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HIGH PRECISION DELIVERY OF A WATER CAPSULE: THEORETICAL MODEL, NUMERICAL DESCRIPTION, CONTROL SYSTEM AND RESULTS OF FIELD EXPERIMENTS

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Abstract − The paper describes an outline of a system of precise delivery of water capsule to a given point. Theoretical model of the capsule's flight, the method of numerical computing its trajectory under various limiting conditions and the scheme of the system of acquisition and transmission of the data serving as initial conditions for numerical computation are presented. Results of field experiments verifying theoretical model and numerical methods of computing the trajectory of a water-capsule by comparison of computed and registered trajectories after its release from a helicopter in the horizontal forward flight are reported as well.

Keywords: drag influenced fall, satellite geodesy, fire fighting

1. INTRODUCTION

Working out an efficient system of extinguishing large open-space fires is a serious and complex problem. One part of the problem consists in designing an extinguishing machine. It is known from some time that water spray is a very efficient extinguishing agent due to its ability of absorbing large amount of heat in a very short time, and cutting off influx of the oxygen [1]. Commercial water-spray extinguishers for quenching small and medium scale fires are already available. In the case of large scale fires, however, a large amount of water-spray of the order of 10^3 kg must be produced in a very short time (about a second). One can achieve this objective using explosion for spraying water bulk and spreading it over an area of ca. 200 m^2. Models of such process and results of numerous experiments verifying the models have been presented on other occasions [2]. One can say that the problem of explosive production of the water-spray is solved except for some technological details that would be important for the commercial version of the system.

On the other hand the system cannot be efficient without delivering a water-bomb to a desired point and exploding it at a desired moment. Description of the elements securing achievement of these two objectives is the subject of this paper. To be suitable for quenching fires that appear at unpredicted points the system must be made airborne, and preferably based on the helicopter as the means of transportation. When the water-capsule is delivered to the area of fire it must be released at a point securing hitting the target and exploded at a desired moment.

The core of the system, consisting of a suitable dynamical model and numerical algorithm for computing the capsule's trajectory, is described in Subsection 2.1. It must be supplemented with a hardware, described in Subsection 2.2, securing instantaneous acquisition and transmission of the data necessary for computing a particular trajectory and determining the moment of explosion for which the efficiency of the water-spray cloud would be the highest.

The paper also present results of the tests verifying the model, numerical algorithms, and fundamental elements of the subsystem that is to serve for communication and for data acquisition and transmission. The tests required development of specific registration and measurement techniques that are described in the subsection 3.1. Subsection 3.2 contains a brief description of the models used to extract parameters of motion for a registered trajectory. Subsection 4.1 presents sample results obtained in the course of the tests with releasing water-capsule from a helicopter in various flight conditions, and comparing registered and computed trajectories. Subsection 4.2 reports basic results of the accuracy test of hitting selected area with a water-capsule released from a helicopter, and Subsection 4.3 contains a discussion of satellite visibility problem. The paper is closed with the concluding section.

2. THE SYSTEM OF DELIVERY OF WATER CAPSULE TO A POINT

2.1. Dynamical model and numerical solutions for the flight of the capsule

Taking into account the size of the capsule and typical ranges of its velocity with respect to the air, one can safely assume that the flight is governed by two forces. One of them is the pressure (Bernoulli) drag force

$$F_{drag} = D\rho A v^2, \tag{1}$$

where ρ denotes density of the fluid, i.e., of the air, v denotes the capsule's velocity with respect to it, A is the frontal cross-section area of the capsule, and D is a dimensionless coefficient depending on the shape. Gravitation is the second force.

Even if the air is still, the problem is essentially two-dimensional and therefore vector description is necessary. To make it easier we show the scheme of forces acting on the capsule in Fig. 1. As one can see, the drag force has in general two components: the horizontal one $F_{(x)drag}$ and the vertical one $F_{(z)drag}$, and the gravitational force Q is always vertical. As is shown, vertical and horizontal air currents can be also taken into account.

