CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF CYBERNETICS

Bachelor thesis

FSS Algorithm Adapted for Swarm Control of Unmanned Helicopters

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Study Program: Cybernetics and Robotics

Specialization: Robotics

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I would like to thank my supervisor Dr. Martin Saska for his unselfish help and advices. I would also like to thank my parents for their support during my studies.

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Prohlášení autora práce

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne 14.5.2015 .... J. Mráček ....

Podpis autora práce

České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra kybernetiky

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

Student: Jindřich Mráček

Studijní program: Kybernetika a robotika (bakalářský)

Obor: Robotika

Název tématu: FSS algoritmus přizpůsobený pro řízení roje bezpilotních helikoptér

Pokyny pro vypracování:

Cílem práce je přizpůsobit optimalizační algoritmus FSS (Fish School Search) pro řízení roje bezpilotních helikoptér. V navrženém algoritmu budou jednotlivé částice FSS reprezentovat fyzické roboty, které se budou pohybovat na základě pravidel FSS. V rámci BP bude do klasického algoritmu FSS integrován kinematický model helikoptér a omezení dané relativní lokalizací entit robotického roje. Algoritmus bude experimentálně otestován a jeho chování porovnáno s metodou založenou na technice PSO.

1. Integrovat model helikoptéry zahrnující reálná omezení jejího pohybu [1].
2. Implementovat a integrovat omezení daná relativní lokalizací členů roje.
3. Nalézt optimální nastavení parametrů FSS [2].
4. Otestovat algoritmus v simulacích a jeho chování porovnat s metodou založenou na technice PSO [4,5].
5. Ověřit funkčnost metody s využitím dostupné robotické platformy. V průběhu řešení projektu vedoucí práce rozhodne, zda navržená metoda bude otestována krátkým experimentem s 2-3 helikoptérami, na lanovém multi--robotu, případně na systému SyRoTek [3].

Seznam odborné literatury:

[1] 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
[2] Carmelo J.A. Bastos Filho, Fernando B. de Lima Neto, Anthony J.C.C. Lins, Antonio I.S. Nascimento, Marília P. Lima: Fish School Search, Nature-Inspired Algorithms for Optimisation, SCI 193, pp. 261–277. 2009
[3] Kulich, M.; Košnar, K. ; Chudoba, J. ; Faigl, J. ; Přeučil, L.: On a Mobile Robotics E-learning System. In Proceedings of the Twentieth European Meeting on Cybernetics and Systems Research. Vienna: Austrian Society for Cybernetics Studies, 2010, p. 597-602. ISBN 978-3-85206-178-8.
[4] Kennedy, J. and Eberhart, R.C.: Particle swarm optimization. In Proceedings International Conference on Neural Networks IEEE, volume 4, pp. 1942–1948, 1995.
[5] Kennedy, J. and Eberhart R.C.: Swarm Intelligence, Morgan Kaufmann Publishers, 2001.

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

Platnost zadání: do konce zimního semestru 2013/2014

L.S.

prof. Ing. Vladimír Mařík, DrSc.
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V Praze dne 10. 1. 2013

Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Cybernetics

BACHELOR PROJECT ASSIGNMENT

Student: Jindřich M r á č e k

Study programme: Cybernetics and Robotics

Specialisation: Robotics

Title of Bachelor Project: FSS Algorithm Adapted for Control of Swarm of Unmanned Helicopters

Guidelines:

The aim of the work is to adapt the optimization algorithm FSS (Fish School Search) [2] for control of swarms of unmanned helicopters. In the proposed algorithm, the individual FSS particles represent physical robots that will move according to the FSS rules. A kinematic model of helicopters will be integrated into the FSS together with restrictions of the relative localization between the swarm particles. The algorithm will be experimentally verified and its behavior compared with the method based on the PSO technique.

1. Integrate the model of helicopters including the real limitation of motion [1].
2. Implement and integrate the constraints of the relative localization of swarm members.
3. Find the optimal parameters of the FSS.
4. Verify functionalities of the algorithm in simulations and compare its behavior with a method based on the PSO technique [4,5].
5. Verify the functionality of the method using the available robotic platforms. Thesis supervisor will decide whether the proposed method will be tested by a simple experiment with 2-3 helicopters, using a rope multi-robot system or on SyRoTek system [3]

Bibliography/Sources:

[1] 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
[2] Carmelo J.A. Bastos Filho, Fernando B. de Lima Neto, Anthony J.C.C. Lins, Antonio I.S. Nascimento, Marılia P. Lima: Fish School Search, Nature-Inspired Algorithms for Optimisation, SCI 193, pp. 261–277. 2009
[3] Kulich, M.; Košnar, K. ; Chudoba, J. ; Faigl, J. ; Přeučil, L.: On a Mobile Robotics E-learning System. In Proceedings of the Twentieth European Meeting on Cybernetics and Systems Research. Vienna: Austrian Society for Cybernetics Studies, 2010, p. 597-602. ISBN 978-3-85206-178-8.
[4] Kennedy, J. and Eberhart, R.C.: Particle swarm optimization. In Proceedings International Conference on Neural Networks IEEE, volume 4, pp. 1942–1948, 1995.
[5] Kennedy, J. and Eberhart R.C.: Swarm Intelligence, Morgan Kaufmann Publishers, 2001.

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

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Prague, January 10, 2013

Abstrakt

Tato bakalářská práce se zabývá algoritmem Fish School Search (FSS). Tento algoritmus slouží k prohledávání vícedimensionálního stavového prostoru. Byl vyvinut pro roj bezrozměrných částic. První část mé bakalářské práce řeší úpravou algoritmu Fish School Search (FSS), díky níž by bylo možné použití FSS pro řízení roje reálných kvadrokoptér. Tato úprava algoritmu tedy využívá roje fyzických částic a zejména zahrnuje omezení způsobená pohybem kvadrokoptér v reálném prostředí (kolize během letu, kolize v cílové pozici) a omezení daná relativní lokalizací jedinců. Člen hejna usiluje o to, aby měl v dohledu n dalších helikoptér.

Druhá část práce se věnuje porovnání FSS se standardním algoritmem Particle swarm optimization (PSO) na námi řešeném problému.

Poslední, třetí část, se věnuje ověření funkčnosti algoritmu na reálných kvadrokoptérách.

Klíčová slova: Metaheuristika, přírodou inspirovaný algoritmus, algoritmus FSS, algoritmus PSO, relativní lokalizace, kvadrokoptéra.

Abstract

This bachelor thesis is concerned with algorithm Fish School Search (FSS). The algorithm is used to searching vice-dimensional state space and it is developed for dimensionless particle. The first part of my bachelor thesis is given to modification of FSS for control a swarm of quadrocopters. The adjustment of the algorithm is given by employment of physical swarm particles mainly includes restrictions that are caused by movement in real search space (collisions during flight, collisions in the target spot) and restrictions that are caused by relative localization. A particle should see n others particles.

The second part deals with the comparison of algorithm FSS with Standard Particle Swarm Optimization (PSO).

The third part is given to verification of algorithm with real quadrocopters.

Keywords: Meta-heuristic, nature-inspired algorithm, algorithm FSS, algorithm PSO, relative localization, quadrocopters.

Contents

Chapter 1

1. Introduction

This paper deals with two optimization algorithm, Particle Swarm Optimization (PSO) and Fish School Search (FSS). Optimization is the process which tries to find the best solution of a given problem. We meet the optimization every day. It is everything around us. Businessmen try to optimize their business strategies, managers of factories try to optimize production process and majority of us try to optimize plans for our holidays. Mathematical optimization studies this planning and tries to find a solution with using mathematical tools.

The simplest method searching for optimum of function should explore the whole set of possible solutions and choose the best one. The advantage of this native method is, that it always finds the best solution, but this method is time-consuming for extensive problems with a lot of parameters (vice-dimensional space). Better methods use heuristic or meta-heuristic algorithms. A heuristic algorithm includes one heuristic approach. Meta-heuristic algorithm includes more heuristic approaches. These heuristic and meta-heuristic algorithms may be based on swarm optimization, genetic algorithms, evolution algorithms or nature-inspired algorithms. Namely there is Ant Colony Optimization (ACO) [1], Honeybee Mating Optimization (HBMO) [2], Glowworm Swarm Optimization (GSO) [3], Practical Swarm Optimization (PSO) [4] or Fish School Search (FSS) [5]. More about Nature-Inspired algorithm you can find in [7].

1.1. Objective of this work

The main objective of this work is to use the FSS algorithm in real world application with a swarm of quadrocopters. For this purposes, it is necessary to define restrictions which ensure fluent movement. It is necessary to prevent collisions and movements outside search space and consider characteristic of the controller. The controller can't control along a path consisting of straight segments, based on the calculated trajectory (oscillation around the resting position, overshoot resting position during stop).

Implementation of a relative localization is an important part of this bachelor thesis. Relative localization is critical in environments without a precise external localization system. FSS keeps the swarm in a close formation, but it is difficult to prove its convergence, because

FSS is stochastic algorithm. This fact is the reason why it is necessary to implement a mechanism, which keeps the swarm in the close formation. The relative localization will be explained in details in Section [3.4].

The algorithm FSS contains parameters which are necessary to be set for its correct function. The setting of these parameters will be described in Section [4.1]. The setting will be realized for the original basic FSS algorithm and for the algorithm adapted for relative localization of quadrocopters.

An optimal setting will be given also for the on PSO and it will be compared with FSS.

The last part of this bachelor thesis should deal with real experiment with swarm of quadrocopters. After consultation with the supervisor, this experiment is planned after the regular term of submission of this bachelor thesis. The experiment is going to be done by researchers from Intelligent and Mobile Robotics Group during their stay at the University of Pennsylvania. It is going to be done within COLOS project whose is this bachelor thesis constituent. (More information will be presented on website [8].)

Chapter 2

2. Basic Fish School Search algorithm (FSS)

FSS is a stochastic nature-inspired population-based optimization technique. It was developed by Bastos-Filiho and Lima-Neto in 2007 and was introduced a year later.

FSS algorithm is inspired by fish school. The fish school shows some social behaviors, which brings advantages to members of the school. These advantages are for example protection against predators or co-operation during search for food.

2.1. Characteristic of FSS

The members of school fish are placed randomly in search space in the beginning. This is their starting position. Each fish represents one solution of the given problem. They are distinguished by their own memory, where information about their best position and weight is stored. Employment of this information will be explained in Section [2.2]. The fish weight is limited by max value W_{scale}. The initial value is a half of the max value. The initial best position is starting position.

