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Group Behavior of UAVs in Obstacles Presence

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***Abstract*—The article deals with the problem of controlling the multi-agent system that consists of *n* UAVs moving in environment with obstacles. One of UAVs is an agent-leader and the others are agent-members. Behavior of an agents group in dynamic environment is considered as aggregation. This task supposes describing UAVs group movement as integrator of the second order, and each agent has information about others. Bypass obstacles and avoidance of collision is the main problem of this paper. Therefore we are considering movement of agents group in potential field, which includes two components: attractive and repulsing. The movement law is only known for agent-leader and agent-members that follow him in potential field. Simulation demonstrates main result of proposed-approach.**

Keywords—*group of UAVs; agents system; aggregation; potential field; dynamic model; Quadrotor*

I. INTRODUCTION

Increased interest in the study of group behavior of unmanned aerial vehicles (UAVs) in recent years is an objective fact. Researchers pay such attention to this topic due to increased availability of this devices and electronic components for their creation. The group of UAVs is able to solve problems for different industries. In the military sphere is monitoring, reconnaissance, jamming and airstrike [1]. Group serves for reducing execution time and energy costs associated with the solution of the assigned tasks. Group actions involves some organization.

The management task of collective behavior is the first one that to be addressed. Traditional scheme generates a control law based on the dynamics of only one machine [2]. When we have group of UAVs, it is necessary to ensure not only the safety of the flight, but also the interaction, to achieve task goal. Flight control of UAV team related also with the transmitted dataflow and with decisions making.

In some cases, the performance of tasks are limited by interference of artificial or natural origin. Protection against harmful interference when the group is applied, forcing the group to restructure or change the route so that the flight objectives are achieved. Thus, the interference signals are parameter of control law.

The problem formulation involves the traditional description of group behavior as a dynamic system with restrictions on the intervals and the distance between the individual elements of the group. The group performs the movement on a route. There are obstacles located on the path of its movement. They are fixed. The task of the group is to reach the goal and do not collide with an obstacle.

This paper discusses the problem of tracking of the agents group on the route. The group consists of agent-leader and agent-members that are trying to avoid obstacles on the route.

II. PROBLEM STATEMENT

As in [1] we consider a group of n UAVs that are labeling $A_1, \ldots, A_n$, which should carry out some task. Further, we call UAV as an agent. To perform a given task agents can use one from a few kinds of behavior tactics as a flier: "bearing", "wedge", "column" and so on or to perform autonomous flight. Using of these tactics corresponds to the behavioral structure of social groups or insects. Such representation of dynamic objects motion can guarantee the absence of collisions, it assumes approximately equal speeds of the movement agents, and it talks about the existence of single formation center along the predetermined path.

Each agent performs coordinated movement by relation to central element according to group's objective. Agent's motion is in three-dimensional Euclidean space. Integrator the second order describes dynamics of each agent

$$\begin{aligned} \dot{x}_i &= y_i, \\ \dot{y}_i &= k_i u_i. \end{aligned} \qquad (1)$$

Here $(x_i,\ y_i,\ \dot{y}_i)^{\mathrm{T}}$ is the coordinates vector that determines agent positon in $3D$ space, wherein x_i is a position, y_i is a velocity and $\dot{y}_i$ is an acceleration of ith agent; k_i is the moment of inertia; u_i is control input, $i = 1, 2, \ldots, n$. In equation (1) $x_i, y_i, \dot{y}_i$ is the function of time t.

The ability of agents' behavior to act in a group we will call aggregation. This feature allows to strengthen the actions of one agent, and collisions with other members of the group are avoided due to by communication and observation of the actions each of agents.

In accordance to [5] for aggregation each agent A_i with position $p_i = (x_i, y_i, \dot{y}_i)^{\mathrm{T}}$ for $D_\varepsilon > 0$ and for $t \to \infty$ control inputs u_i should support

$$p_i \to D_\varepsilon(p_c)\,, \qquad (2)$$

where $D_\varepsilon(p_c)$ is the measure of agents' group configuration and

$$p_c(t) = \frac{1}{n}\sum_{i=1}^{n} p_i(t), \quad (3)$$

and

$$D_\varepsilon(p_c) = \{p \in \Re^3 : d = \| p - p_c \| < \varepsilon\}. \quad (4)$$

In equation (4) ε is the constructive parameter that is defined by the system designer. Equation (4) is the criterion of motion group.

In the presence of obstacles the movement of the group is changed, selected type motion for overcoming it, that in common case leads to an increase value $D(p_c)$. These approaches based on obstacle avoidance or change of movement direction.

