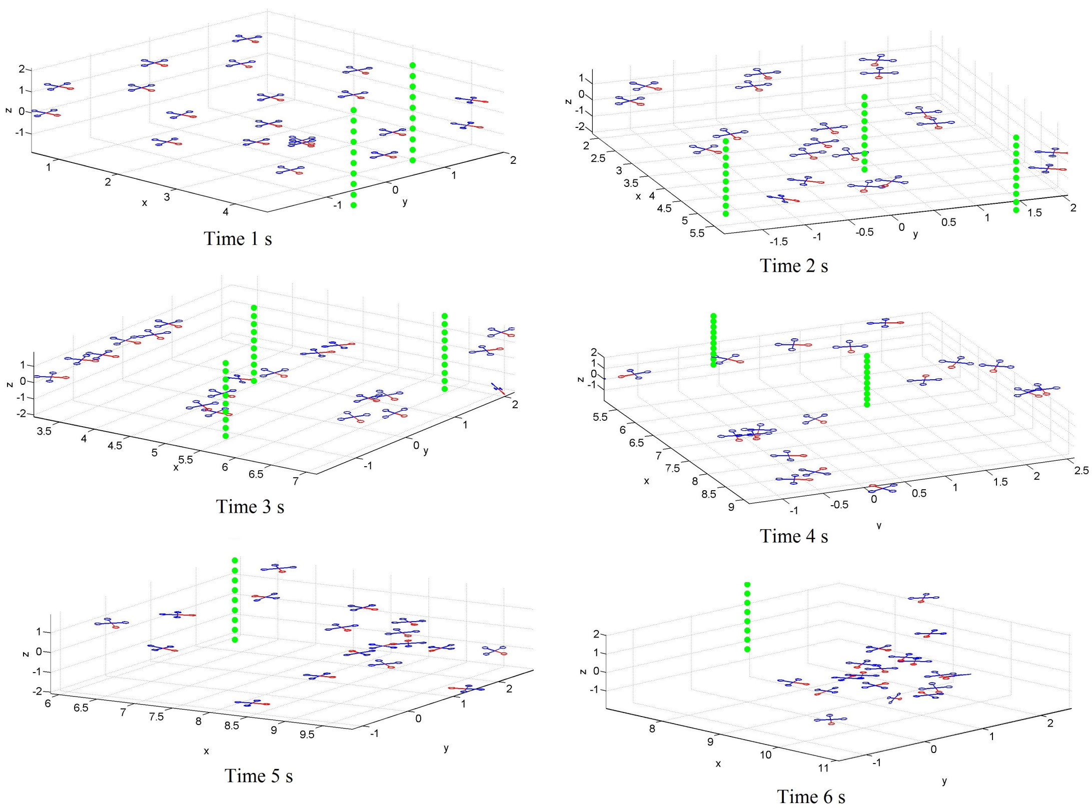

Figure 31 Sample of simulation. The number of neighbours is set N = 1. The swarm splits to 4 groups in time 3 s. The swarm rejoins in time 6 s, when the quad-rotors reach the goal.

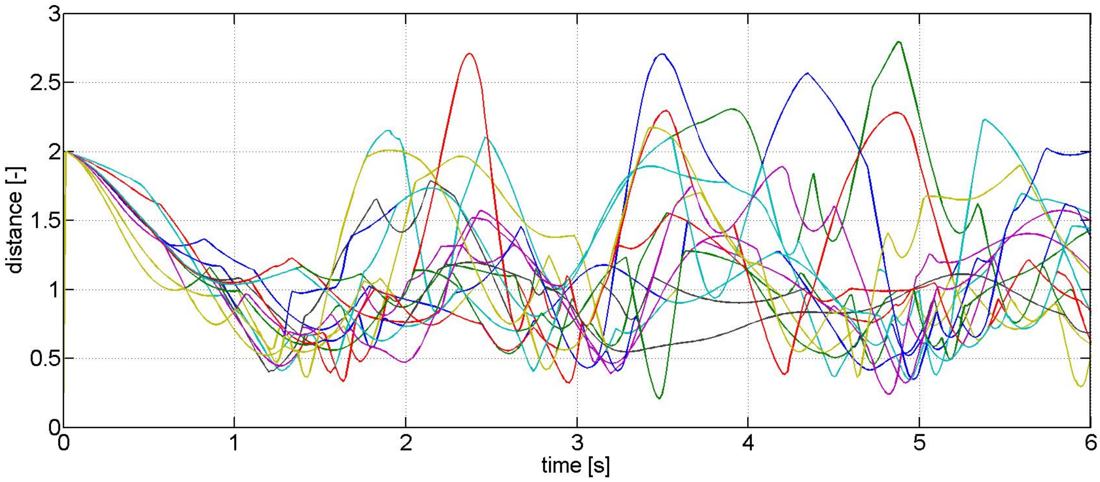

Figure 32 The shortest distances to other quad-rotor. The number of neighbours is set N = 3.