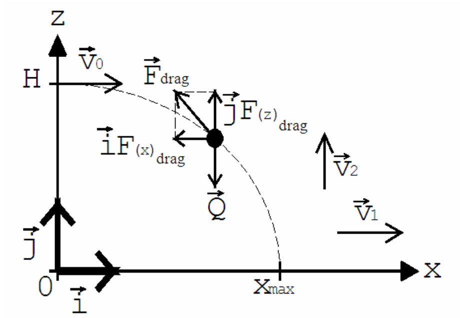

Fig. 1. Forces acting on a body falling with initial horizontal velocity.

The vector form of the drag force in the case of flight in still air is as follows

$$\vec{F}_{drag} = -\frac{c\rho A}{2}\sqrt{v_x^{\,2}+v_z^{\,2}}\,\vec{v}\,, \tag{2}$$

where c is, in general, a tensor coefficient. In such a case one can write equation of motion of the capsule in the form

$$\begin{cases} OX: ma_x(t) = -b\left(\sqrt{v_x^{\,2}(t)+v_z^{\,2}(t)}\right)v_x(t) \\ OZ: ma_z(t) = -mg - k\left(\sqrt{v_x^{\,2}(t)+v_z^{\,2}(t)}\right)v_z(t) \end{cases} \tag{3}$$

in the case of flight in the still air, and in the form

$$\begin{cases} OX: ma_x(t) = -b\sqrt{(v_x(t)-v_1)^2+(v_z(t)-v_2)^2}\,(v_x(t)-v_1) \\ OZ: ma_z(t) = -mg - k\sqrt{(v_x(t)-v_1)^2+(v_z(t)-v_2)^2}\,(v_z(t)-v_2) \end{cases} \tag{4}$$

if the air currents with respect to the ground are taken into account. In both formulae v_x and v_z denote the horizontal and the vertical coordinate, respectively, of the capsule's velocity with respect to the ground, v_1 and v_2 are analogous coordinates of the velocity of the air current with respect to the ground, m denotes the capsule's mass, and g is the gravitational acceleration. Coefficients b and k correspond to the coefficient $c\rho A$ in Eq. (2) taking into account variation of both the cross-section area A and the shape coefficient c between the horizontal and vertical components of the motion.

The equation of motion for v_x and v_z should be solved for the initial conditions: $v_x(0) = v_0$, and $v_z(0)=0$. If already known, one can obtain the flight trajectory using the formulae

$$\begin{cases} x(t) = \int_0^t v_x(\tau)d\tau + x(0) \\ z(t) = \int_0^t v_z(\tau)d\tau + z(0) \end{cases} \tag{5}$$

with $x(0)=0$ and $z(0)=H$, where H is the height above the ground at which the capsule is released.

Analytical solution of equations (4) and even of equations (3), simplified by the assumption: $b=k=d$, cannot be found. Therefore one has to develop an algorithm for numerical solving of equation of motions (4). In solving the Cauchy problem for the equations of motions (4) several versions of the Runge-Kutta methods had been tested [3,4], and finally the method RK(4,4) was chosen for implementation as a reasonable compromise in terms of speed and accuracy.

2.2. Elements of the system of control, and data acquisition and transmission

The general scheme of the whole system network is shown in Fig. 2.

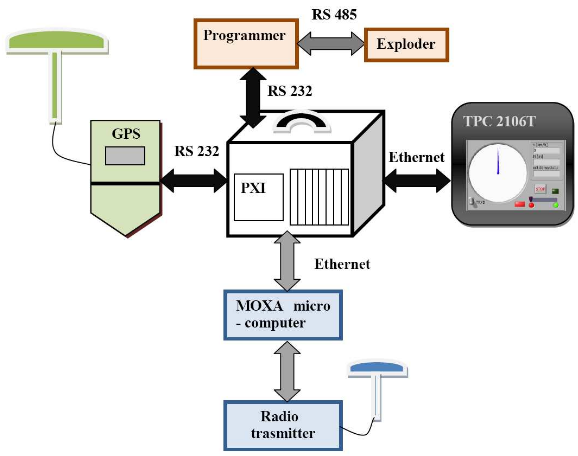

Fig. 2. A general scheme of the system of control.

The core of the network consists of the industrial computer whose role is to perform computations and to correlate action of all the subordinate devices.

For building the network under consideration the industrial computer NI PXI of the family 1000B from the National Instruments was chosen to fulfil the role of the primary control computer (PCC). PXI - PCI eXtensions for Instrumentation – is an open, modular standard of PC class computers, used for measurements and industrial automation, developed by the National Instruments in 1997.