The algorithm FSS contains two important parameters that have to be set according to the optimization problem, individual step and Collective-Volitive step, the setting of these steps will be specified in Section [4.1].

The algorithm is possible to terminate by more ways. For example at a predetermined radius of flocks. In this work, the algorithm is terminated after reaching a definite amount of cycles.

2.2. School movement (searching search space)

The fish movement, its behavior and behavior of the fish school depends on two operators, eating and swimming. The swimming operator is possible to be divided into Individual Movement, Collective-Instinctive Movement and Collective-Volitive Movement.

2.2.1. Eating operator

The eating process causes an increase of the fish weight. The amount of food in the new position is used to calculate a new weight according to the equation

$$W_i(t+1) = W_i(t) + \frac{f[x_i(t+1)] - f[x_i(t)]}{max\{|f[x_i(t+1)] - f[x_i(t)]|\}}, \qquad (1)$$

where t is time (in our case it is a number of an iteration, i is the number of fish, $W_i(t)$ is weight of fish, x_i is position i-th fish and $f[x_i(t)]$ is a fitness function. Value of the fitness function represents quality of the found position (solution).

2.2.2. Swimming operator

As it was mentioned, the swimming operator comprises between three other movements.

Individual Movement

The individual movement generates a new position to explore. Each fish in the school alone decides on the form of individual movement. The direction of movement is generated randomly. The path length is defined by an individual step.

The fish approaches a new position. The fitness function is calculated from this position. The best position is superseded only if the new position is better.

Collective-Instinctive Movement

Direction and path length of this movement defines equation

$$x_i(t+1) = x_i(t) + \frac{\sum_{i=1}^{N} \Delta x_{indi} \{f[x_i(t+1)] - f[x_i(t)]\}}{\sum_{i=1}^{N}\{f[x_i(t+1)] - f[x_i(t)]\}}, \qquad (2)$$

where N is fish amount in the school and Δx_{indi} is position alteration of the i-th fish during its individual movement.

The equation shows that direction and path length are the most affected by the most successful fish in the school. Whole school moves towards set of the most successful fishes.

Collective-Volitive Movement

This movement contracts the fish school if the school was successful. Otherwise, the fish school is spread. The weight decides about success of the fish school. If the weight increases then the fish school is successful and new positions are defined by equation

$$x_i(t+1) = x_i(t) - step_{vol} \cdot rand \cdot [x_i(t) - Bari(t)]. \tag{3}$$

If the weight decreases then fish school isn't successful and new positions are defined by equation

$$x_i(t+1) = x_i(t) + step_{vol} \cdot rand \cdot [x_i(t) - Bari(t)], \tag{4}$$

where $rand$ is a random number from interval $(0,1)$ and function $Bari(t)$ is defined as

$$Bari(t) = \frac{\sum_{i=1}^{N} x_i(t) W_i(t)}{\sum_{i=1}^{N} W_i(t)}. \tag{5}$$

2.3. Pseudocode

Below you can see the course of the algorithm FSS.

```
Initialization
Randomly distribution of fishes
for 1 : amount of iterations
       for 1 : fish amount
              Individual Movement
                     Generate a new position
                     Evaluation a new position
       end

       for 1 : fish amount
              Eating operator (1)
       end

       for 1 : fish amount
              Collective-Instinctive Movement (2)
       end

       for 1 : fish amount
              Collective-Volitive Movement (3), (4)
       end
end
```

Chapter 3

3. Adapted FSS

In the following text, designation “fish” will no longer be used for member of the school. These members will be quadrocopters adapted for the algorithm from now.

3.1. Quadrocopters

Quadrocopter is composed of a frame, four propellers with motors and a control unit, as one can see in the Figure 1. For a better controllability the motors should be placed at the vertices of a square. Quadrocoter has several advantages. This is simple mechanical solution. Quadrocopter is driven by change revolutions of motors. It doesn’t need a main tilt rotor and a rear rotor as helicopters [6].

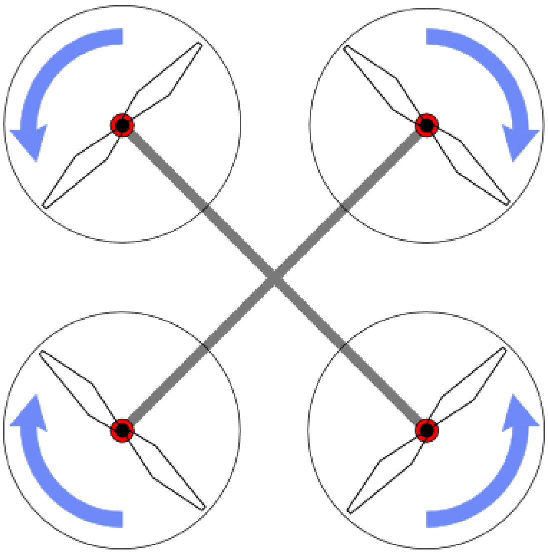


Figure 1: Quadrocopter is composed of four rotors. They are located on the ends of a frame, which is in the form “X”.

3.2. Reasons of restrictions

The implementation of the algorithm FSS, which is explained in Chapter [2], doesn’t take into account restrictions, which is necessary for deployment of a quadrocopter as the swarm particles of FSS. It is primarily important to avoid collisions and mutual interference of the airflow from the rotors. It is necessary to pay attention to regulator imperfections. They are oscillating around target a position, overshoots of the target position during deceleration and an imperfect tracking of a calculated trajectory. It is impossible to turn the quadrocopter at an acute angle.

3.3. Safety zone

The basic component of the protection against collisions is a dual band safety zone around each quadrocopter, as we can see in Figure 2. The safety zone is cylindrical. Inner zone delimits an area into which another quadrocopters can't fly. The inner safety zone avoids side collisions and mutual interference of the airflow from the rotors.

The external safety zone is a cylindrical too. The size of this zone is used to calculate trajectories of members of the school. The external safety zone can be violated during real flying. This gives enough space for quadrocopters oscillations around target position and enough space for overshoots during deceleration.

The values of the inner and external zone should be set experimentally according to used quarters.

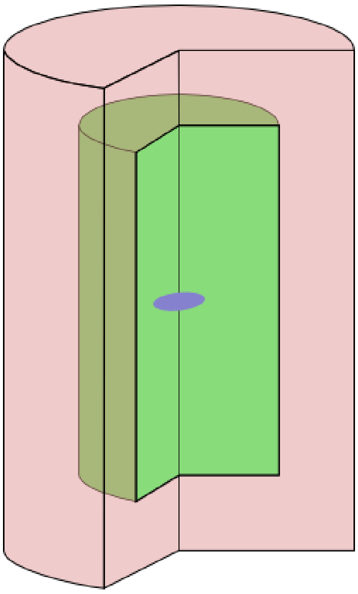


Figure 2: Safety zones around a quadrocopter. External safety zone mustn't be violated by another quadrocopter/quadrocopters during calculation of the trajectory. Inner safety zone mustn't be violated another quadrocopter/quadrocopters during real movement. Quadrocopter has the external safety zone to compensate imperfections of regulator. The violet ellipse represents a quadrocopter.

3.4. Relative localization

We assume that quadrocopters are equipped with omnidirectional cameras and a mutual visual localization. The condition of relative localization means that each quadrocopter is able to see other two quadrocopters.

The solution of the relative localization problem is divided into three parts:

a) **Adjustment of the starting position** – the starting position is generated randomly and it doesn’t meet conditions of relative localization. Therefore, in the first part of the algorithm the starting position is changed to meet the condition of relative localization.
b) **Individual Movement**
c) **Movement to the end position**

3.4.1. Adjustment starting position

Adjustment of the starting position takes place in three steps:

1. List of quadrocopters is generated. The list includes quadrocopters which are violating conditions of the relative localization.
2. A quadrocopter is chosen randomly from the list.
3. A new position which meets the condition of relative localization is generated.

3.4.2. Individual Movement

A random unit direction vector and value of the individual step is used in the basic algorithm to generate a new position, which should be explored, in the following interaction. This method has two major disadvantages. The first disadvantage means that a collision may occur during movement to a new position. The second disadvantage means that a new position may lay in safety zone another quadrocopter. This position can’t be reached.

The new process of individual movement, which is used in the adapted algorithm, is based on the division route into stretch called “step of movement”. Each step is checked if a collision becomes, if quadrocopter is still within the search space and if quadrocopter see another two members of the school. The size of the step of movement shouldn’t be greater than a difference between inner and external safety zone. This size determines perceptiveness to errors. It should be noted that demands of calculation increases with increasing perceptiveness.

Below you can see pseudo-code of the Individual Movement:

```
Unit direction vectors are generated randomly for all members.
while traveled distance < size of individual step
        for 1 : number of quadrocopters
                A new position based on unit direction vector and step size of
                movement
                The checking of the new position (Collisions, in search space,
                relative localization)
                        if is collision
                                collision=1;
                        else
                                collision=0;
                        end
        end
        if collision == 0
                The new position = an interim position
                Traveled distance = traveled distance + the step of movement
        else
                The last movement is ignored for all members.
                For the problem with member of the school a new unit direction vector
                is generated randomly.
                The real movement all members to the last safe positions
        end
end
The real movement to the final positions
```

The solution of the next problem, which is associated with real movement, is seen in the code – blue line. If a quadrocopter changes the direction of movement the quadrocopter must turn. Quadrocopter isn't able to change the direction of flight in an infinite short time therefore it deviates from the calculated trajectory. This deviation could cause a collision. Therefore our goal was to avoid turning.

The trajectory is calculated by unit direction vector and step size of movement. If a collision occurs, calculating is stopped and quadrocopters move to the last safety position. It is generated a new unit direction vector for quadrocopter/s in the collision and the calculating of trajectory continues. The quadrocopters move only in a straight line.

A resulting motion can be seen in Figure 3.