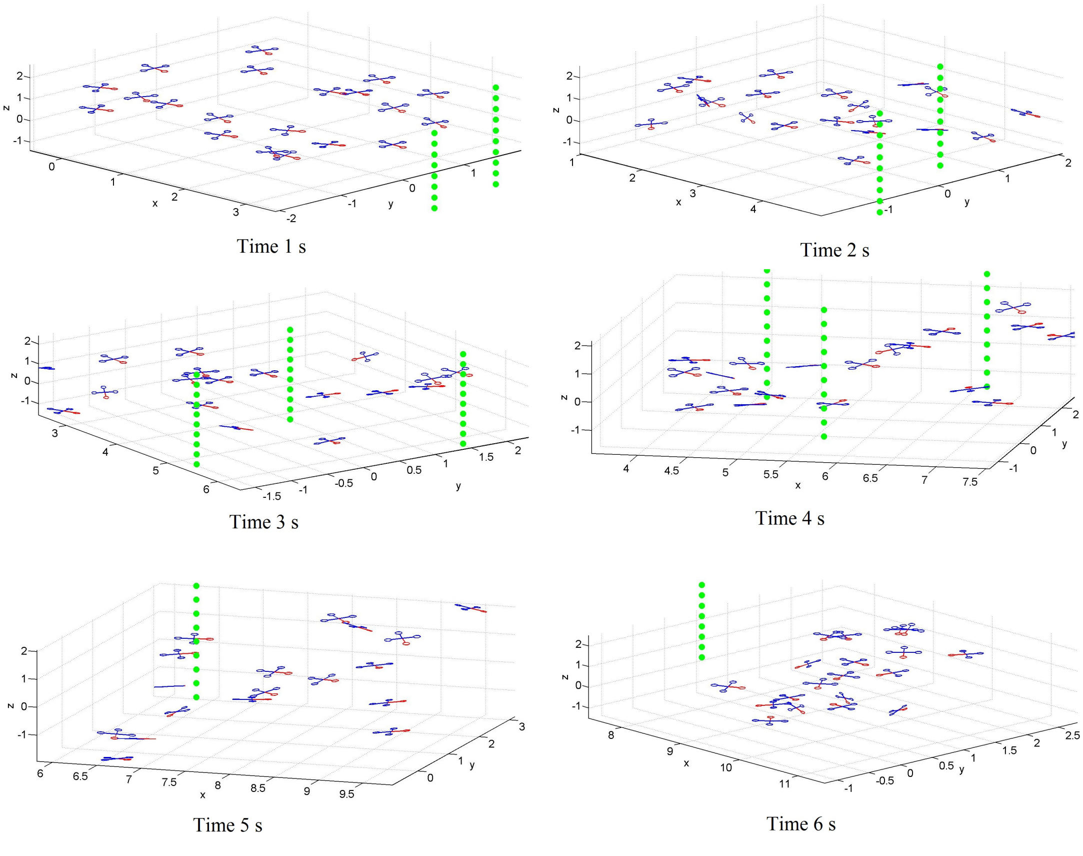

Figure 33 Sample of simulation. The number of neighbours is set N = 3. The swarm doesn't split during the flight. The higher number of neighbours reduces the possibility of the splitting.

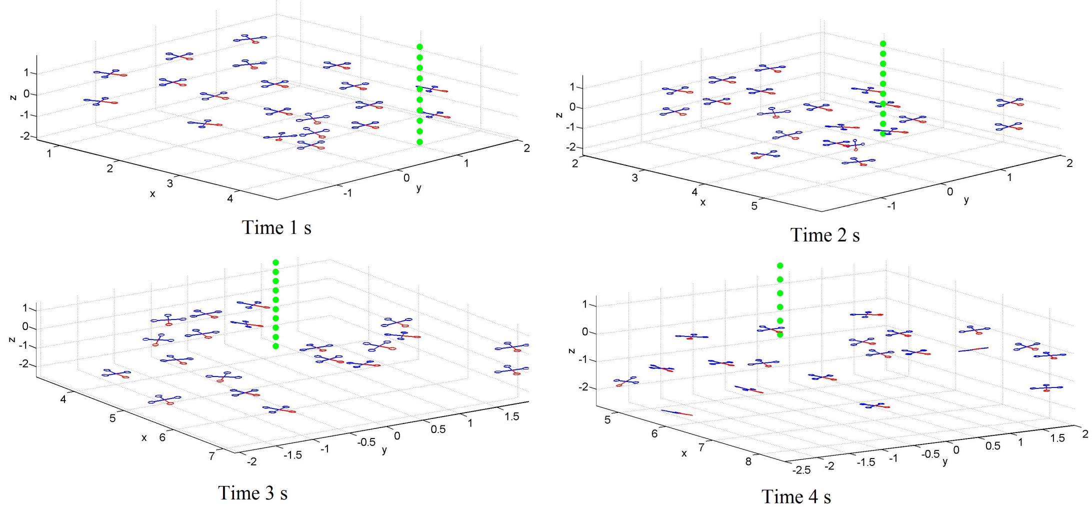

Figure 34 Sample of simulation with attract force between mean distance md and far distance fd. The quad-rotors rejoins to a swarm behind the obstacle.

