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New proposed implementation of ABC Method to Optimization of Water Capsule Flight

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Abstract—**The physical model of Water Capsule Flight is relatively simple but analytically unsolvable. The input data includes the mass of the capsule, velocity, altitude, aerodynamic coefficients of the capsule, and horizontal and vertical winds. The ABC optimization is focused on those attributes. This article is a part of the series dedicated to Inspired by Nature Methods of AI and their implementation in the mechatronic systems. A bag filled with water is an excellent source of explosion-produced water spray which can be used for extinguishing large fires or for other purposes. The paper presents theoretical models of flight of a bag filled with water, dropped from an aircraft moving horizontally. Results of numerical computations based on this model are compared with results of measurements for the trajectory of a bag dropped from a helicopter. A description of the experimental and numerical setup for this experiment are also discussed.**

I. Introduction

BEHAVIOR of many animal species in nature is similar to the swarm behavior. Shoals of fish, flocks of birds and flocks of land animals are created as a result of the biological drive to live in a group. Specific individuals belonging to a flock or a shoal are characterized by higher survival probability because predators or raptors usually attack only one individual. Group movement is characteristic for flocks of birds and other animals as well as shoals of fish. Flocks of land animals react quickly to changes of movement direction and velocity of neighboring individuals. Herd behavior is also one of the main characteristic features of insects living in colonies (bees, wasps, ants, termites) Communication between individual insects of the swarm of social insects has already been thoroughly studied and is still subject of studies. The systems of communication between individual insects contribute to creation of "collective intelligence" of swarms of social insects [4], [11]. Thus the term "Swarm intelligence" emerged, meaning the above mentioned "collective intelligence" [6], [10], [9], [15], [16]. The swarm intelligence is part of the Artificial Intelligence as per examination of activities performed by separate individuals in decentralized systems [14]. The Artificial Bee Colony (ABC) metaheuristics has been introduced quite recently as a new trend in the Swarm intelligence domain [17][13][2]. Artificial bees represent agents solving complex combinatorial optimization problems. This article presents proposed optimization of water capsule flight using ABC method [10][9]. Data obtained from real water capsule flights developed for firefighting was used here. A very efficient way of water spray formation is explosion method consisting in detonation of an explosive placed in a water container [19]. Water sufficiently eliminates undesired consequences of detonation, which provides potential possibility for applications of that method. Water spray can be used, e.g. to extinguish fire and to neutralize contaminated areas [12][5]. Water capsule suspended under a helicopter or another aircraft enables fast transport of water to the area of airdrop. Described system allows automatic release of the water capsule at such a distance from the target so that, after some time of its free fall, it is located over the target at the specified altitude and then detonated to generate spray which covers specified area of the ground [5][18].

II. Physical methodology of the water capsule flight analysis

In principle the problem of delivering a water capsule to a given point on the ground is very similar to the problem of hitting a surface target by a bomber with an unguided bomb. There are, however, two problems that make difficult a direct

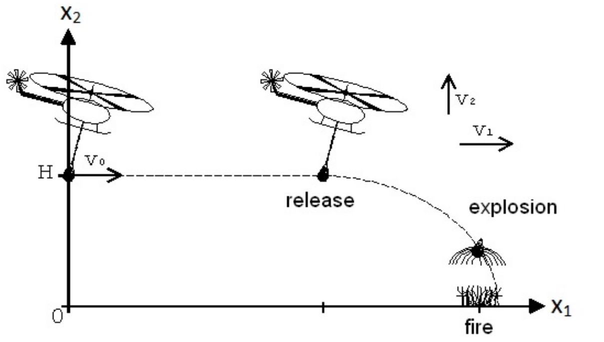

Fig. 1. Schematic view of the procedure of delivering water-capsule to a designed point.

application of the procedures used by military aviation. The first follows from the fact that such procedures, as majority of procedures used by the military are either classified as a whole or comprise classified crucial components [1] [7]. The second problem is connected with much higher safety standards that must be observed in the case of placing water-capsule "in target". It seems then more reasonable to develop procedures from the very beginning than to try to adopt non-classified components of similar military procedures. The ultimate objective consists in developing a high precision system of delivering by an aircraft (presumably a helicopter) a water-capsule to a defined point where it should be exploded in order to generate cloud of water-spray playing role of the fire-extinguishing agent. A scheme of such procedure is shown in Fig. 1.

Designing a suitable system must be based on theoretical models that can serve as a foundation of numerical programs. The models are founded on the assumption that the water-capsule moves in the air under the influence of a constant and vertical gravitational force and of the Bernoulli drag (pressure drag) that acts against its motion with respect to the air and is proportional to the square of the velocity of this motion. After denoting the velocity by $\overrightarrow{v}$ one can write the following formula the drag force.

$$\overrightarrow{O} = \frac{c\rho A}{2} v \overrightarrow{v}, \tag{1}$$

where $v = |\overrightarrow{v}| = \sqrt{v_1^2 + v_2^2}$,
c is the drag coefficient depending on the shape of the moving body, ρ denotes density of the air, and A is the frontal cross-section of the body.