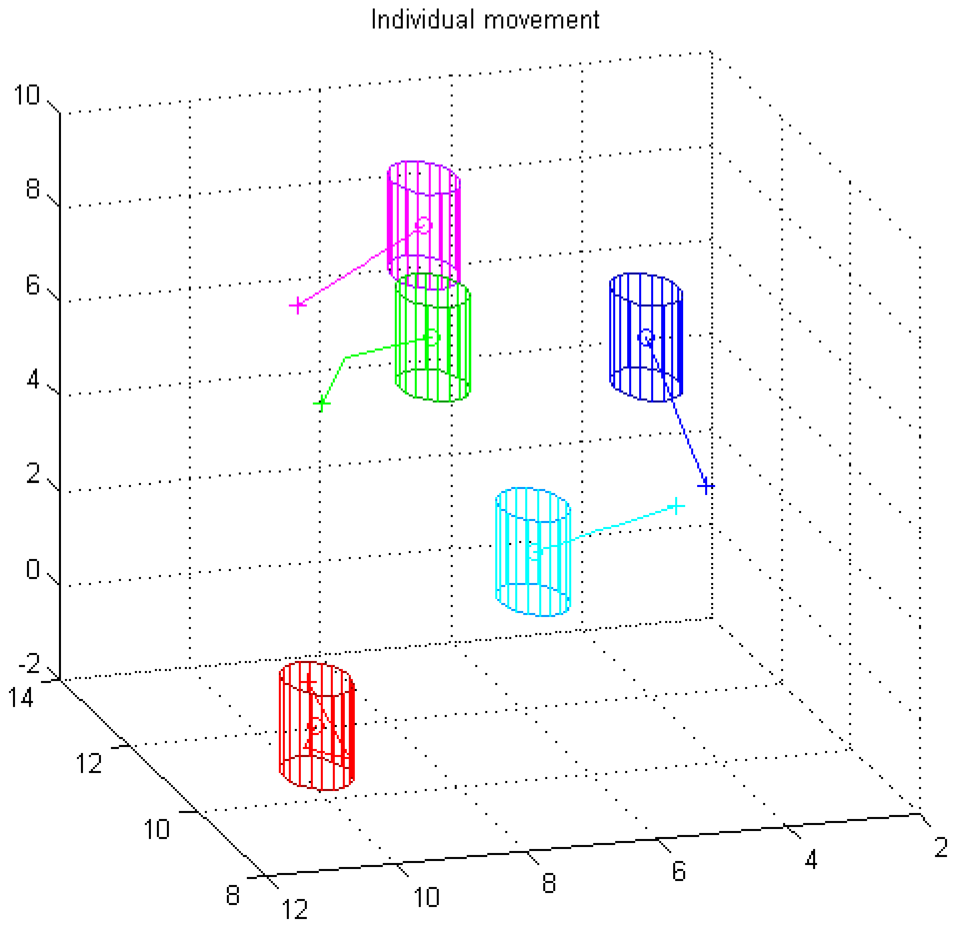


Figure 3: In the picture there we can see trajectory which illustrates individual movement. The color cylinders symbolize the external safety zones, the cross marks symbolize the starting positions, the circle marks symbolize the final positions and the line marks symbolize trajectories. In the pictures there we can see that the green and the red quadrocopter change their direction of movement.

3.4.3. Movement to the ending position

The term "ending position" represents the position, which is generated by the Collective-Instinctive Movement and Collective-Volitive Movement.

It isn't possible to avoid shifting to the pre-calculated position in this movement. This ending position is determined by equations (2), (3) and (4). It is obvious that it will not be always possible to reach the ending position. The first reason may be that the path from starting position to the ending position will be blocked by another quadrocopter or quadrocopters. The second reason may be that the ending position is located in the safety zone of another quadrocopter or quadrocopters. For solution of these problems an algorithm is developed which is based on the algorithm of Individual movement.

There are the main changes:

a. <u>Ending step</u> – It is the last step to ending position. Its size is smaller than the size of the step of movement and it is in the range $(0, step\ of\ movement)$.

b. <u>Direction to the ending position</u> – If a collision happens during flight a new unit direction vector is generated for a quadrocopter which is in collision. So quadrocopter flies to another direction in the next step. If the quadrocopter maintains this another direction for the next step it wouldn't reach the ending positions. The unit direction vector is again changed. It seeks the ending position. This ensures that all quadrocopters are still heading to the ending position.

c. <u>Restriction attempts to achieve the ending position</u> – The changes of unit direction vector could take place infinitely. With a lot of changes it was watched that a quadrocopter was able to fly around an obstacle. However this method avoidance isn't optimal because it occupies much time. The number of changes of unit direction vector is restricted in this algorithm.

Below you can see pseudo-code of movement to the ending position:

```
while true
	for 1: number of quadrocopters
		if Use ending step
			The calculation of the step of movement by the ending step
		else
			The calculation of the interim position
		end
		The checking of the new position (Collisions, in search space,
		relative localization)
		if is collision
			collision = 1;
			break;
		else
			collision = 0;
		end
	end
```

```
    if collision == 0
    for 1: number of quadrocopters
            if changing unit direction vector in the previous step
                Re-counting the unit direction vector back to the ending
                position
            end

            if end of attempts to get to the ending position
                End of movement
            end

            if quadrocopter is in the ending position
                End of movement
            end
        end
    else
        The real movement to the interim position
    end
    if all quadrocopters terminated their movement
        break;
    end
end
```

In the following figure we can see the individual movement and the movement to the ending position.

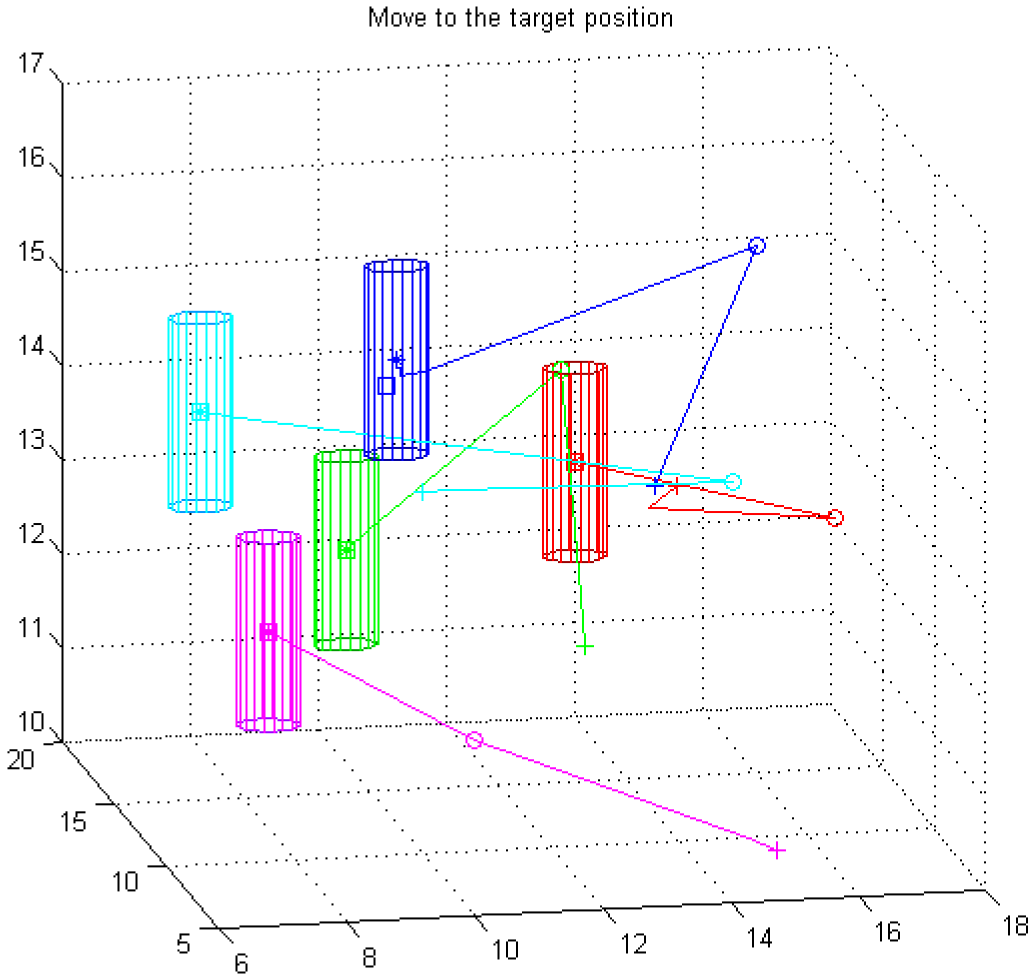


Figure 4: The figure shows trajectories of the movement during one of the iteration. The crosses symbolize the starting positions of movement, the circles symbolize the end of the Individual Movement, the squares symbolize the calculated ending positions and stars symbolize the real ending positions. – The blue member of the school wasn't able to fly to the calculated ending positions. In the figure, we can see that the reason for the failure is the green member, which blocks the blue member.

3.5. Advantages and disadvantages of the proposed solution

When the algorithm was started at the first time, the school moved to some optimum, it contracted around this optimum but then it expanded in the entire search space.

3.5.1. Cause a solution of the problem

The weight of the school decides about expansion and contraction. The size of the weight is changed if at a last one quadrocopter finds better positions (with better fitness function) during the iteration. The school contracts if its weight increases. If no quadrocopters found a better position the weight is the same and the school expands.

In the basic algorithm it is a very small probability that all members of the school will be located directly in optimum. This is reason why some members of the school have always increased its weight.

In the adapted algorithm members of the school are physical. They can’t flip through each other. This fact causes that the quadrocopters can’t improve their position after a while. The weight of the school is constant and the school expands as it was observed.

The state with constant weight is considered as success and this is the solution of problem. So the school contracts in this case too.

The adapted algorithm works well due to the small adjustment. The algorithm became more resistant against incorrect settings Individual step and Volitive step. This fact will be explained more in Chapter [4].

Chapter 4

4. Parameters setting and comparison

4.1. Parameters setting

The behavior of the algorithm FSS is strongly dependent on setting of these parameters:

- **Individual step** – gives the step size of the individual movement. The size of this step decreases in each iteration. In the source code, it is defined by variable *step_ind.* It is a row vector. Its length is created by number of iterations. Each value determines the size of step for corresponding iteration. The values of *step_ind* are calculated by uniform distribution the interval (*step_ind_init*, *step_ind_fin*).
- **Collective-Volitive step** – gives the step size of the Collective-Volitive movement. Collective-Volitive step has the same format as the Individual step. In the source code, it is defined by variable *step_vol*. The values of *step_vol* are calculated by uniform distribution the interval (*step_vol_init*, *step_vol_fin*).

4.2. Optimal setting

4.2.1. Optimization problem

In the Figure 5 it is seen the optimization problem which is used for setting of the parameters. It is a cube with dimensions of 10x10x10. Sources of signal are located in the vertices of the cube and in the middle of sides. Optimum is a place with the lowest intensity of signal.