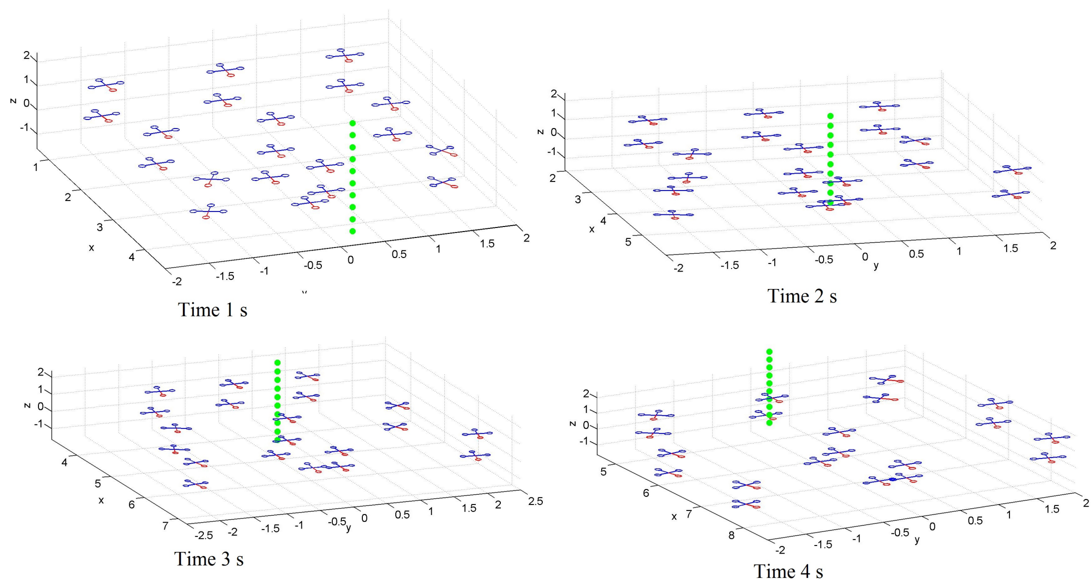

Figure 35 Sample of simulation without attract force between md and fd. The swarm splits to three groups behind the obstacle.

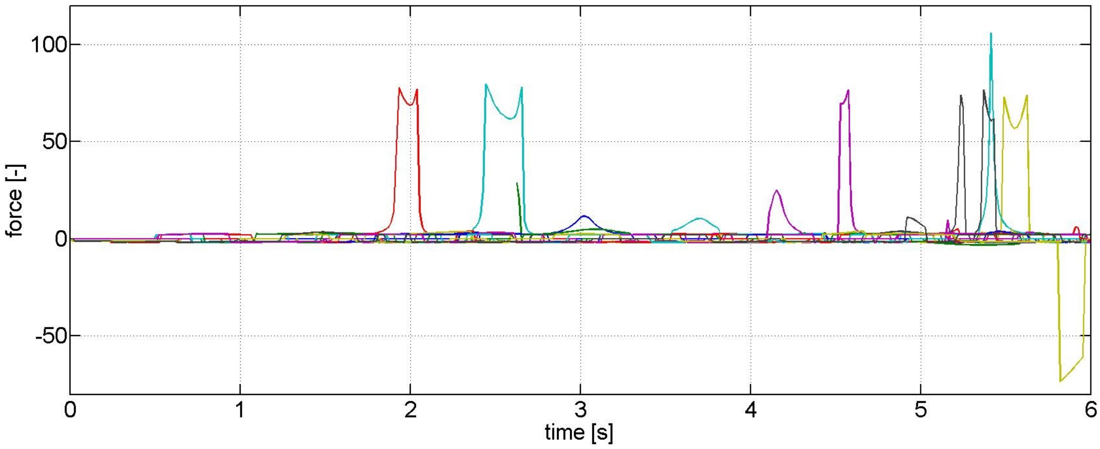

Figure 36 The value of force acting between quad-rotors. The attractive force has negative values and the repulsive force has positive values.

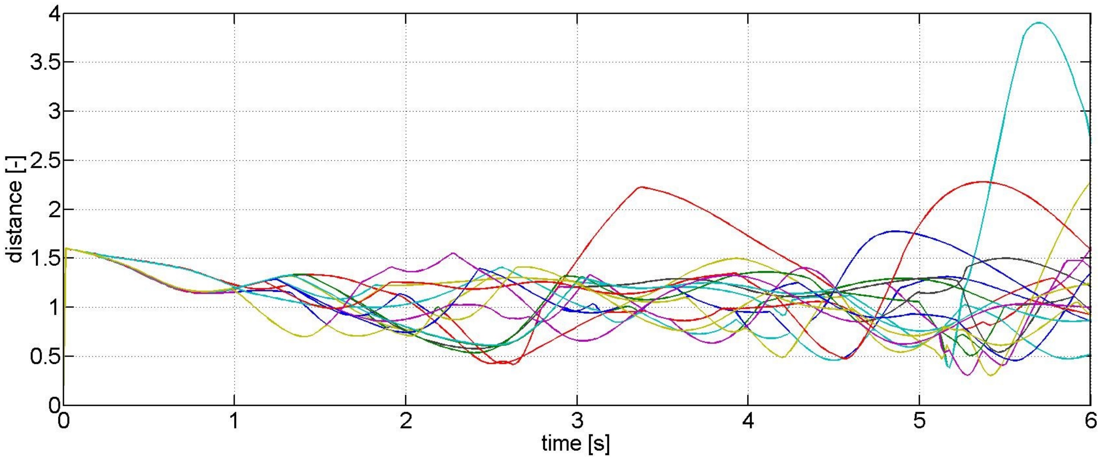

Figure 37 The shortest distances to other quad-rotor.

