Randomized Algorithm for UAVs Group Flight Optimization ⋆

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Abstract: The problem of small UAVs flight optimization is considered. To solve this problem thermal updrafts are used. For the precise detection of the thermal updrafts center the simultaneous perturbation stochastic approximation (SPSA) type algorithm is proposed.
If UAVs use thermal updrafts so they can save the energy during the flight. Therefore the flight time will be vary for different UAVs. In order to optimize the area monitoring, the consensus approach has been proposed.

Keywords: Unmanned aerial vehicle (UAV), UAVs network, UAVs group, simultaneous perturbation stochastic approximation, randomized algorithm, consensus.

1. INTRODUCTION

In recent years autonomous unmanned aerial vehicles (UAVs) are widely used for area monitoring. Technological advances, miniaturization of actuators, their availability and functionality allow to begin an effective use of small UAVs for area monitoring. On the one hand, a relatively small size and light weight provide a low cost of such technical solutions, but, on the other hand, it does not allow to use powerful navigation systems, high-capacity battery, onboard generators. It limits a flight distance of UAV up to 10 − 15 km. Therefore, the problem of small UAVs flight optimization is very important for the control system. Thermal updrafts are caused by convection in the lower atmosphere. The usage of thermal updrafts is one of the methods to conserve the energy and increase the flight range. Single UAV can fly a network of updrafts. Low cost and availability of small UAVs allow using them in a group, that is more efficient for area monitoring problem than using a single UAV (Amelin et al. [2009]). New capabilities of using network of updrafts arise when we use the group of small UAVs with autonomous communication with each other. The need for solutions of optimization problems with noisy observations for the limit time arise when we solve the problem of flight optimization for single and group of small UAV. In such conditions the recurrence randomized stochastic optimization algorithms were used (Granichin and Polyak [2003]). Monograph Granichin and Polyak [2003] initiate the detailed analysis of the randomized algorithm capability in estimation and optimization problems under arbitrary noise. The new type of the randomized algorithms, called Simultaneous Perturbation Stochastic Approximation (SPSA), was considered. It was proposed by O.N. Granichin, B.T. Polyak, J.C. Spall, T.E. Duncan, and B.A. Pasik-Duncan. The new algorithm is based on the gradient approximation along a randomly chosen direction (randomization), which it based on some controlled random variables. This variables affect on results of observations, that exist in system or were added by an experimenter.

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The research was applied to our practical project “Multi-Agent System for Controlling the Group of UAVs”.

The paper is organized as follows. In Section II, the basic characteristics and the architecture of UAVs are introduced. In Section III, the SPSA method to determine the center of termal updraft is described. The modified SPSA method is presented in Section IV. In Section V, some formulas for the optimal distance between the UAVs are shown. In Section VI, the consensus approach for area

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monitoring is considered. Section VI contains conclusions and future plans.

2. UAV FOR THE GROUP

We consider the multi-agent system of UAVs as an autonomous group of UAVs with communication between agents (single UAVs). The ability of communication is the main difference from traditional systems of UAVs. To implement multi-agent system of UAVs it is necessary to reconstruct a hardware equipment of a single UAV and a base station (Amelin [2010]).

The control system of our single UAV is consists of three layers. On the upper layer we have a base station — a computer (notebook, netbook or desktop computer) with different communication modules (Wi-Fi, Internet or radio modem). Basic tasks of a base station are:

- indicate the global mission for the group of UAVs (parameters of the monitoring area, objects of the monitoring, flight altitude, etc.);
- define individual tasks for each UAV-agent based on the number of UAVs and specifics of the problem;
- exchange of the information with UAV-agents;
- collect and process the information from the group of UAVs;
- define the new global mission for the group of UAVs based on the new information that was received.

In our project we use the model of lung glider as UAV-agent. Its parameters are: length — 1 m, wing span — 2 m, max take of weight — 2-2.1 kg, payload — 600 g, velocity — 40-100 km/h, range — 50 km.