4.2.2. Fitness function

The fitness function is given by equation

$$f(x_i) = \sum_{j=1}^{J} \left[\sqrt{\left(x_i - s_j\right)^2} \right]^{-5}, \qquad (6)$$

where s_j is position of j-th source of signal, J is number of sources and x_i is position of i-th member of the school.

Solutions were considered as acceptable if final value of the fitness function was smaller than 0.0028. These areas are seen in the Figure 6.

Marking in meters is important for the adapted algorithm FSS only.

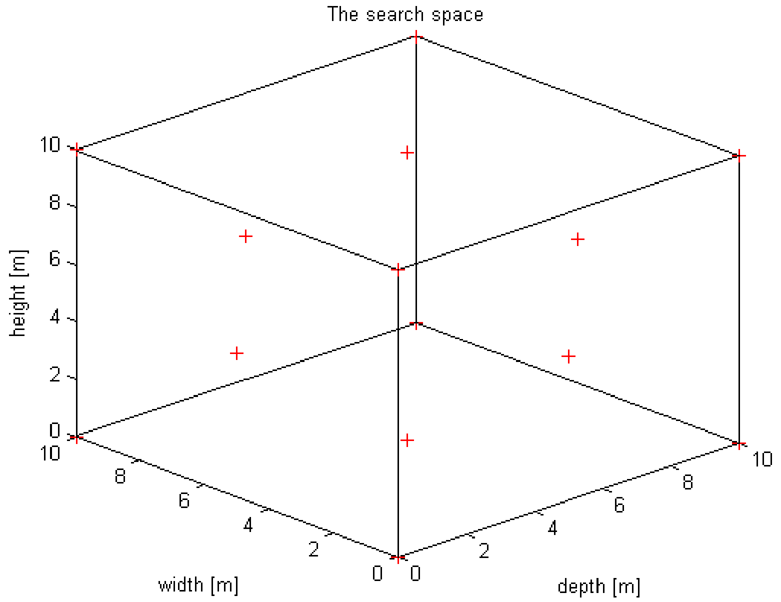


Figure 5: The search space is a cube with dimensions of 10x10x10 m. The red stars represent a source of signal. They are located at the vertices of a cube and in the middle of sides.

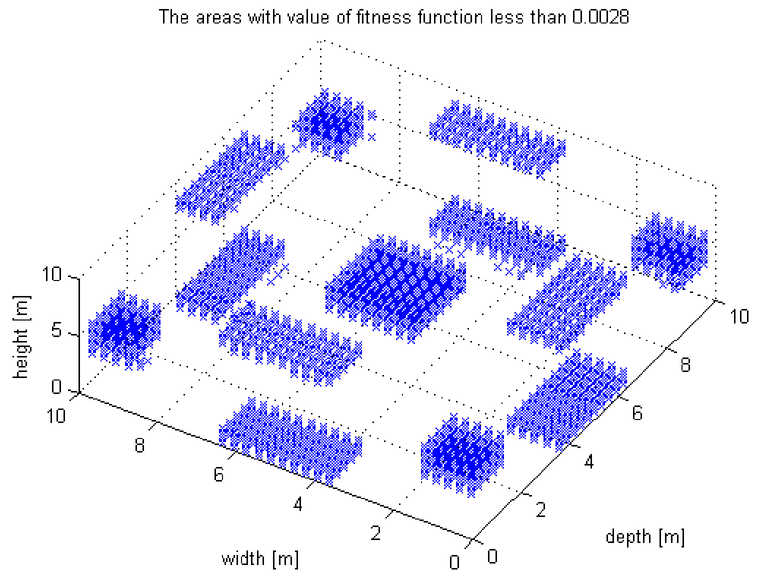


Figure 6: The areas around the optimums with value of the fitness function less than 0.0028. For this value of the fitness function the barycenter of the school was located within a radius of 1.5 meter from the optimum.

4.2.3. Setting of values

The parameter values have to be changed according to properties of the particular searching problem. The most important factors which contributes to the final outcome of the search is a combination of sizes of search space, the size of quadrocopters, the size of their safety zones and distribution of optimums.

During the determining of the optimal setting it was focused on the identification of the intervals (*step_ind_init*, *step_ind_fin*) and (*step_vol_init*, *step_vol_fin*), which are calculated by the value of the steps. Their optimal size was found in the interval (0, 10).

4.2.4. Characteristics of testing

The optimal setting was found for both algorithms and it is possible to compare an impact of limiting conditions on the set parameters.

Each setting of parameters was running hundred times and it was calculated average of final value of the fitness function of barycenter (center of mass).

4.3. The setting of the basic algorithm FSS

From experiments on the basic algorithm it emerged that the best values of the fitness function is achieved in the case when the values of *step_ind_init* and step_vol_init were in the interval (3, 0.8) and values of *step_ind_fin* and *step_vol_fin* were close to zero. In the Figure 7 we can see courses of the fitness function for the two best setting.

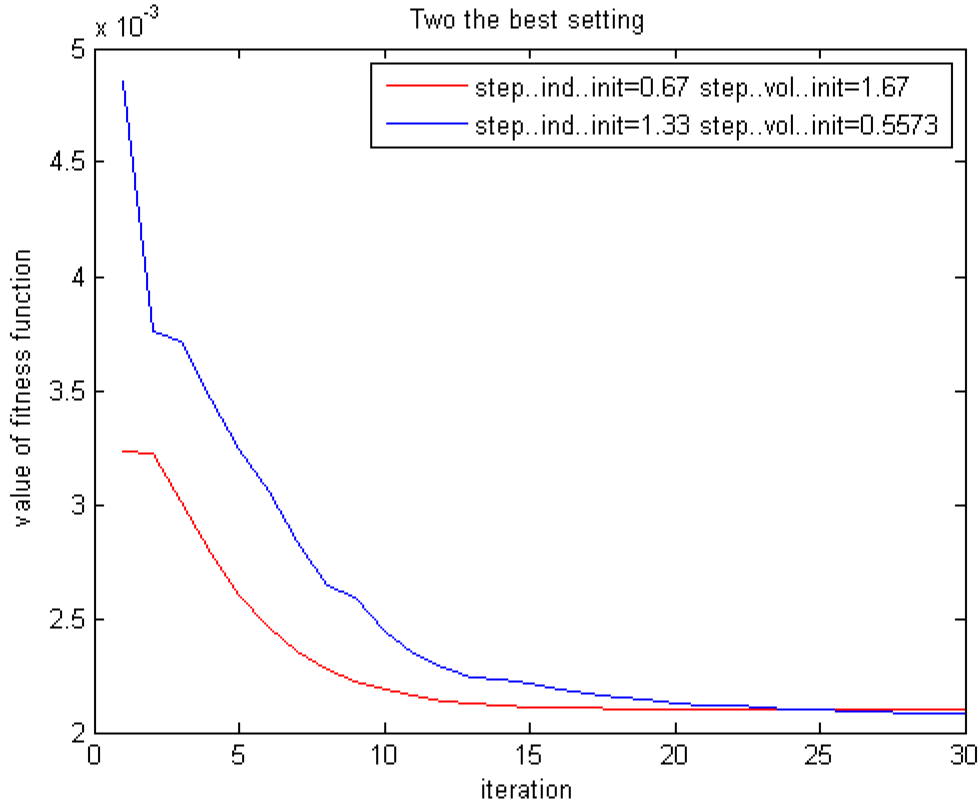


Figure 7: The courses of the fitness function of barycenter for the two best setting of parameters of the basic algorithm FSS. The values of *step_ind fin* and *step_vol fin* are constantly 0.01.

4.4. The setting of the adapted algorithm FSS

In the basic algorithm is possible that all members of the school were in the same place at the same time. This behavior was avoided by the restrictions which were descripted above because this behavior causes collisions. It is necessary to consider characteristic of an optimization problem and select appropriately setting of size of the safety zones and number of quadrocopters in the school before finding the optimum setting.

In the following description the required values are determined approximately, because it wasn't possible to experimentally find out these values. This description aims to describe the procedure for their setting.

4.4.1. The size of quadrocopter and safety zones

In the following consideration, it will be worked with real sizes which will be given in meters. An optimum (place with the highest signal intensity) will be looked for in the searched space. The search space is show in the Figure 5 . In the Figure 8 we can see the size of quadrocopter.

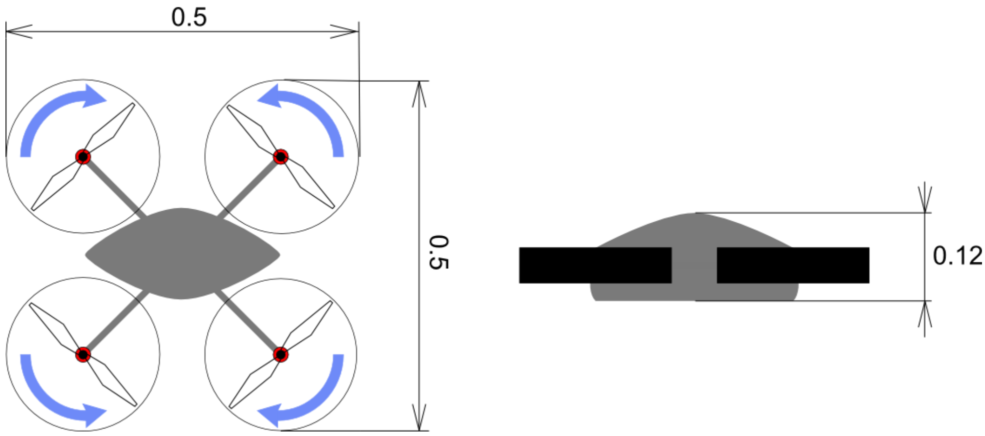


Figure 8: The size of quadrocopter. All sizes are in meters.

Figure 8 shows the choice of size of the safety zones. The diameter of the inner safety zone was chosen as the max size of quadrocopter. There is $\sqrt{0.5^2 + 0.5^2} \cong 0.7$.

The diameter of the external safety zone is increased by the value of overshoot over the target position during stopping. The size of overshot is determined as 0.1.

The height of the inner safety zone was determined as sum of height of quadrocopter and the reach of wind from the propellers.

The height of the external safety zone is increased by the same overshoot as diameter.