9 Obstacles

More complex obstacles are described in this chapter. Obstacles were implemented as point or line which a quad-rotor should avoid. The implementation of more complex two-dimensional obstacles are described in this chapter. A complex obstacles can modelling a wall, door or window.

The model of door was chosen for description of the obstacle and analysis of swarm behaviour.

The easiest implementation of the model of door is shown at the figure 38.

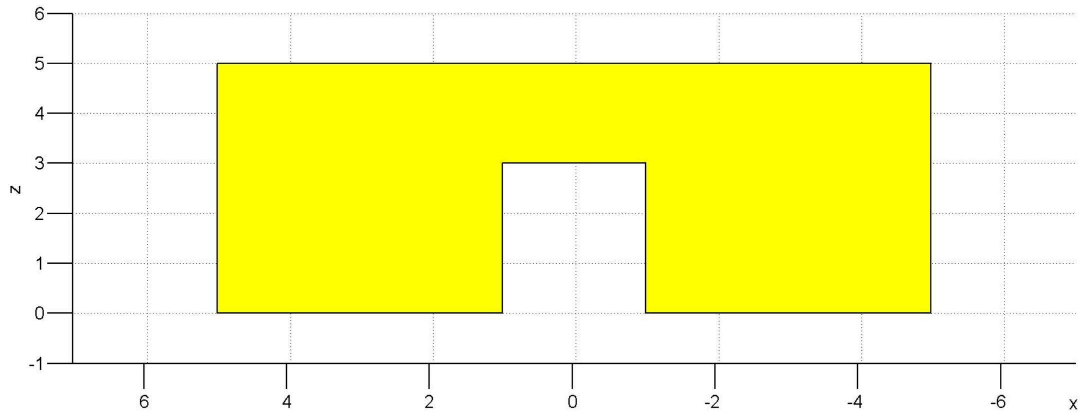

Figure 38 Model of obstacle with doorway

This representation of obstacles has a disadvantage. The calculation of the force to obstacles $\mathbf{F}_{obs}$ is not suitable for this obstacle. If the obstacles is more complex (wider and higher), the quad-rotor does not fly around the obstacle. The quad-rotor flies through the obstacle, although the force to obstacle acting at the quad-rotor.

A solution of this disadvantage is to design the obstacle so that a quad-rotor slides around the obstacle. This is achieved by the obstacle, which consists of inclined planes. The force to obstacle guides a quad-rotor along the inclined plane of obstacle. An example of this obstacle is shown at the figure 39.

To the force to obstacles $\mathbf{F}_{obs}$ is added repulsive force from the obstacle $\mathbf{F}_{o\perp}$. The direction of the force $\mathbf{F}_{o\perp}$ is the same as the direction of relative position vector $\mathbf{L}_{oi}$ between $i-$th quad-rotor and an obstacle. This force prevents a quad-rotor approaching too close to an obstacle. The force $\mathbf{F}_{o\perp}$ acts only at a small distance between quad-rotor and obstacle. The force $\mathbf{F}_{o\perp}$ is designed as

$$\mathbf{F}_{o\perp} = e_{oi} \cdot \mathbf{L}_{oi}, \tag{35}$$

where e_{oi} is distance function.

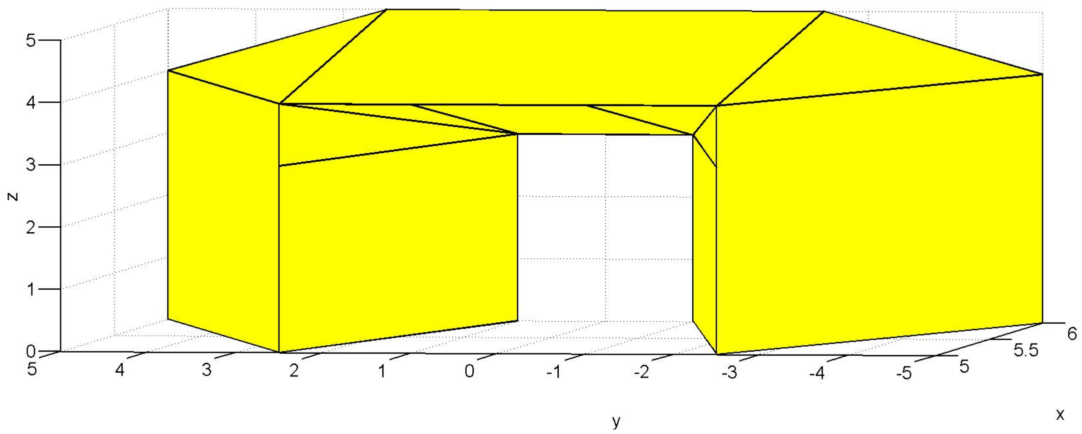

Figure 39 Obstacle

9.1 Force from the ground

The ground is an obstacles too. The difference between the ground and an obstacles is that a quad-rotor cannot get under the ground. The level of the ground was chosen in the plane $z = 0$. The force from the ground $\mathbf{F}_{gnd_i}$ is force acting at $i-$th quad-rotor if the quad-rotor approaches to the ground. The direction of the force $\mathbf{F}_{gnd_i}$ is perpendicular to the plane of the ground and it is acting upward.