On the middle layer we have a microcomputer (Linux, ARM processor). A microcomputer is the basic device of the UAV-agent control system. Its main purpose is to perform tasks with the minimum amount of time and resources. It implements the following actions:

- generate updates to the autopilot flight program;
- process data for navigation equipment and telemetry;
- work with additional equipment;
- communicate with other UAVs microcomputers, if work occurs in a group;
- send data to a base station;
- receive new tasks from a base station.

A microcomputer receives basic information from the base station (initial states, endpoints, a task for the group, etc.). A general task for group divides into particular tasks for each UAV. During a task execution a microcomputer carries out communication with other team members (UAVs-agents), who are in the range of the radio. Interaction in group allows to perform a general task more effectively, as well as avoid collision. Based on the data obtained from the base station, the navigation equipment and other UAVs microcomputers can generate a new program for the autopilot if the old one does not support the necessary requirements to perform a common task. While UAV flies in the area of communication with the base station, the microcomputer sends a new accumulated data and receives new tasks. In this case, the data can be accumulated not only due to UAVs own sensors and detectors, but also in connection with other UAVs. Microcomputer has information about the particular problem of the UAV and the general task for the group. In communication process the microcomputer gathers information about a general task. The data about the performance of its particular task could be obtained from on-board sensors.

On the lower layer we have autopilot software. It controls the actuators and processes sensor data.

3. SPSA METHOD TO DETERMINE THE CENTER OF TERMAL UPDRAFT

Consider the solve of the UAVs flight optimization problem by using thermal updrafts (updrafts). It will increase the range and allows to conserve the energy of UAVs (Amelin [2010]). The UAV's speed and pressure sensors allow to measure the speed of the vertical displacement at each point along its flight path. The algorithm of centering in the flow is started if the area with positive vertical airspeed is detected. The UAV moves by spiral around the updraft center to climb and increase its altitude. After climbing the UAV save its energy by switching to soaring mode (i.e. keep its engine off, hide the engine mount if its exists). It should return to its course. The flight time increase in about of 4 to 6 times by using updraft. Such research was done in Allen [2005], were the solution of the long area monitoring problem by one airplane with the using of updrafts was proposed. If the positive vertical speed is fixed by sensors, the aircraft uses strategy provided by Reichmann [1978]:

- if the vertical speed is positive, then airplane reduces the radius of its flight path;
- if the vertical speed is negative, than airplane increases the radius of its flight path;
- if the vertical speed is constant, than airplane fixed the radius of its flight path.

For the group of UAVs we consider the problem of the detection of the updraft's center in order to transmit this information to another UAVs. It was showed in Edwards [2008] that the method of Allen [2005] is imprecise and time-consuming. In Antal et al. [2010] it was proposed to use simultaneous perturbation stochastic approximation method (SPSA) for thermal updraft center detection. The maximization of the velocity function is the iterative process of coordinates adjustment. SPSA presents a recursive optimization algorithm that does not depend on direct gradient information or measurements. This algorithm is based on an approximation of the gradient and formed from measurements (generally noisy) of the objective function. Detailed description of SPSA can be found in Granichin [1989, 1992, 2004]). The algorithm starts with an initial "guess" of a solution, and this estimated solution updates on an iteration-by-iteration basis with the aim of improving the performance measure (objective function). However, in practical applications we can't use this method because it is technically difficult to implement the path hit in the chosen point. It turns out, that the modified SPSA method with two variables is more appropriate.

4. MODIFIED SPSA METHOD

The following step-by-step summary shows how SPSA iteratively produces a sequence of updraft center estimates.

(1) **Initialization and coefficient selection.** To set counter index $i = 0$. To pick initial guess $\widehat{\mathbf{x}}(0) \in \mathbb{R}^2$ and a fairly small non-negative coefficient $\alpha > 0$. The initial guess in our implementation of the algorithm is the point where a positive updraft was first measured.
(2) **Iteration $i \to i + 1$.** To set $i := i + 1$.
(3) **Generation of the simultaneous perturbation vector.** To generate by Monte Carlo a 2-dimensional random perturbation vector $\mathbf{\Delta}_i$ which components are independently generated from a zero mean probability distribution satisfying the preceding conditions. A common choice for each component of $\mathbf{\Delta}_i$ is to use a Bernoulli ± 1 distribution with probability of 1/2 for each ± 1 outcome.
(4) **Proceeding to the new waypoints.** To proceed to next two points $\mathbf{u}_i^-$ and $\mathbf{u}_i^+$. They are intersections of the UAV trajectory projection on 2D plain and the line which goes through the point of the previous estimate $\widehat{\mathbf{x}}(i-1)$ in the direction of the vector $\mathbf{\Delta}_i$ (see Fig. 1).
(5) **Velocity function evaluations.** Obtain two measurements at the points $\mathbf{u}_i^\pm$ of the velocity function