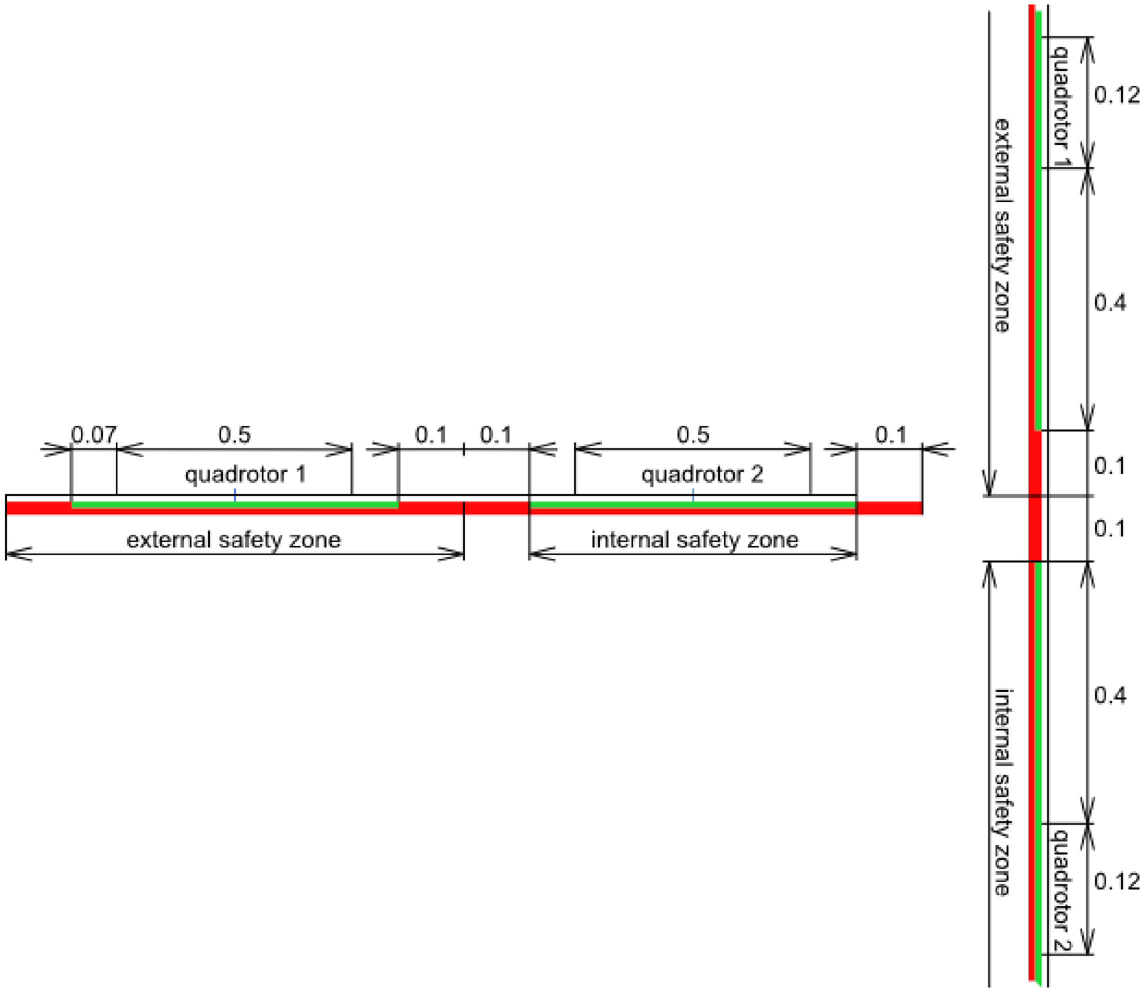


Figure 9: The size of the inner and the external safety zone.

4.4.2. Test results

Solutions were considered as acceptable if final value of the fitness function was smaller then 0.003. For this value of the fitness function the barycenter of the school was located within a radius of 1.5 meter from the optimum.

The best values of the fitness function were reached during the testing of the adapted algorithm FSS if the value of *step_ind_fin* and *step_vol_fin* were close to zero. The values of *step_ind_init* were in the interval $(0.8, 4)$ and the values of *step_vol_init* were in the interval $(0.5, 1)$. In the Figure 10 and Figure 11 we can see some values of these intervals. The best setting is always marked as a green curve.

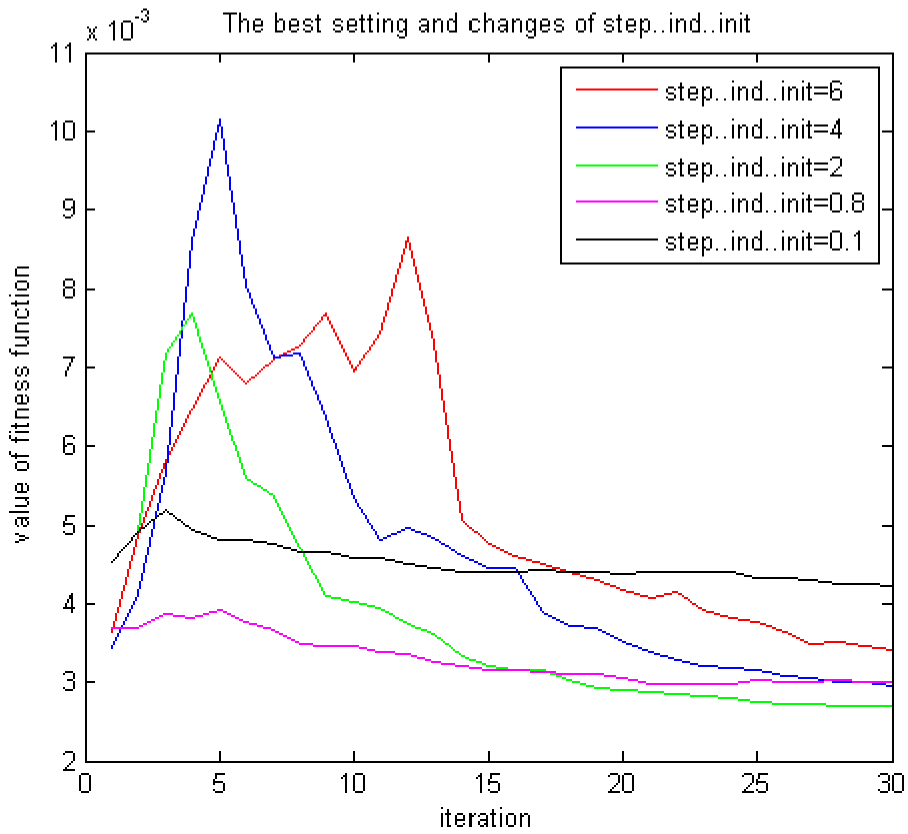


Figure 10: The courses of the fitness function of barycenter for several settings of parameters of the adapted algorithm FSS. The value of *step_vol_*init is for all curves 0.64 and values of *step_ind_fin* and *step_vol_*fin are 0.01. The barycenter is located within a radius 1.5 meter from optimum for values of the fitness function which is smaller than 0.0028.

It is obvious from the Figure 10 that the fish school has problem with increasing value of *step_ind_init*. The school contracted into tight formation (blue and red curve). Conversely, the fish school almost doesn't move with decreasing value of *step_ind_init* and value of the fitness function was almost constant (black and purple curve). The fish school contract too because the Collective-Volitive step (value of *step_vol*) become predominant.

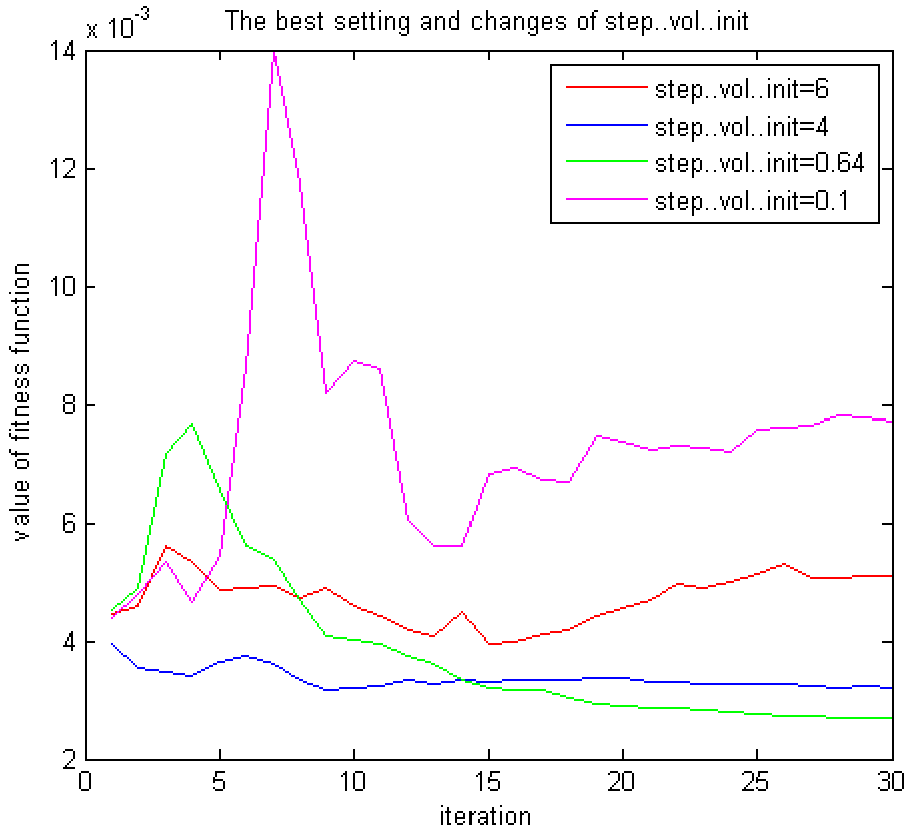


Figure 11: The courses of the fitness function of barycenter for several settings of parameters of the adapted algorithm FSS. For all curves is value of *step_ind_init* 2 and values of *step_ind_fin* and *step_vol_fin* are 0.01. The best setting is marked as green curve. The barycenter is located within a radius 1.5 meter from optimum for values of the fitness function which is smaller than 0.0028.

The Figure 11 shows that if is set too small value of *step_vol_init* the fish school doesn't contract (purple curve). If is set too big value of *step_vol_init* the fish school contracts quickly and it continues in searching in close formation (blue and red curve).

Several other settings are in the following Table 1 with the corresponding value of the fitness function.

		step_ind_init		
		0.8	2	4
step_vol_init	0.1	0.0053	0.0159	0.0058
	0.64	0.0032	0.0028	0.0030
	4	0.032	0.0034	0.0035

Table 1: There are final values of the fitness function for several others settings values of *step_ind_init* and *step_vol_init*. The values of *step_ind_fin* and *step_vol_fin* are 0.01.