The paper poses and solves the problem of control synthesis of a group that consists of n UAVs and moves on a given route with obstacles of natural type that specified by coordinates x, y in condition the group size $D(p_c) \le D_\varepsilon(p_c)$.

III. Problem solution

We considered multi-agent system as a field of agents, each of which is oriented in a certain direction. In this case, we have to introduce the concepts of attractive and repulsive fields. Attractive field allows moving group together on the route and repulsive field does not allows collisions another agents and obstacles.

As known, the energy of a potential attractive fie described as

$$W_{att}(\Delta p) = \frac{1}{2}\xi(\Delta p)^2,$$

where $\xi > 0$ is scaling factor, and $\Delta p_i = \| p_i - p_c \|$ i Euclidian distance between the ith agent and the agent ce The attractive control in this case constructed as

$$u_{att}(\Delta p) = -\operatorname{grad} W_{att}(\Delta p) = -\xi(\Delta p).$$

The classical repulsive energy calculated as

$$W_{rep}(\Delta p) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{d(\Delta p)} - \frac{1}{d_0}\right)^2, & \text{if } d(\Delta p) \le d_0, \\ 0, & \text{if } d(\Delta p) > d_0, \end{cases}$$

where $\eta > 0$ is scaling factor, $d(\Delta p)$ is the minimum dista between the agent and agent centric in group, and $d_0 > 0$ is constant that determines the active impact of obstacles on agents.

Repulsive control we can present as

$$u_{rep}(\Delta p) = -\operatorname{grad}\ W_{rep}(\Delta p) = \begin{cases} \eta\left(\frac{1}{d(\Delta p)} - \frac{1}{d_0}\right)\frac{1}{d(\Delta p)^2}\frac{p - p_0}{d_0(\Delta p)}, & \text{if } d(\Delta p) \le d_0, \\ 0, & \text{if } d(\Delta p) > d_0. \end{cases}$$

In equation (8) p_0 is the coordinates closest agent to the obstacle boundary, and $d_0(\Delta p) = \| p - p_0 \|$ is the its Euclidean distance.

Then, general control law u^g that allows to reach to the final target for i-th agent with the N obstacles is given as

$$u_i^g = u^l + u_i^{att} + u_i^{rep}, \quad (9)$$

where u^l is the motion law of agent-leader that is a free-agent, and u_i^{att}, u_i^{rep} are the controls that determined by (6), (8) for member-agents.

The agent-leader has designed trajectory, its control does not depend on robot-members, and its control is determined early, but its dynamics is determined equations system the same as (1)

$$\begin{aligned} \dot{x}^l &= y^l, \\ \dot{y}^l &= k^l u^l, \end{aligned} \quad (10)$$

where u^l is the known law, i.e. this agent exactly know how it should move.

A. Motion along line

This case supposes that leader acceleration is absent. Then mission of ith agent is to save its position in a group, if it is agent-member, or to support in location in this formation, i is a free-member. Control law provides sufficient informati about positions and velocity both leader and free-member

$$u_i = \begin{cases} -k_y(y_i - y^l) - k_x(x_i - x^l), & \text{if } i \text{ is free-memder}, \\ 0, & \text{if } i \text{ is not free-member}. \end{cases} \quad (1$$

Here $k > 0$ is the positive factor that set velocity of agent-fr If leader is in the center of a group, then its coordina calculated by (3)

$$x^l = \frac{1}{n^*}\sum_{i=1}^{n^*} x_i, \quad y^l = \frac{1}{n^*}\sum_{i=1}^{n^*} y_i \quad (1$$

where n^* is the quantity of neighbors or agents in a group.

LEMMA 1. If group includes n agents, its movement is presented as dynamic system of the second order by

$$\dot{p}_1 = p_2, \qquad \dot{p}_2 = \overline{u} = -k_y(y_i - y^l) - k_x(x_i - x^l). \tag{13}$$

where $p = p^l - p^a$, p^l and p^a are the appropriate coordinates, which are measured in system related with leader.

Proof. This statement follow from (11).

Corollary 1. Closed loop dynamic system (13) converges to the equilibrium position

$$p_{1i} = x_i - x^l, \qquad p_{2i} = y_i - y^l. \tag{14}$$

Corollary 2. Agent-members velocity asymptotically converges to the agent-leader velocity.

Corollary 3. In system (13) coordinates x_i is $x_i \neq x_j$ for any $i \neq j$, $t \geq 0$.

B. Motion along curve

This kind of movement always occurs in the presence of an acceleration, i.e. $\dot{y} \neq 0$. We will assume that each agent-member has information about the parameters of the agent-leader's movement, and then the dynamical system (13) is transformed to

$$\dot{p}_1 = p_2, \qquad \dot{p}_2 = \dot{p}_2^l + \overline{u}. \tag{15}$$

LEMMA 2. Movement of a system (15) has exponential stability, if $k_y > 0$, $k_p > 0$ and inequality $0{,}5k_y / k_p < 0$ is true.