$$y_i^\pm = F(\mathbf{u}_i^\pm).$$

(6) **Computing the values $\beta_i^\pm$.** To measure the distances from the the point of the previous estimate $\widehat{\mathbf{x}}(i-1)$ and points $\mathbf{u}_i^-$ and $\mathbf{u}_n^+$ and compute such two values $\beta_i^\pm$ that

$$\mathbf{u}_i^\pm = \widehat{\mathbf{x}}(i-1) + \beta_i^\pm \mathbf{\Delta}_i.$$

(7) Quasigradient calculation. To calculate the quasigradient:

$$\widehat{g} = \mathbf{\Delta}_i \frac{y_i^+ - y_i^-}{\beta_i^+ + \beta_i^-}.$$

(8) Updating center estimation. Use the standard stochastic approximation form

$$\widehat{\mathbf{x}}(i) = \widehat{\mathbf{x}}(i-1) + \alpha \widehat{g}$$

to update the current center estimation.
(9) **Iteration or termination.** To return to Step 2 or to terminate the algorithm if there is little change in estimations obtained on several successive iterations or the maximum allowed number of iterations has been reached.
(10) **Climbing in the updraft.** Circle around estimated updraft center in order to climb.

This method provides a good approximation of the updraft center using a small number of measurements and no a priori knowledge on updraft location.

5. GROUP OF UAVS

In a line with the SPSA algorithm when the UAV-agent "finds" the updraft and determines the center of updraft, it sends the data to other UAV-agent. Those assess the distance to the updraft and possible energy savings, and determine whether it is profitable to fly to this updraft. In Antal et al. [2010] the advantages of using thermal updrafts by the group of cooperative UAVs compared with a single glider were presented. Authors proved the following condition for the optimal distance between the UAVs flying in a group:

$$l = \frac{d}{2c(K-1)},$$

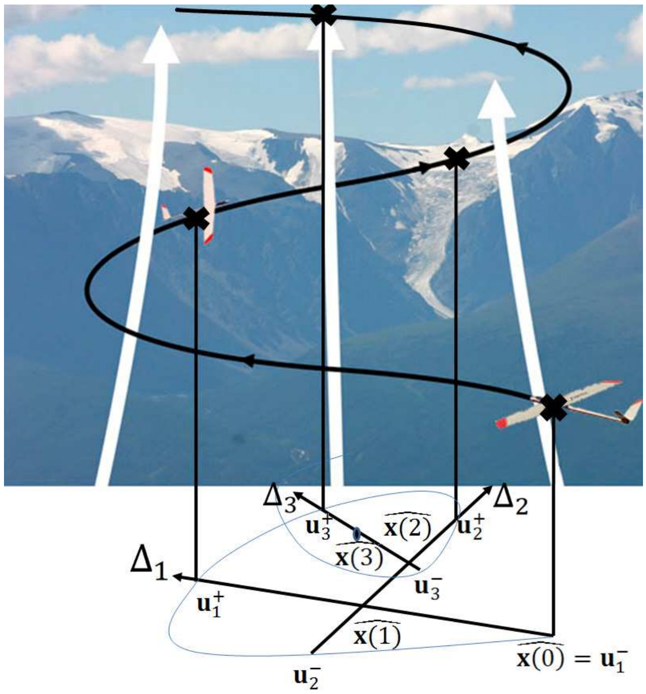

Fig. 1. Sequence of estimates and waypoints

and, as a consequence, give for the distance r the inequality

$$d - 4rc > 0,$$

under which the average power consumption of one UAV-agent reduces while using of updrafts founded by another UAV-agent. Here and above, d is the energy benefit obtained from using the thermal updraft, c is the energy sink rate for a single UAV flying at the cruise speed, K is a number of UAVs in the group.