4.4.3. Comparison the best setting of basic FSS and adapted FSS

The following Figure shows courses of basic FSS and adapted FSS with using the optimal setting of parameter.

The optimal setting of parameters		
parameters	basic FSS	adapted FSS
step_ind_init	1.33	2
step_ind_fin	0.01	0.01
step_vol_init	0.5573	0.64
step_vol_fin	0.01	0.01

Table 2: The optimal values of parameters of algorithm FSS.

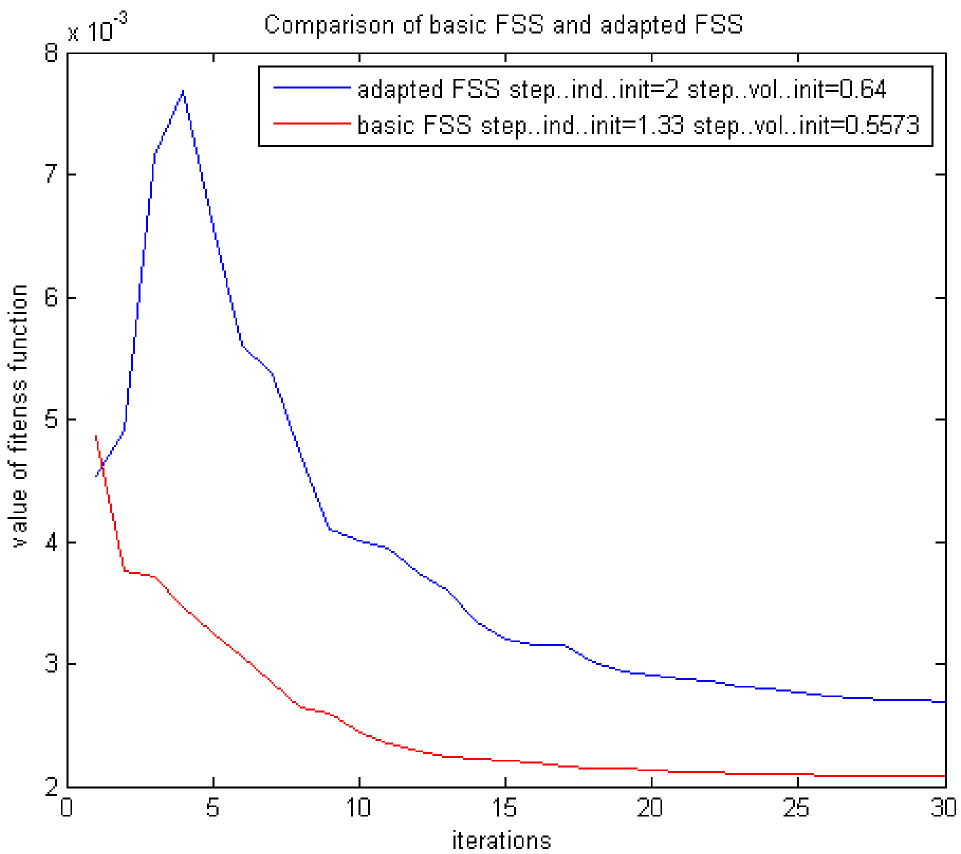
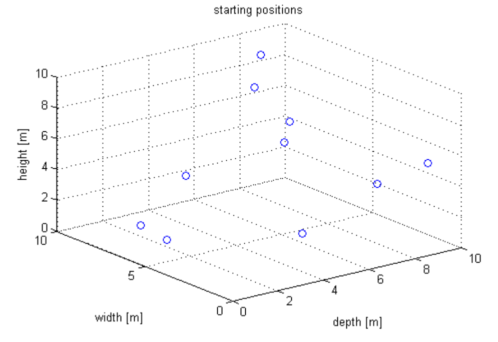
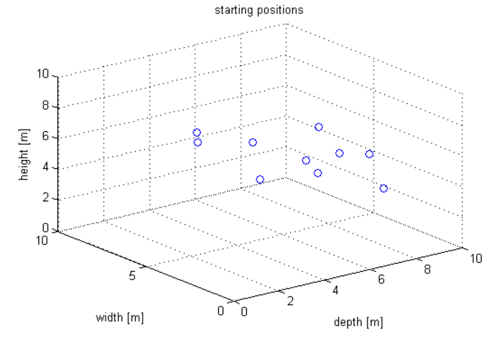


Figure 12: Comparison of basic FSS and adapted FSS. Values of step_ind_fin and step_vol_fin are 0.01. The barycenter is located within a radius 1.5 meter from optimum for values of the fitness function which is smaller than 0.0028.

We can see that the settings are similar for both algorithms. The adapted algorithm has worse value of the fitness function as the basic algorithm but it is able to find some of optimums because it's the ending value of the fitness function is smaller as 0.0028.

The next Table shows the comparison of curses of the fish school with optimal setting.