A. Equations describing flight of a water capsule

A water capsule dropped from a horizontally moving aircraft (e.g. helicopter) falls down under composite action of the drag force that has both vertical and horizontal components and the gravitational force that acts all time vertically. Introducing Cartesian coordinates: the horizontal one x_1 and the vertical one x_2, one can write equations of motion in the form

$$\dot{v_1} = -\frac{c_1\rho A_1}{2M}\sqrt{v_1^2 + v_2^2}v_1, \dot{v_2} = -\frac{c_2\rho A_2}{2M}\sqrt{v_1^2 + v_2^2}v_2 - g \tag{2}$$

where v_1 and v_2 are the horizontal and vertical coordinates of the capsule's velocity respectively, M is its mass and g denotes gravitational acceleration. One has to do with a set of ordinary, first order, nonlinear differential equation with respect to the Cartesian coordinates of capsules velocity. Having these equations solved, one can obtain coordinates of the capsule by simple integration coordinates of velocity with respect to time. Unfortunately, the equations (2) cannot be solved analytically without far going simplifications. It is so due to the coupling square root term. As such, one has to apply numerical methods for solving the equations.

B. Numerical solutions

In this case the standard fourth order Runge-Kutta method was used, and numerical computations were performed inside the MATLAB environment. In practice some additional work aimed, e.g., on optimization of the length of the step of integration, had to be done, but we will not go into technical details [14].

The solution is obtained for standard initial conditions given by the equations

$$v_1(0) = v_0, v_2(0) = v_0 \tag{3}$$

which corresponds to horizontal motion of the water-capsule at the moment of release. Provided the value of the drag coefficient c is known, one can obtain both components of capsule's velocity as functions of time. Since the main objective consists in computing trajectory of the capsule, one has to compute its horizontal and vertical component using integrals

$$x_1(t) = \int_0^t v_1(\tau)d\tau + x_1(0),$$
$$x_2(t) = \int_0^t v_2(\tau)d\tau + x_2(0) \tag{4}$$

that, in general, have to be computed numerically since the functional form of v_1 and v_2 with respect to time are not known. The numerical solution of equations for the components v_1 and v_2 of the capsule's velocity has one more advantage. After some modifications such a procedure can be applied to the problem of flight in the air moving with respect to the ground. In fact, equations (2) describe velocity of the capsule with respect to the ground under the assumption that the air is still. If, however, velocities of wind and that of ascending or descending current are considerable, the equations have to be modified

$$\dot{v_1} = -\frac{c_1 \rho A_1}{2M} \sqrt{\tilde{v_1}^2 + \tilde{v_2}^2} \tilde{v_1}$$
$$\dot{v_2} = -\frac{c_2 \rho A_2}{2M} \sqrt{\tilde{v_1}^2 + \tilde{v_2}^2} \tilde{v_2} - g \tag{5}$$

where

$$\tilde{v_i} = \tilde{v_i} - \tilde{V_i}, i = 1, 2 \tag{6}$$

are coordinates of the capsule's velocity with respect to the air; V_1 denotes velocity of wind and V_2 velocity of vertical current (a further generalization, we will not discuss here, would be taking into account the fact that strong and random winds make the problem 3-dimensional instead of 2-dimensional planar problem of a flight in the still air).

Numerical solution of equation of motion requires inserting numerical data from the very beginning. Some of them like the mass M of the capsule or the density of the air are at hand, but the drag coefficients $k_1 = cA_1$and $k_2 = cA_2$, appearing in (2) and (5) have to be determined from experimental data.

III. ABC APPLICATION TO OPTIMIZATION OF FUEL CONSUMPTION OF A HELICOPTER

A. Numerical solutions

Artificial bee colony (ABC) is a model proposed in 2005 by a Turkish scientist Dervis Karaboga [10][3][9]. Like other algorithms described herein, it is also based on herd behavior of honey bees. It differs from other algorithms in the application of higher number bee types in a swarm. After the initialization phase, the algorithm consists of the following four stages repeated by iteration until the number of repetitions specified by the used is competed:

- Employed Bees stage,
- Onlooker Bees stage,
- Scout Bees stage,
- storage of the best solution so far.

The algorithm starts with initialization of the food source vectors x_m, where $m = 1...SN$, while SN, is the population size. Each of those vectors stores n values $x_m, i = 1...n$, that shall be optimized during execution of that method. The vectors are initialized using the following formula:

$$x_{mi} = l_i + rand(0, 1)x(u_i - l_i) \tag{7}$$

where:

l_i-lower limit of the searched range,

u_i- upper limit of the searched range,

Bees adapted to different tasks participate in each stage of the algorithm operation. In case of ABC, there are 3 types of objects involved in searching:

- Employed Bees - bees searching points near points already stored in memory,
- Onlooker Bees - objects responsible for searching neighborhood of points deemed the most attractive,
- Scout Bees - (also referred to as scouts) this kind of bees explores random points not related in any way to those discovered earlier.