6. CONSENSUS APPROACH FOR OPTIMIZATION OF AREA MONITORING

For the future plans we'll consider the problem statement of consensus approach to optimize the area monitoring by group of UAVs.

We assume that in the initial time all UAVs have the same battery level and battery capacity. All UAVs have the common task (for example, area monitoring) and their own particular tasks aimed on achieving the common task. Usually the general problem does not change over a long period of time, while the particular tasks may change due to various external influences. If one of the UAVs used the thermal updraft and saved the energy, the others at this time, perhaps, lost their energies. It turns out, that the energy expenditure will vary for different UAVs. In this case if some UAV lose the energy very fast so it will not take part in the common task performance. But this agent might got some information that is needed by others. That's what it is reasonable to redistribute the information among agents despite the fact that the agent will also spend some energy to sent the information to neighbors. To ensure that all UAVs will redistribute the information depending on the battery level the consensus approach is proposed. The local voting protocol (consensus protocol) will help to balance the energy and redistribute the information of UAVs during the flight and assign tasks for the flight in accordance with the UAVs battery level.

In Amelina and Fradkov [2012], Amelin et al. [2012], Amelina [2012] the consensus problem in multi-agent stochastic system with nonlinear dynamics, measurements with noise and delays, and uncertainties in the topology and in the control protocol was considered. As an example of such a system, the load balancing system in network with noisy information about the load and switched topology was presented. The load balancing problem was reformulated as consensus problem.

We consider the UAVs network of n UAV-agents (agents) that collect different type of information with feedback. Denote $N = \{1, \ldots, n\}$ as a set of agents which can collect the information, get the information from its neighbors and send the information to the base station. The information can be redistributed among agents.

At any time t, the state of agent i, $i = 1, \ldots, n$ is described by two characteristics:

- q_t^i is the information flow of agent i at time t;
- p_t^i is the energy level of agent i at time t.

The dynamics of each agent are described by

$$p_{t+1}^i = p_t^i - r\ln(t);\;\; i \in N,\; t = 0, 1, \ldots, T, \qquad (1)$$
$$q_{t+1}^i = q_t^i + z_t^i + u_t^i;\;\; i \in N,\; t = 0, 1, \ldots, T,$$

where r is the rate of battery discharge, z_t^i is the new information received by agent i at time t, u_t^i is the result of information redistribution between agents, which is obtained by using the selected protocol of information redistribution. In the dynamics we assume that $\sum_i u_t^i = 0,\; t = 0, 1, 2, \ldots$.

We assume that each agent $i \in N$ at time t can receive the following information to form the control strategy:

- noisy observations about its information flow $y_t^{i,i}$
- noisy and delayed observations about its neighbors' information flow $y_t^{i,j}$
- information about its energy level p_t^i and about its neighbors' energy level $p_t^j,\;\; j \in N_t^i$.

Let T_t denotes the time before the redistribution of all information between all agents, and the fraction $\frac{q_t^i}{p_t^i}$ denotes the information capability of agent i at time t. We set the control goal

$$T_t \to \min_{\bar{u}_t}. \qquad (2)$$

To achieve the goal it is natural to redistribute the information over time. In stationary case the best strategy is to redistribute information by such a way as

$$q_t^i/p_t^i = q_t^j/p_t^j,\; \forall i, j\; \in N.$$

Hence, if we consider $x_t^i = q_t^i/p_t^i$ as state of each node i then our goal is to achieve consensus. Thus, it is enough to consider the problem of how to keep the equal information capabilities of all agents in the network.

7. CONCLUSION

The problem of flight optimization by the example of the using thermal updrafts was considered. It was shown that the use of updrafts is more efficient for the accumulation of high. SPSA method for determining the center of thermal updrafts was introduced. The center of updraft is the information that passes from the UAV agent to other agents.

To ensure that all UAVs will redistribute the information depending on the battery level the consensus approach was proposed. This problem will be considered in details in our future works.

In future works we also plan to study the algorithms for collision avoidance of UAVs-agents. We also plan to research data transmission protocols and conversion of product pictures for faster data transfer.

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