The choice was based on the following qualities of the computer: high immunity with respect to electromagnetic perturbations, stable work for a broad spectrum of the air temperature and humidity, high immunity with respect to mechanical shocks and vibrations, possibility to easily change configuration and enlarge the computer and last but not least, availability of reliable and comprehensive servicing from the producer.

A general view of the computer is shown in Fig. 3. The computer used in the system consist of the chassis, the built-in controller NI 8196 based on the Pentium IV 2.0 GHz processor and 1 GB RAM DDR2, and of supplementary modules.

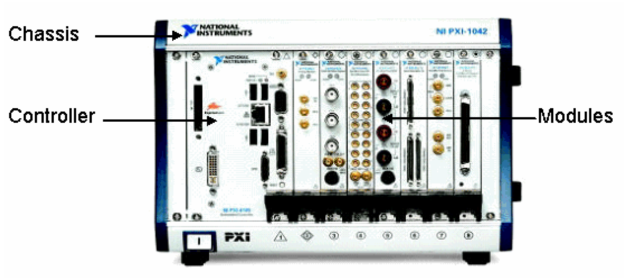

Fig. 3. General view of the PXI computer.

It is supplied with the National Instruments' LabVIEW (LABoratory Virtual Instrumentation Engineering Workbench) RT system that secures computer's work in the real time regime. Visualization of the PXI computer status, and of the aircraft flight parameters, as well as inserting necessary information is made possible by a mini-computer TPC - 2106T, supplied with a touch panel, and connected with the PXI computer via the Ethernet. The mini-computer is shown in Fig. 4a.

The mini-computer unites in itself the functions of the display, keyboard and mouse used for communication with ordinary PC computers.

The GPS receiver installed on the board of the helicopter is another very important component of the control system. Its principal objective consists in providing computer with precise data concerning position of the helicopter and its velocity. It has to be connected with the PCC via serial port. With a typical velocity of the helicopter and the required accuracy of the helicopter position coordinates about 1 m in each direction the receiver must acquire satellite signals at least 10 times per second. Therefore an ordinary GPS receiver used for car navigation cannot do the job. The GPS receiver for the system must have probing frequency 20 Hz working in the NMEA (National Marine Electronics Association) standard, broadcasting a GGA sentence containing data on the zone time, on the hemispheres and the latitude and longitude (in degrees), and on the altitude above the sea level and VTG sentence containing data on the value of velocity of motion and its direction.

To increase accuracy of positioning the helicopter, two of GPS receivers GX1230GG from Leica Geosystems (Switzerland), working in the difference regime are used – one serving as the reference is located on the ground (base station), and the moving one (rover) is installed on the board of the helicopter. The position of the reference receiver is determined with high accuracy, and of the order of several centimetres [8]. A view of a GPS receiver GX1230GG is shown in Fig. 4b.

a) b)

Fig. 4. Front view of the TPC - 2106T mini-computer (a). GX1230GG receiver with RX1210T controller (b).

The subsystem of data transmission is another essential component of the whole system. It is too complex to describe it here in detail. A general scheme of the network is shown in Fig. 5.

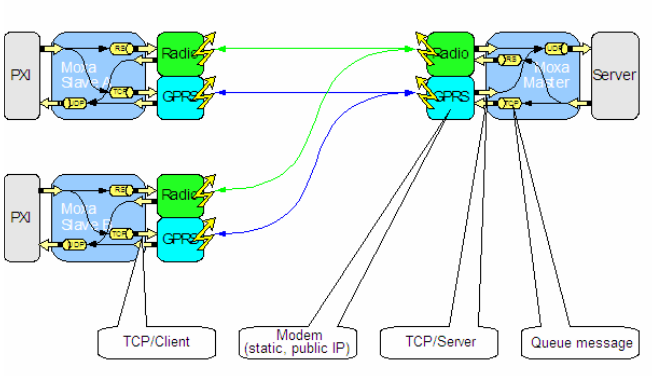

Fig. 5. Schematic view of interconnections within the system of data transmission.