<table>
<tr><th>basic FSS</th><th>adapted FSS</th></tr>
<tr><td>
</td><td>
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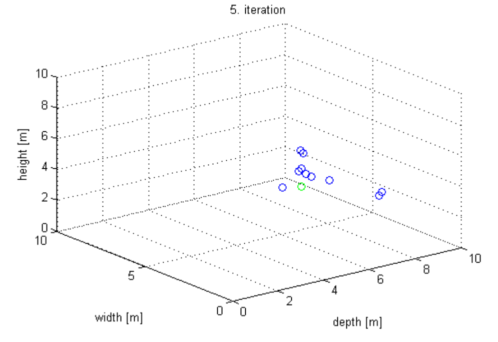
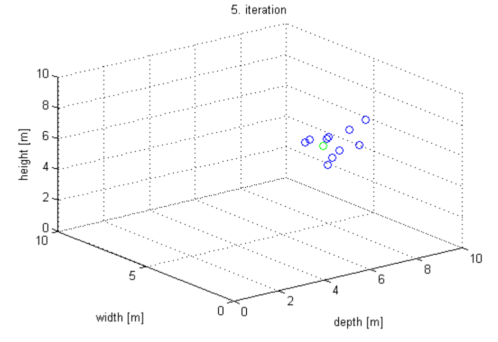
<tr><td>
</td><td>
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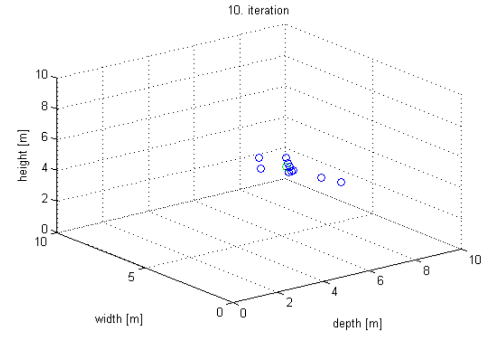
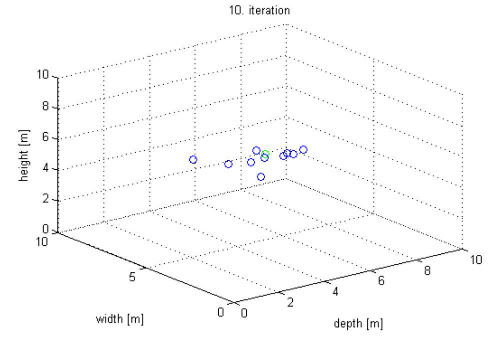
<tr><td>
</td><td>
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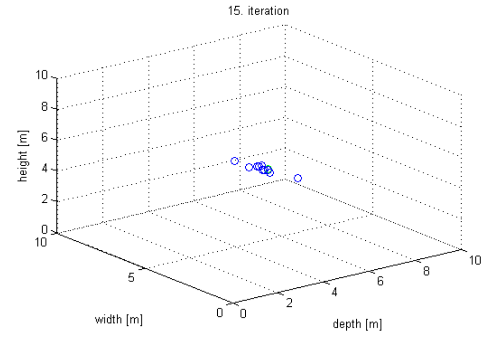
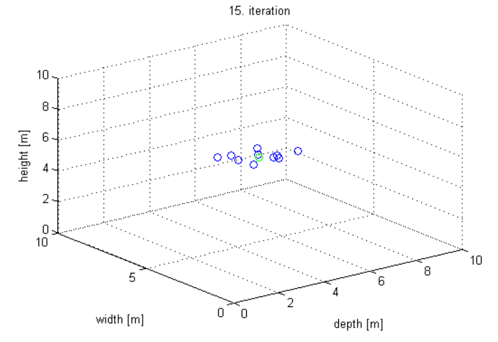
<tr><td>
</td><td>
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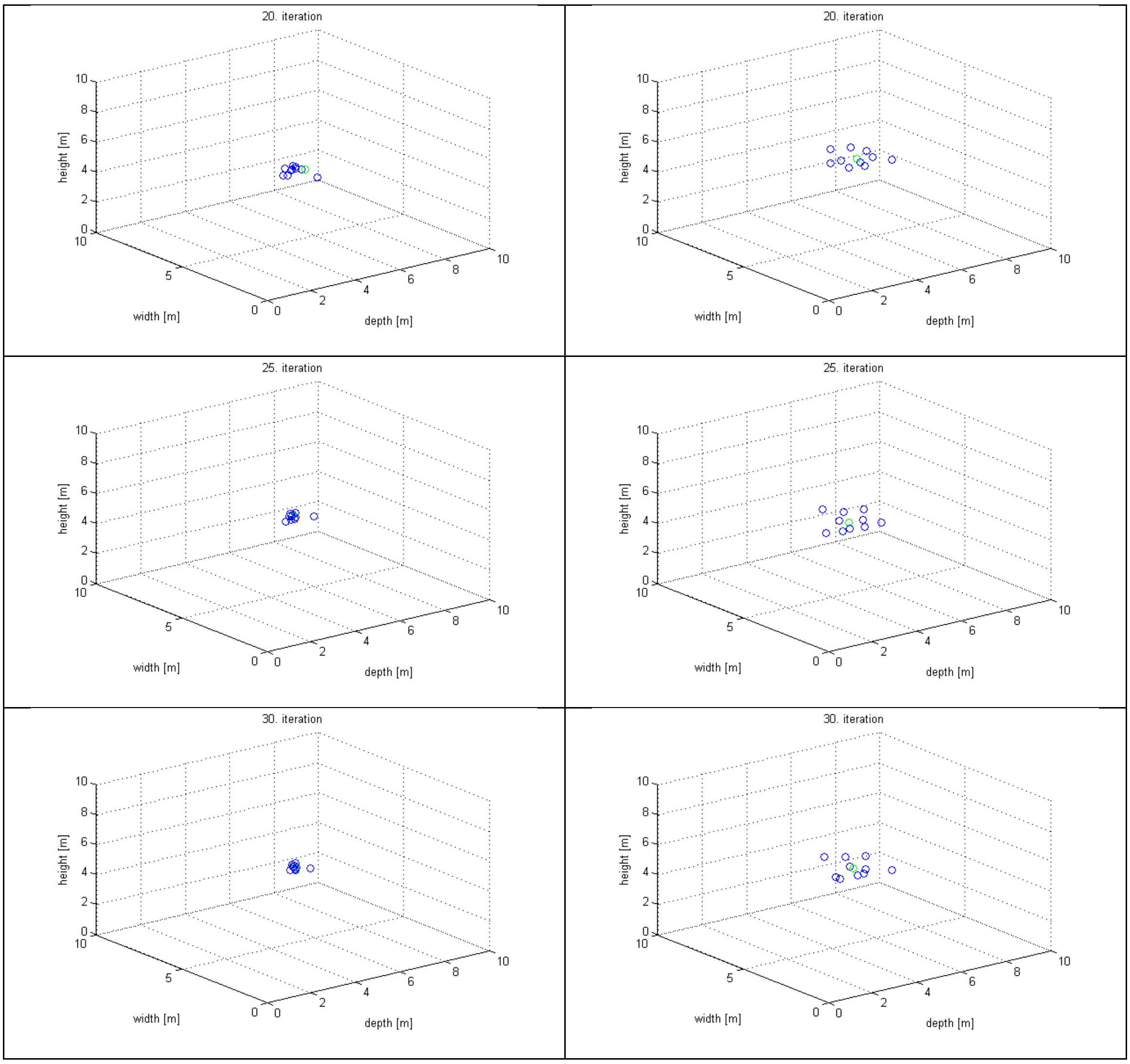
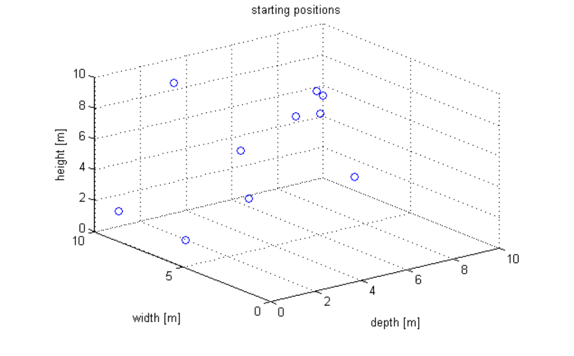
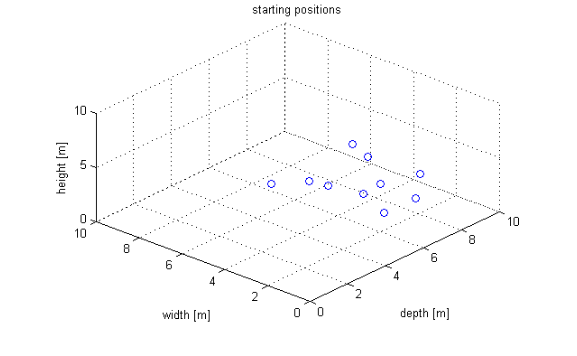
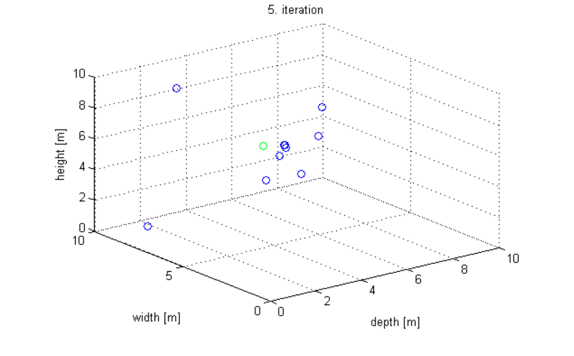
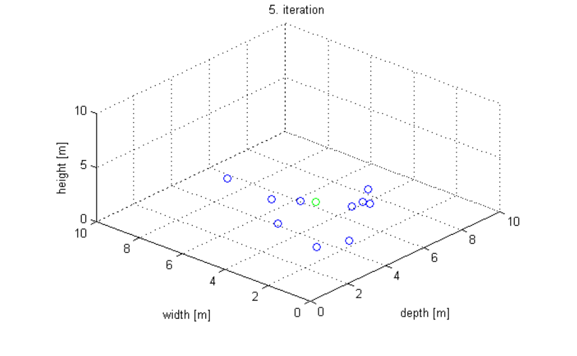
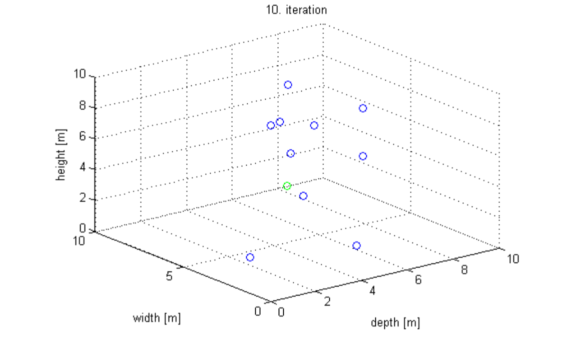
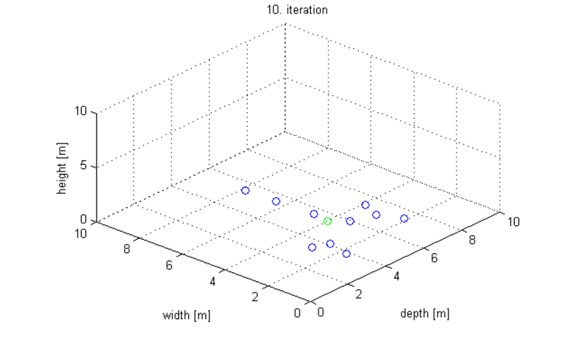
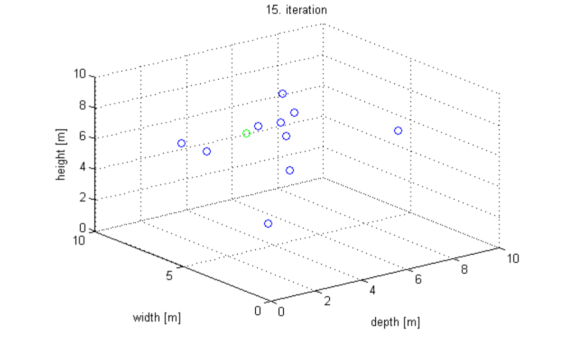
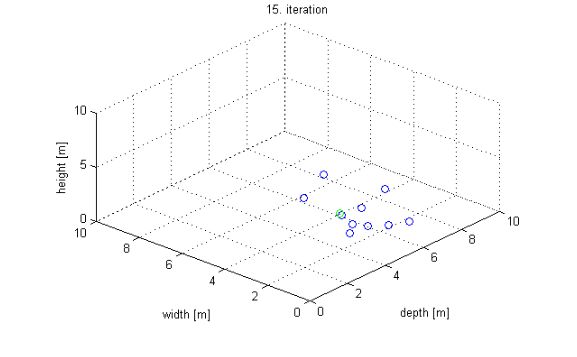


Table 3: The comparison of courses of the fish school with using basic and adapted algorithm with the optimal setting.

In Table 3 we can see influence restrictions given by employment of physical swarm particles. The members of basic algorithm FSS are almost contracted to single point in 30. iteration. The members of adapted FSS maintain spacing given by the safety zones.

The next Table shows the comparison of courses of the fish school whit a bad setting of parameters, *step_ind_init=6*, *step_ind_fin=0.01*, *step_vol_init=0.02* and *step_vol_fin=0.01* for both algorithms.

basic FSS	adapted FSS
	
	
	
	