Once initialization is completed, Employed Bees start their work. They are sent to places in the neighborhood of already known food sources to determine the amount of nectar available there. Results of the Employed Bees work are used by Onlooker Bees. Onlooker Bees randomly select a potential food source using the following relationship:

$$v_i = x_{mi} + \varphi_{mi}(x_{mi} + x_{ki}) \tag{8}$$

where:

v_i-vector of potential food sources,

x_k- randomly selected food source,

φ_{mi}- random number from the range [-a,a] Once the vector is determined its fitting is calculated based on the formula dependent on the problem being solved and the fitting v_m is compared with x_m. If the new vector fits better than the former one, then the new replaces the old one. Another phase of the algorithm operation is the Onlooker Bees stage. Those bees are sent to food sources classified as the best ones and in those very points the amount of available nectar is determined. The probability of the x_m source selection is expressed with the formula:

$$p_m = \frac{fit_m(x_m)}{\sum_{k=1}^{SN} fit_k(x_k)} \tag{9}$$

where:

$fit_m(x_m)$- value of fitting functions for a given source.

Obviously, when onlooker bees gather information on the amount of nectar, such data is compared with results obtained so far and if the new food sources are better, they replace the old ones in the memory. The last phase of this algorithm operation is exploration by scouts. Bees of that type select random points from the search space and then check nectar volumes available there. If newly found volumes are higher than the volumes stored so far, they replace the old volumes. The activity of those bees makes it possible to explore the space unavailable for the remaining types of bees thus allowing to omit any extremes.

B. Application of ABC

The reach of the capsule flight is calculated so that the distance from the helicopter does not exceed 140 m and then the initial velocity V0 and the altitude Z are optimized. The fuel consumption at the power of 2225KM - 292 g /KMh (i.e. 292 g of fuel per horse power per hour) is assumed as the cost. At the moment the program estimates the results only approximately, but author believes that he shall be able to make the results more real in the near future.

Random selection of the initial altitude and velocity of the helicopter;

REPEAT

The selected altitude is put into the water capsule flight reach formula;

The selected velocity is put into the water capsule flight reach formula;

Then we calculate the function of the cost of rising the helicopter to the specified altitude and accelerating it to the specified velocity so that the capsule is dropped not further than 140 m
away from the target;
Sources;
The verified velocity and altitude are replaced by new values;
The best velocity and altitude are stored in the memory;
UNTIL (the conditions are met)

The main underlying idea of the optimization is to select such altitude and velocity of the helicopter that shall enable the capsule to reach the target. The path covered by the capsule falling from the helicopter to the vicinity of fire depends on the altitude from which the capsule was dropped. It is obvious that increase of altitude or velocity depends directly on helicopter rotor power. The power to be generated influences specific fuel consumption. As illustrated in the graph, vertical climb of the helicopter at zero horizontal velocity generates huge power demand. One can significantly reduce power needed to climb the helicopter to the specified altitude by increasing its horizontal velocity. This relationship results from the way of generating aerodynamic lift by the helicopter [8]. However, too high horizontal velocity can significantly increase power demand causing increased specific fuel consumption.

IV. Conclusion

Obviously, the power required during forward flight will also be the function of GTOW (Gross Takeoff Weight). Representative results illustrating the effect of GTOW on the rotor power required are provided in Fig. 2 for a sample helicopter at sea-level (SL) conditions. It should be noted that with increasing GTOW, the excess power available decreases gradually, this phenomenon applies in particular at lower airspeed where the induced power requirement is a higher percentage of the total power. In the subject case, the power available at SL is 2800 hp and for a gas turbine this remains relatively constant versus airspeed. The airspeed value at the intersection of the power required curve and the power available curve indicates the maximum level flight speed. However, the maximum velocity is limited by probable onset of rotor stall and compressibility effects before this point is reached. Multi-objective optimization of a helicopter flight carrying a water capsule is a non-trivial problem. ABC algorithm application enables efficient optimization of fuel costs. Due to high complexity of that problem, one must bear in mind that optimization results may deviate from real results. These can be caused by the fact that wind drag and direction were skipped. The distance at which the helicopter must approach the fire can have significant impact on the final result while the air temperature can significantly influence the fuel demand of the helicopter engine. There is also an issue of the angle at which the capsule is dropped. That aspect can also be taken into account in further studies on ABC application to fuel consumption optimization and as a consequence, on reduction fire extinguishing cost using that method. Summing

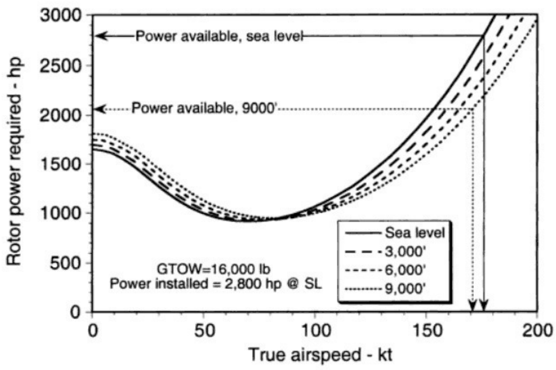

Fig. 2. The graph of fuel consumption versus the velocity and altitude of the helicopter flight.

up, that problem is very complex, which makes it a good example of ABC application.

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