Proof. We present the system of differential equations (15) in the form of a differential equation

$$k_p \ddot{e}_p(t) + k_y \dot{e}_y(t) + k_{\dot{y}} e_{\dot{y}}(t) = 0, \tag{16}$$

where $e_p = p_1 - p^l$, $e_y = y - y^l$, $e_{\dot{y}} = \dot{y} - \dot{y}^l$. If the $k_p \neq 0$, and the (k_p, k_y, $k_{\dot{y}}$) are positive factors, this equation can be presented as

$$s^2(t) + k_y / k_p s(t) + k_{\dot{y}} / k_p = 0. \tag{17}$$

The condition exponential stability of (15) is a negative real parts of the roots (17), that is satisfied for $k_y /(2k_p) < 0$.

Corollary 1. If $k_y = 0$, we have oscillation movement of leader with constant amplitude and it frequency is equal to $\sqrt{k_{\dot{y}} / k_p}$.

Corollary 2. If $k_y / \sqrt{4k_{\dot{y}}k_p} > 0$, we have asymptotically stability movement.

Corollary 3. If $0 < k_y / \sqrt{4k_{\dot{y}}k_p} < 1$, we have decreasing movement with oscillation.

Corollary 4. If $k_y / \sqrt{4k_{\dot{y}}k_p} > 1$, we have aperiodic movement of agent-members.

C. Motion with obstacles

Existing approaches to the consideration of the motion agents with obstacles assume a repulsive force from the obstacle that is located on the route to goal. Action of this forces increases when agent comes up to obstacle (deceleration of agent), and diminishes with distance. To bypass the obstacles agent should make additional efforts that will lead to the deflection of the original route. It can be solved by introducing in repulsive force of the additive components of the agent velocity and acceleration of motion with respect to the obstacles

$$u = \begin{cases} u_{\text{rep}\,d} + u_{\text{rep}\,v} + u_{\text{rep}\,a}, \text{ if } (d - 2r) \leq d_0, \quad v_{ao} > 0, \quad a_{ao} > 0, \\ u_{\text{rep}\,d} + u_{\text{rep}\,v}, \quad \text{if } \quad (d - 2r) \leq d_0, \quad v_{ao} > 0, \quad a_{ao} \leq 0, \\ 0, \text{ if } \quad (d - 2r) > d_0, \quad \text{or} \quad v_{ao} \leq 0. \end{cases}$$

Here

$$u_{\text{rep}\,d} = k_1 \left(\frac{1}{d - 2r} - \frac{1}{d_0} \right), \quad u_{\text{rep}\,v} = k_2 v_{ao}, \quad u_{\text{rep}\,a} = k_3 a_{ao},$$

value r is the maximal geometric size of an agent,

$$v_{ao} = (v - v_{obs})^{\text{T}} n_{ao}, \quad \text{and} \quad a_{ao} = (a - a_{obs})^{\text{T}} n_{ao},$$

where n_{ao} is a unit vector pointing from agent to obstacle. The sign of value v_{ao} show agent's movement, if $v_{ao} > 0$ is agent moving toward to obstacle, and $v_{ao} \leq 0$ moving performed away from obstacle.

IV. UAV MODEL

We selected Quadrotor as dynamic model of UAV that has vertical take-off and landing. A complete description of the model is presented in [7]. Model is presented by following equations system

$$\begin{cases} \ddot{\phi} = \dot{\theta}\dot{\psi}\left(\dfrac{I_y - I_x}{I_x} \right) - \dfrac{J_r}{I_x}\dot{\theta}w + \dfrac{l}{I_x}U_2, \\ \ddot{\theta} = \dot{\phi}\dot{\psi}\left(\dfrac{I_z - I_x}{I_y} \right) - \dfrac{J_r}{I_y}\dot{\phi}w + \dfrac{l}{I_y}U_3, \\ \ddot{\psi} = \dot{\phi}\dot{\theta}\left(\dfrac{I_x - I_y}{I_z} \right) + \dfrac{1}{I_z}U_4, \\ \ddot{z} = -g + (\cos\varphi\cos\theta)kU_1, \\ \ddot{x} = (\cos\varphi\cos\theta\cos\psi + \sin\varphi\sin\psi)kU_1, \\ \ddot{y} = (\cos\varphi\cos\theta\cos\psi + \sin\varphi\cos\psi)kU_1 \end{cases}$$