9.2 Simulation

The behaviour of the swarm in simulation with obstacle is shown in this section. Sample of simulation is shown at the figure 41. There is shown flight of quad-rotors around the obstacle. The graph of distance to the obstacle is shown at the figure 40. Two quad-rotors fly through the obstacle. It is caused by that the force to obstacle is not sufficient for this obstacle. The design of obstacle so, that a quad-rotors slide around obstacle, don't prevent it. The solving should be add a algorithm for search of path around obstacle. Oscillation of values in the graph 40 is caused by changes of the nearest part of obstacle. Graph of the shortest distance to other quad-rotors for this simulation is shown at the figure

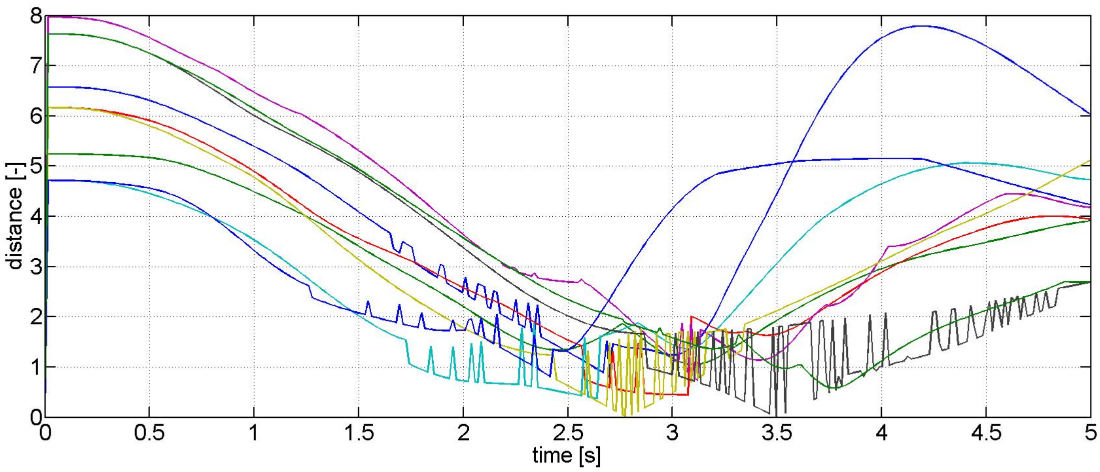

Figure 40 Distance to obstacle

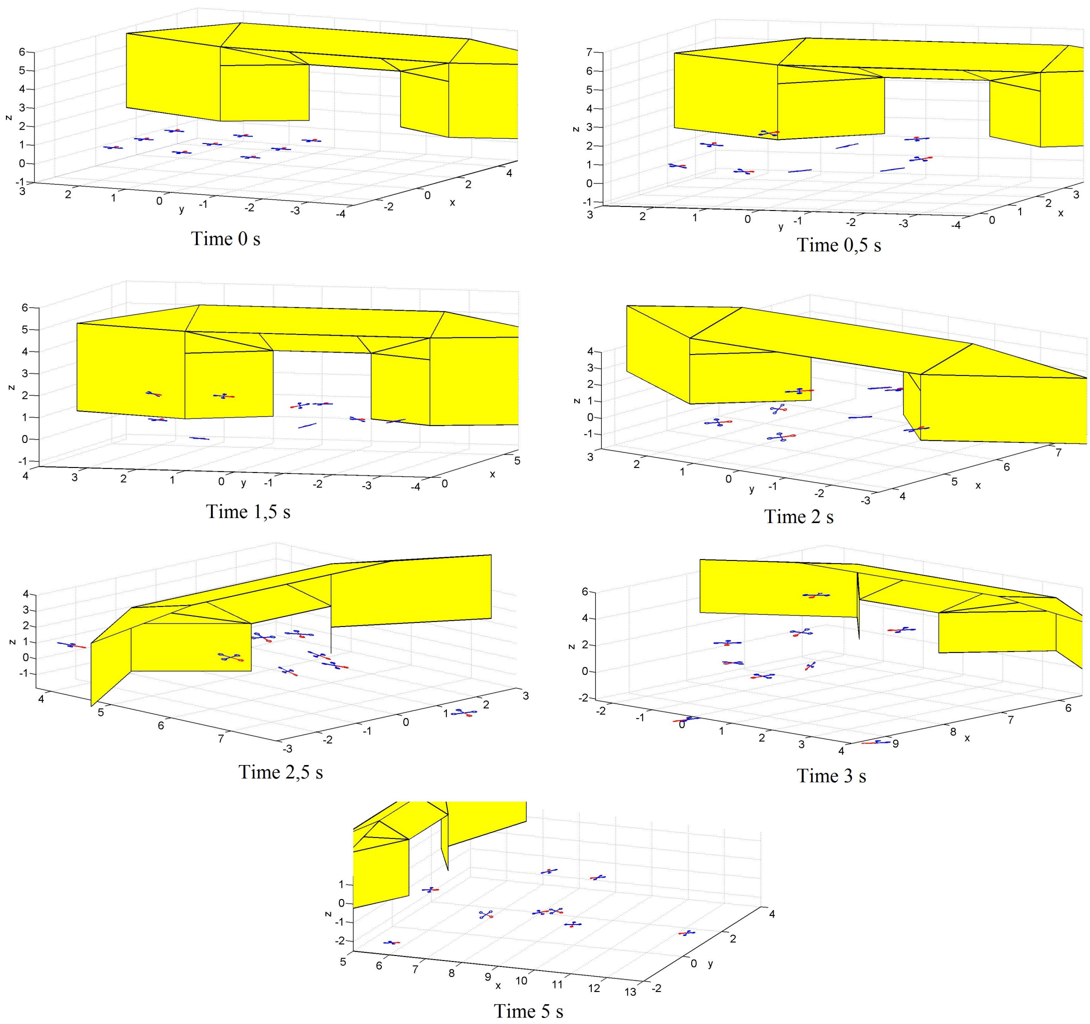

Figure 41 Samples of simulation. The swarm of 9 quad-rotors flies to the goal, which is placed behind the obstacle. The obstacle consists of the inclined plane.