An important role in the system, apart from the main and reserve radio networks, is played by the communication micro-computers. The Moxa UC 7408 LX Plus micro-computers (cf. Fig. 7), supplied with the operating system Linux 2.6 have been chosen for the network under construction. Its basic data are as follows: processor Intel XScale IXP-422/425 266/533 MHz; 128 MB RAM, 32 MB Flash Disk; 2 ports 10/100 Mbps Ethernet; power: 12 – 48 V DC; 8 input and 8 output channels; 8 serial ports RS-232/422/485; PCMCIA, Compact Flash; C/C++ or VB.NET/C# libraries; installation on a DIN rail or on a flat surface. The Moxa computers do not contain moving elements, which enhances their stability and durability.

Fig. 7. A view of Moxa micro-computer.

The communication micro-computers serve also as a protection against an unauthorized access to the server.

All the elements described above serve as the means to secure transportation of the water-bomb capsule to the desired area and dropping it along a desired trajectory.

A programmable exploder is the element of crucial importance for producing the water cloud at a desired altitude over the ground.

The programmable exploder consists of a programmer connected with the PCC via a serial interface RS 232 and of a proper exploder connected with the programmer via the serial interface RS 485.

3. EXPERIMENTAL METHODOLOGY

Solution of the problem of comparing computed trajectories with the real ones requires working out an accurate method of registration both of the shape of trajectory and of such parameters as the altitude at which the water-capsule is released and the velocity of helicopter's forward flight. The parameters are used as initial conditions for computing the numerical trajectory model. Only then one can compare both of them to estimate accuracy of the model and numerical algorithm [5].

3.1. Experimental setup and registration procedure

A fast camera is the primary tool used for registration of the actual trajectory of the water-capsule released from the helicopter. Its arrangement within the experimental setup is schematically shown in Fig. 8.

As can be seen in the figure, the camera is located 300 m from the centre of the 50 m long interval marked by two calibration poles, each 7 m tall, along the normal to the interval. Such an arrangement ensures safety of the camera, small parallax errors, and provides registered frames with the length etalon.

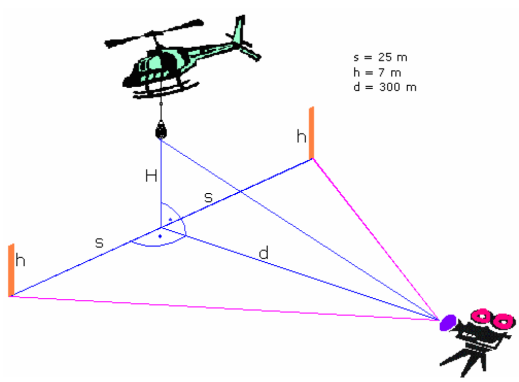

Fig. 8. Schematic view of the registration post.

For registering the capsule flight a fast camera FASTCAM–ultima 1024 was chosen. It registers the capsule at the frequency 250 fps (frames per second), which means that the time span between two subsequent shots of the capsule is Δt = 4 ms.

For converting the images registered in individual frames into a sequence of pairs of coordinates of the capsule's position in the plane of its motion two independent methods were used for the sake of cross-checking. The coordinates have been extracted with the Viana program (written by Thomas Kersting – Universität Essen, Didaktik der Physik) and, independently, by a direct inspection of selected frames, from which coordinates of the capsule image in pixel numbers were determined to be later converted into coordinates given in meters.

With such a procedure the time error could be safely assumed to be Δt = 4 ms, and the accuracy of the position of the capsule's center was assumed at the level $\Delta x = \Delta z$ = 2 m. Taking into account the size of a single pixel which corresponds to 0.2 m in the plane of capsule's motion, and the fact that the image of the capsule extends over several pixels both in the horizontal (x) and the vertical (z) direction such an assumption of the error size can be considered to be only too cautious.

3.2. Extracting motion parameters

The sequence of data (t_n,x_n,z_n), expressed in standard units, i.e. seconds and meters, corresponding to the while the n-th frame has been registered, and the determined horizontal and vertical coordinates of the capsule's center serve as raw data for extracting important parameters that could be later used for computing a model trajectory.