Here (ϕ, θ, ψ) is the roll, pitch and yaw angles, $I_{x,\,y,\,z}$ is the inertia UAV, J_r is the inertia rotor, l is the lever in coordinate system with the Quadrotor, $k = 1/m$, m is the mass UAV, w is the rotor speed, and U_1, U_2, U_3, U_4, are calculated as

$$\begin{cases} w = w_2 + w_4 - w_1 - w_3, \\ U_1 = b(w_1^2 + w_2^2 + w_3^2 + w_4^2), \\ U_2 = b(w_4^2 - w_2^2), \\ U_3 = b(w_3^2 - w_1^2), \\ U_4 = d(w_2^2 + w_4^2 - w_1^2 - w_3^2), \end{cases} \quad (18)$$

where b is the thrust factor, and d is the drag factor.

For simulation the model (18) transformed to a space-state form $\dot{X} = f(X,U)$, where $X \in \Re^{12}$ is the state vector with the coordinates

$$x_1 = \phi,\ x_2 = \dot{x}_1 = \dot{\phi},\ x_3 = \theta,\ x_4 = \dot{x}_3 = \dot{\theta},\ x_5 = \psi,\ x_6 = \dot{x}_5 = \dot{\psi},$$
$$x_7 = z,\ x_8 = \dot{x}_8 = \dot{z},\ x_9 = x,\ x_{10} = \dot{x}_9 = \dot{x},\ x_{11} = y,\ x_{12} = \dot{x}_{11} = \dot{y}.$$

Then, equations system we can be presented as

$$\dot{X} = \begin{cases} x_2, \\ x_4 x_6 a_1 + x_4 a_2 w + b_1 U_2, \\ x_4, \\ x_2 x_6 a_3 + x_2 a_4 w + b_2 U_3, \\ x_6, \\ x_4 x_2 a_5 + b_3 U_4, \\ x_8, \\ -g + (\cos x_1 \cos x_3) k U_1, \\ x_{10}, \\ u_x k U_1, \\ x_{12}, \\ u_y k U_1, \end{cases}$$

where

$$a_1 = \frac{(I_y - I_z)}{I_x},\ a_2 = -\frac{J_r}{I_x},\ a_3 = \frac{(I_z - I_x)}{I_y},\ a_4 = \frac{J_r}{I_y},$$

$$a_5 = \frac{(I_x - I_y)}{I_z},\ b_1 = \frac{l}{I_x},\ b_2 = \frac{l}{I_y},\ b_3 = \frac{l}{I_z},$$

$$u_x = \cos x_1 \sin x_3 \cos x_5 + \sin x_1 \sin x_5,$$
$$u_y = \cos x_1 \sin x_3 \cos x_5 - \sin x_1 \sin x_5.$$

The movement of UAVs group, in which each is Quadrotor and it moved in potential field to given target on the route, is simulated. We assume that this group consists of three agent-member and agent-leader. The agents route gives start positions and goal position: $p_{A1} = (100, 30)^T$, $p_{A2} = (75, 20)^T$, $p_{A3} = (130, 50)^T$, $p_{A4l} = (110, 70)^T$, $p_t = (600, 270)^T$. The coordinates of the located stationary obstacles on the route are known as $p_{o1} = (270, 130)^T$, $p_{o2} = (220, 210)^T$, and $D_\varepsilon(p_A) \leq 50$. The movement to target of agent-members and agent-leader is shown on the Fig. 1.

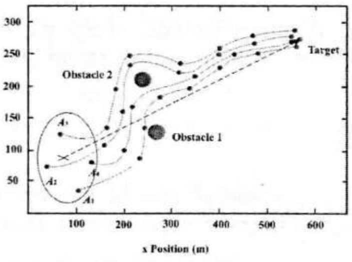

Fig. 1. Movement to the goal of agent-leader and agent-members.

Figure 1 shows that agents group bypasses obstacles an further is moving to target. In time overcoming obstacle agents group can change formation size and if obstacles ar absent on the route, the formation of agents is maintains.

V. Conclusions

In this paper, a new approach for tracking multi-age system on the given route with ability to avoid obstacles i presented. In this approach is created the control law with th special potential functions, one of them is attractive agents i movement on the route and other repulsive for neighbor agen in case of obstacles. The result of a control law in the presenc of obstacles is the change of configuration of multi-age system and increase of its size.

On base, these laws were constructed algorithms an proposed the simulation of this system. The examples o simulation behavior of multi-agent system show the ability t control the behavior of agents group. Its behavior include such stages as gathering into group, tracking on the give trajectory and avoidance of the obstacles.

Research shows that successful simulation depends fro on such parameters as ξ and η of potential function. Th investigation of influence these parameters on effectiveness o proposed potential functions is the topic of our future research.

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