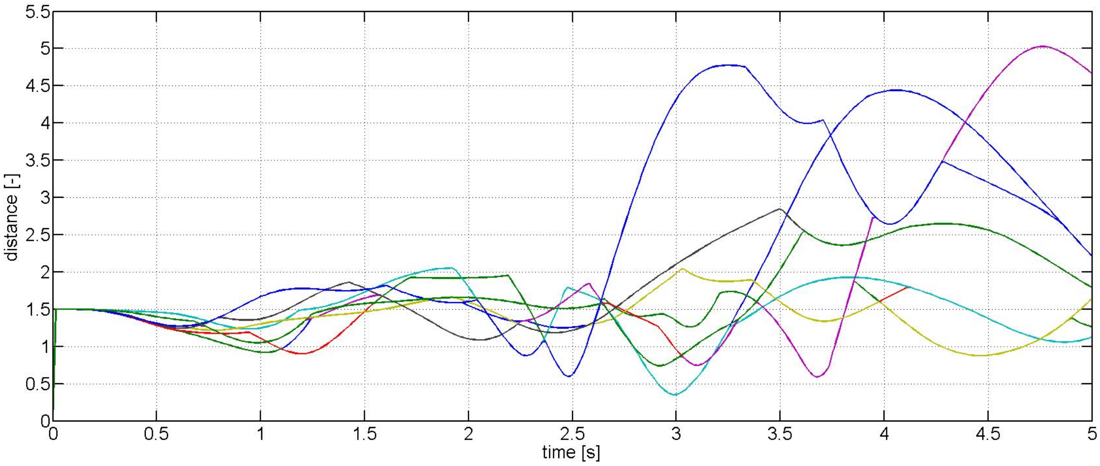

Figure 42 The shortest distances to other quad-rotor

10 Simulator of university of UPENN

Verification of functionality of the constraints given by the relative visual localization in simulator of University of Pennsylvania is shown in this chapter. The simulator was developed at University of Pennsylvania by Justin Thomas [9].

The simulator uses a predefined trajectory to movement of quad-rotors. Repulsion and attraction of quad-rotors is implemented as change of the next point of trajectory farther from a neighbouring helicopter for repulsion or closer to a neighbouring helicopter for attraction. This ensure the required distance between quad-rotors. The effect of repulsion is shown at the figures 44 and 45. The graph of distance between quad-rotorts with origin setting is shown at the figure 43. The constant close distance cd determines the minimal distance between quad-rotors. Close distance for simulation is set $cd = 1.4$ for graph 44 and $cd = 1.5$ for graph 45.