The parameters to be obtained are as follows: the horizontal and vertical coordinates of the capsule's velocity v_x, v_z, the horizontal and vertical coordinates of its acceleration a_x, a_z, the horizontal and vertical drag coefficients b and k. It is achieved by approximating the sequence of pairs (t_n, z_n) with a 3rd step polynomial whose parameters were obtained with the least square method

$$z(t) = a_1 \cdot t^3 + b_1 \cdot t^2 + c_1 \cdot t + d_1 \tag{7}$$

and the sequence of pairs (t_n, x_n) with a linear function obtained as well with the least square method.

With the polynomial models of dependence on time of the horizontal and vertical coordinates x and z, one can easily compute by differentiating the dependence on time of both the velocity coordinates v_x and v_z, as well as those of the acceleration coordinates a_x, a_z. Having the above coordinates one can compute both the horizontal and the vertical drag coefficients b and k.

3.3. GPS in calculating helicopter position

The global positioning system (GPS) is commonly used in surveying as well as in aerial navigation. It allows one to compute instantaneously, automatically and with high precision the three-dimensional position irrespective of the time of the day and weather conditions. There are several autonomous positioning systems including the American GPS (NAVSTAR) and the Russian GLONASS. First of them consists of 27 satellites located on six semi-synchronous circular orbits at the altitude of 20 200 km [6]. The second system, which is still under construction, consists of 14 operational satellites at present. With application of both systems probability of being able to watch simultaneously at least five GPS satellites at any point of the Earth reaches 0.9996 [7]. Modern GPS receivers make possible registration of signals from both systems, which guarantees higher precision of observations.

The GPS functioning is based on measuring the distance between the receiver and the satellite whose position is already known. Computing the position of a point based on marking distances between the GPS receiver and reference satellites is based on the code method. In the alternative method (phase measurement) the phase of the signal reaching the receiver is measured. Navigation receivers use the code method and therefore they are not very precise [8].

Various methods of position measurements using satellite systems can be used [7]. Position and velocity can be obtained either with the absolute method (one receiver, and low precision measurement) or the relative method that is much more accurate. In this project, due to precision requirements, it was necessary to use the relative (difference positioning) method based on applying at least two GPS receivers, and using differences between the GPS-measured and the a priori known coordinates of the fixed (base) receiver for correcting coordinates of the movable (rover) receiver. The helicopter's position and velocity coordinates are computed in the real time regime RTK (Real Time Kinematics) GPS.

To achieve the goal, two double-frequency, 20Hz, surveying receivers Leica GPS – GX1230GG of Swiss production are used. One of them, playing the role of the base station in the computations, is located on the ground at a point of known coordinates. This station determines the error in the measured position, and sends the correction message to the second receiver (rover) fixed to the helicopter via the radio-modem. Correction from the base station, when combined with the phase method give the positioning accuracy of the RTK GPS measurements of the order of a centimetre. Such accuracy, of course, is excessive but it is better than the unsatisfactory accuracy of the absolute method.

GPS antenna of the rover receiver is fixed to the nose part of the helicopter (Fig. 9) and the radio-modem (0.5 W) sends the signal to the helicopter flying about 3-4 kilometers from the base station. Applying a 10 W radio-modem would secure communication between the base station and the helicopter at a considerably larger distance.

Fig. 9. The GPS antenna fixed to the nose of the helicopter.

4. RESULTS OF TEST FLIGHTS ANALYSIS

In this section results of analysis of data obtained in flight tests are presented. The first tray of results consists of numerically computed trajectories whose parameters like initial velocities, drag coefficients etc., are obtained from the registered trajectory. The second tray of results shows how accurate the system of hitting a selected point with a water capsule can be.

4.1. Comparison of the registered and computed trajectory

Parameters of a trajectory registered with the means described in Subsection 3.1, and extracted with the methods described in Subsection 3.2 can be used as input data for numerical computation of a "theoretical" trajectory with an algorithm based on the mechanical model described in Subsection 2.1.

Results of comparison of one of the registered trajectories with its model counterpart is shown in Fig. 10.