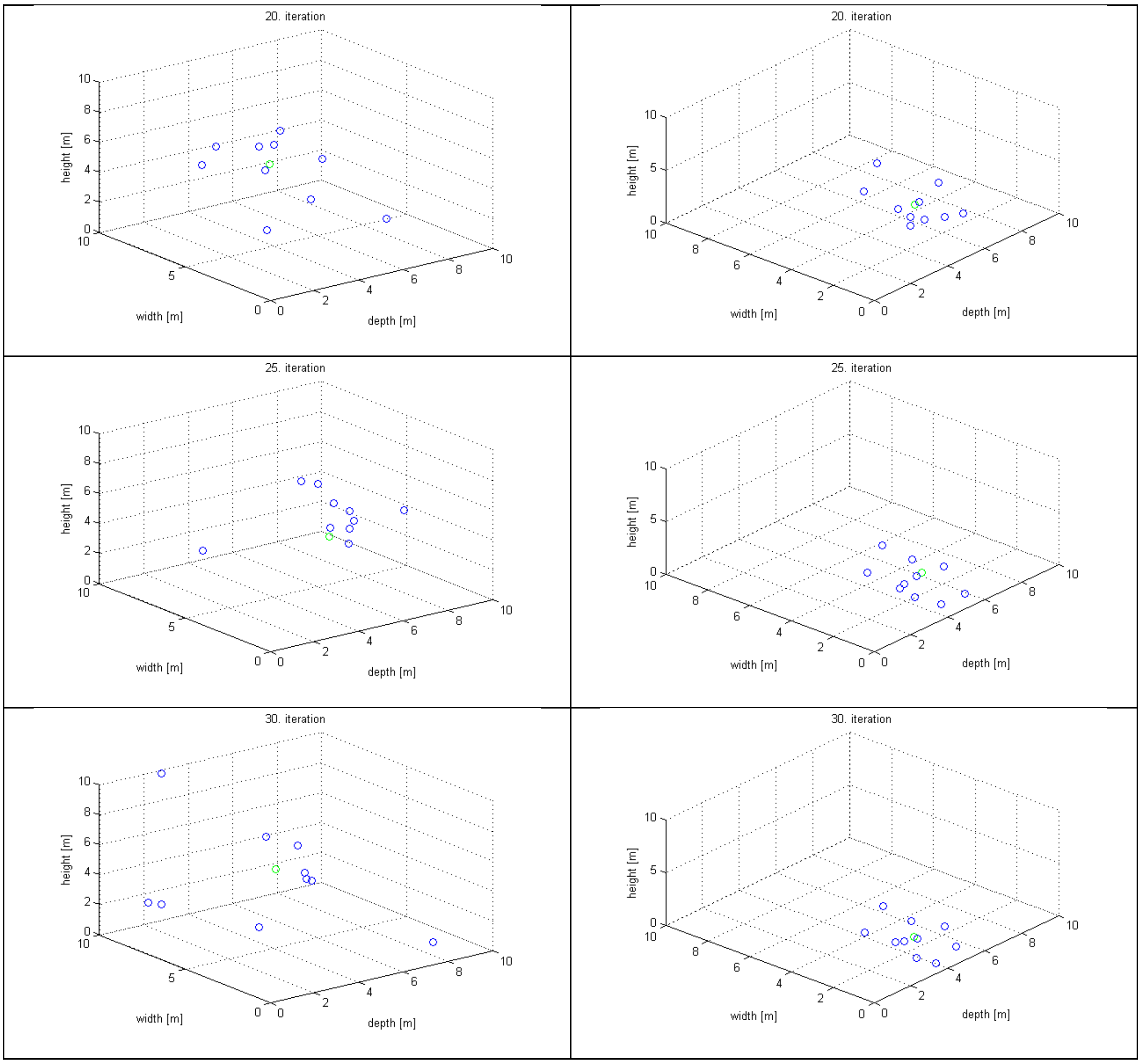


Table 4: The comparison of courses of the fish school with using basic and adapted algorithm FSS. The using setting of parameters is *step_ind_init=6, step_ind_fin=0.01, step_vol_init=0.02 and step_vol_fin=0.01.*

The table above shows the influence of relative localization. The basic algorithm FSS doesn't able to keep members in close formation whit using an incorrect setting of the parameters. The adapted algorithm with the relative localization keeps members in the close formation for incorrect setting of parameters as well.

Chapter 5

5. Comparison of algorithms FSS and PSO

Many versions of algorithm PSO exist. For this comparison it is used the Standard PSO which is developed by Daniel Bratton and James Kennedy [4].

5.1. Characteristic of Standard PSO

Each member of the school is determined its position and velocity and it remember its the best position. It is calculated the global optimum which is used to determine.

The algorithm PSO contains two parameters which is possible to change. It is parameter c and w. In the following text will be found the optimal setting these parameters.

5.2. Optimal setting of PSO

The optimal setting was found for the same optimization problem as in the Section [4.2.1], the same number of fish will be elected and the fitness function is given by equation (6). The value of the fitness function for barycenter was used for finding the best setting in the algorithm FSS. The members of the PSO algorithm haven't weight. For calculation of barycenter the weight are constantly set to unitary value. The position of barycenter is given by evaluation

$$Bari_{PSO}(t) = \frac{\sum_{i=1}^{N} x_i(t) W_i}{\sum_{i=1}^{N} W_i}, \qquad (7)$$

where x_i is position i-th member, N is number of members and W_i is weight i-th member.

Acceptable solutions were again considered solution whose final value of the fitness function was smaller as 0.0028. The barycenter is located within a radius of 1.5 meter from the optimum.

The best values of the fitness function were achieved when the parameter c was in interval $(0.6,\ 1.8)$ and parameter w was in the interval $(0.1, 0.9)$.

In the Figure 13 we can see courses of the fitness function for the two best setting of parameters basic PSO.

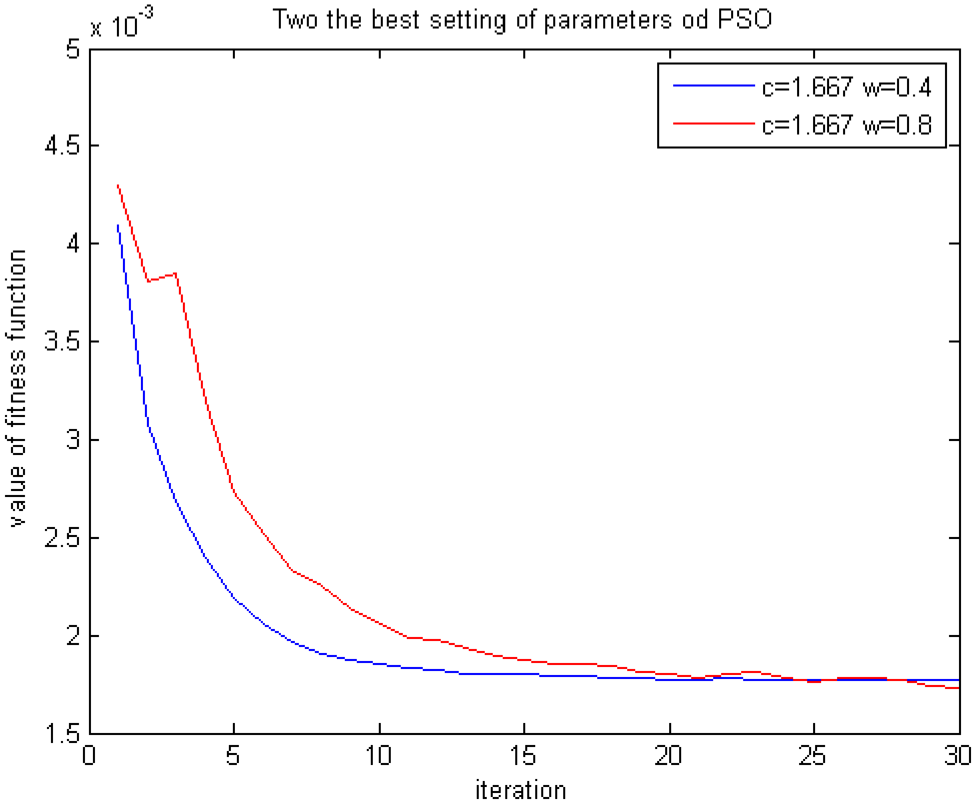


Figure 13: Two the best setting of PSO parameters c and w.

5.3. Comparison of algorithm FSS and PSO

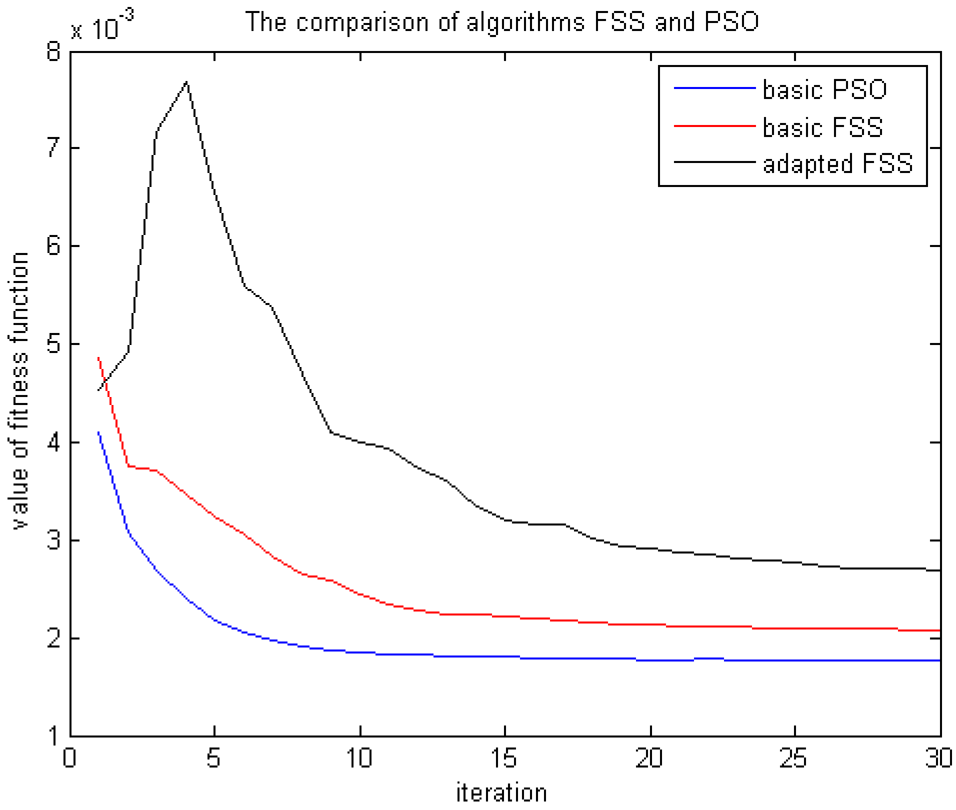


Figure 14: Comparison the best result of FSS and PSO.

In the Figure 14 we can see that basic algorithm PSO is better than basic FSS. This difference is negligible against fact that both curves are under threshold 0.0028 which is important for unambiguous reaching an global optimum. (Figure 6)

Chapter 6

Conclusion

The adaption of the basic algorithm FSS for employment of physical swarm particles was the main objective of this bachelor thesis. Quadrocopters are physical particles in this adaption. It was necessary to realize restrictions to keep the quadrocopters in search spaces and avoid collisions and restrictions which is given by relative localization.

This main objective was realized with using the preliminary calculation of trajectory. The “step of movement” was used for this calculation. The dual band safety zones around each members of the school were used for detection of collision. An advantage of this solution is its universality. It is easy to set the algorithm for different optimization problems and different size of quadrocopters. Its disadvantage is an increasing of time-consuming with increasing of number of steps which are necessary for the calculation of the safe trajectory.

The optimal parameters setting of algorithm FSS was the next part of this bachelor thesis. The setting was done over the basic algorithm FSS and also over the adapted algorithm FSS. The best setting of these algorithms is shown in the Table 2. Due to the restrictions which are given by relative localization of the adapted algorithm the school is kept in the “close” formation although an incorrect parameters setting are used.

The basic algorithm FSS was compared with another meta-heuristic algorithm, exactly with algorithm PSO. The algorithm PSO has also parameters which is possible to set. These parameters were set for the same optimization problem. In the Figure 14 is shown that PSO is a better than FSS but the difference is negligible. The ending values of the fitness function of both algorithms are less than 0.0028. So, the barycenter of swarm is placed in the areas which is shown in the Figure 6.

As it was mentioned in the introduction, the real experiment was the last part of this bachelor thesis. The real experiment is already planned after the regular term of submission of this bachelor thesis and its result will be published on the website [8].

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Appendix A

CD attachment

Data structure of the attached CD:

- Matlab files
    - source codes of basic FSS, adapted FSS and basic PSO
    - data structures and pictures
- Bachelor thesis.pdf