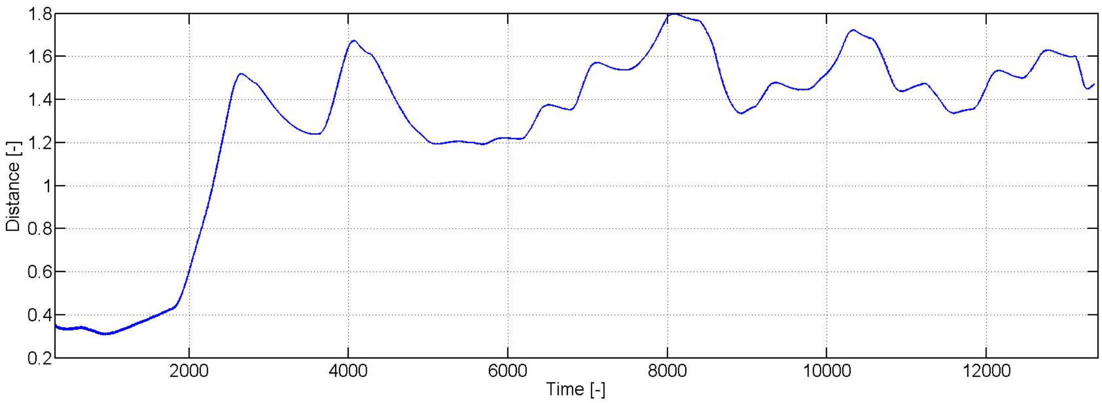

Figure 43 Distance between quad-rotors without repulsion

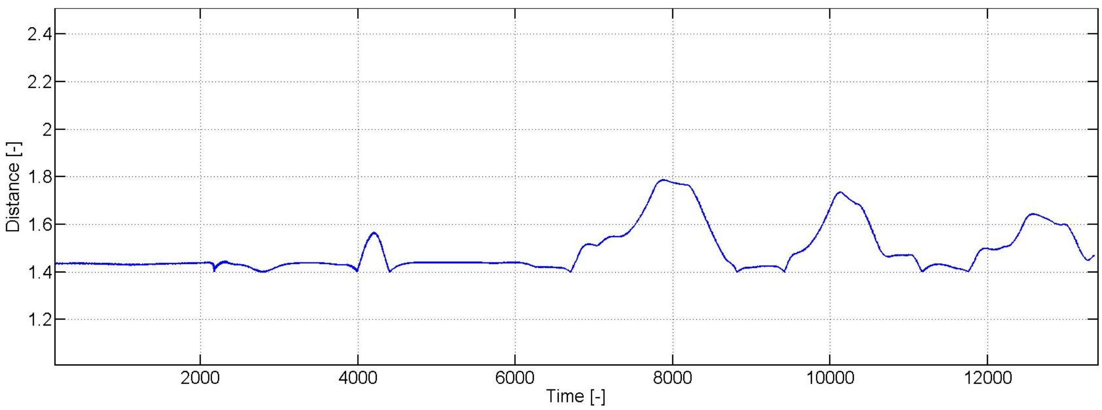

Figure 44 Distance between quad-rotors with close distance $cd = 1.4$

The distance between quad-rotors at the graph 45 is smaller than close distance at the begin of simulation. It is caused by initial distance between helicopters. The quad-rotors didn't approach to each other elsewhere during the simulation.

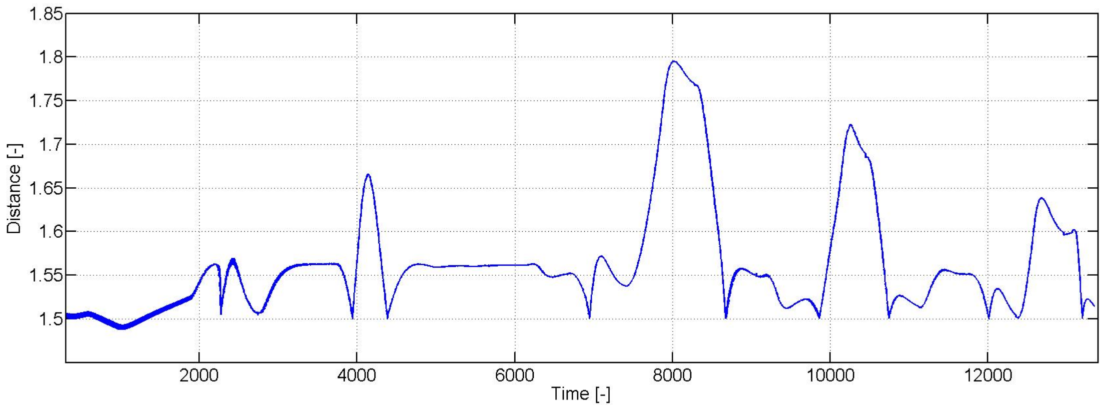

Figure 45 Distance between quad-rotors with close distance $cd = 1.5$

The samples of simulations are shown at the figure 46. There two quad-rotors are shown during the flight. The constant close distance is set $cd = 1.5$.

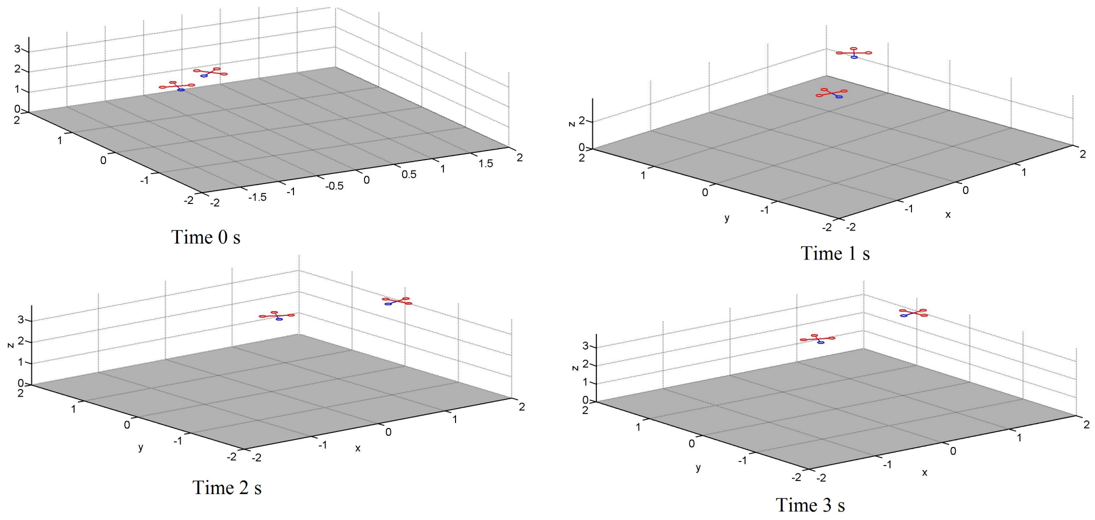

Figure 46 Samples of simulation with close distance set $cd = 1.5$. The quad-rotors fly along the desired trajectory and avoid to other one

11 Conclusion

The methods, which ensures that the constraints given by the relative visual localization and by mutual influence of quad-rotors in a swarm, were described in this thesis. These methods were designed to prevent the collision of frames of quad-rotors and the collision of a quad-rotor with a air flow induced by rotor of another helicopter in a swarm. The methods are implemented to the algorithm of escape behaviour of swarm of unnamed quad-rotors. The functionality of designed algorithm was verified by simulations in program Matlab using a swarm of quad-rotor.

The method to prevent the collision of frames of quad-rotors was designed and implemented as attractive and repulsive force. The value of the force depending on distance between quad-rotors and number of neighbouring quad-rotors. The method to prevent the collision of a quad-rotor with a air flow induced by rotor of another quad-rotor was designed as offset of z coordinate to which relative position vector between quad-rotors is calculated.

The simulations of behaviour of swarm are presented in chapter 7. Snapshots of simulations capturing the swarm flight are shown in this chapter. The functionality of attractive and repulsive force are shown by graph of the shortest distance between quad-rotors.

The attractive and repulsive force prevent collision of quad-rotors and separation of a quad-rotor from a swarm better than original algorithm. A quad-rotor usually doesn't exceed minimal or maximal required distance. The exceeding of minimal required distance is caused by pushing of a quad-rotor to another by two other quad-rotor, but this does not happen very often. The composite repulsive force from two neighbouring quad-rotors push quad-rotor to another against its repulsive force. It can not be avoided even by increasing the repulsive force.

The conditions of splitting of a swarm is described in chapter 8. A swarm splits to the groups, if a group of quad-rotors gets out of reach of the attractive force of the rest quad-rotors. Both groups must contain enough quad-rotors to satisfy the condition on the number of neighbour. If a group does not have enough members, the forces attract the groups together.

More complex obstacles are described in chapter 9. This obstacles consist of planes to which the force to obstacles are calculated. The current algorithm is not satisfactory for this kind obstacles. A quad-rotor cannot flies around the obstacle. A solution may be using of strategy for searching a path.

References

[1] Atomic force microscopy, 2008,
$http : //www.jhu.edu/chem/fairbr/teach/AFM/AFwebpage.html$.
[2] Embedded visual control, 2014,
$http : //www.es.ele.tue.nl/\ heco/courses/EmbeddedVisualControl$.
[3] Sarah E. Ard. Search and rescue, 2005,
$http : //www.navy.mil/view_{i}mage.asp?id = 23913$.
[4] Paul Cantrell. Helicopter aerodynamics,
$http : //www.mionome.com/Uni/Helicopter\%20Aerodynamic.pdf$.
[5] John D'Errico. Matlab function inhull, 2006,
$http : //www.mathworks.com/matlabcentral/fileexchange/10226 - inhull$.
[6] Nassim Khaled. Matlab functionstraight line and plane intersection, 2007,
$http : //www.mathworks.com/matlabcentral/fileexchange/17751 - straight - line - and - plane - intersection$.
[7] Hongkyu Min and Zhidong Wang. Design and analysis of group escape behavior for distributed autonomous mobile robots. IEEE International Conference on Robotics and Automation 2011.
[8] N. Harris McClamroch Taeyoung Lee, Melvin Leok. Geometric tracking control of a quadrotor uav on se(3).IEEE International Conference on Robotics and Automation 2010.
[9] Justin Thomas. Research in micro aerial vehicles.
$http : //www.jtwebs.net$.
[10] Jan Vakula. Bachelor's thesis Escape behavior in swarms of unmanned helicopters,CTU in Prague, 2012.
[11] Faigl, J. - Krajník, T. - Chudoba, J. - Přeučil, L. - Saska, M.: Low-Cost Embedded System for Relative Localization in Robotic Swarms, Proc. of IEEE International Conference on Robotics and Automation (ICRA), 2013
[12] Martin Saska, Jan Vakula, and Libor Preucil. Swarms of micro aerial vehicles stabilized under a visual relative localization. Accepted for IEEE ICRA, 2014