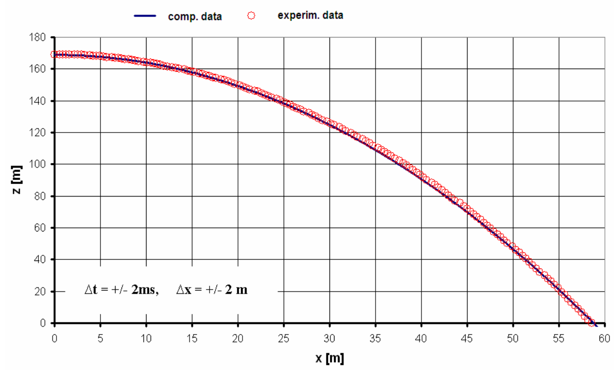

Fig. 10. Model trajectory compared with positions of the capsule registered with camera.

As is visible, both the real and the model trajectory are very close to each other, which gives an evidence in favour of both the theoretical model and the technique of registration and processing the motion data. In the computations air current velocity was not taken into account, since, as other tests have shown, up to some 10 m/s they have no measurable influence on the shape of trajectory.

4.2. Test of mark-hitting accuracy

As was mentioned before, the ultimate objective of the discussed research is to produce a water-spray cloud directly over a desired point on the ground or at least as close to it as possible. Therefore the test of hitting accuracy is of crucial importance for the whole experimental program concerning the water-capsule transportation and dropping technique. General success of earlier tests on particular aspects of the technique allowed to arrange a series of such crucial tests. A series of 6 tests of point-hitting accuracy have been carried on. In their course the water-capsule was released by the helicopter pilot at the signal from the control system, which in turn was emitted at the moment that was predicted by numerical computations.

Parameters of helicopter's flight in these tests are shown in Table 1. The first column gives flight's number, and the second mass m of the capsule. In the third values of the horizontal velocity at the release moment v_0 are given. The fourth column presents horizontal distances d_0 of the releasing point from the mark, and the fifth shows altitudes H_0 of the capsule above the ground at the moment of release. Finally, the sixth column presents declination φ_0 of helicopter's horizontal velocity from the direction pointing to the mark.

Table 1. Parameters of helicopter's flight in mark-hitting tests

No.	m [kg]	v_0 [km/h]	d_0 [m]	H_0 [m]	φ_0 [°]
1.	600	112	132	93	-5
2.	600	114	122	78	-2
3.	1200	93	91	65	-5
4.	1200	105	91	53	-1
5.	1200	91	83	57	-4
6.	600	110	105	65	0

The water-capsule was hanging on a 40 m long rope under the helicopter. Such a length of the rope was chosen for the sake of helicopter's safety.

The results of the tests can be in general considered to be satisfactory [9]. In fact, three of the six capsules reached the ground less than 10 m from the mark, and two other within 15 m from it. Taking into account diameters of explosively produced water-spray clouds (50–60 m) the accuracy achieved in these five tests would be sufficient to suppress or even quench fire completely at the desired point. Only the test No. 3 was a failure. In this case the spray cloud would have barely reached the point with its margin. Therefore this single test should be treated as a bad miss that could be caused, e.g., by an error made by the helicopter pilot who was releasing capsules manually. In a fully developed system one miss in six trials might be consider no impressive result but at the stage of building the system and testing its various elements it is more than promising.

4.3. Satellite visibility problem

Fixing the GPS antenna in the nose of the helicopter limits the accessible area of the sky and, consequently reduces the number of visible satellites. During test flights with water capsule the accuracy of marking positions was very high (FIX status – accuracy in centimetres). When the direction of flight was changed rapidly (e.g. after releasing a water capsule), however, the position errors increased to several meters for a short time (1-3 seconds) due to obscuring signals from some of the visible satellites by the helicopter's fuselage. Moving the rover receiver antenna to another point of the helicopter will remove this effect and secure high accuracy of position measurements irrespective of the flight direction. This however requires some additional construction improvements.

In the nearest future it is planned to test the use of corrections from the ASG-EUPOS system. When the full and stable access to this system is available it will be possible to achieve centimetre accuracy in determining coordinates without corrections from the base station. Consequently the system will become simpler and the problem of the limited range of the radio-modem will disappear.

5. CONCLUSIONS

The described system of high precision delivery of the water-capsule to a desired point is in principle complete as the mark-hitting accuracy tests show. The theoretical model and the corresponding algorithm for computing trajectory assure high accuracy as comparative tests show. The system of acquisition and transmission of data is efficient enough to provide input for real time computations, and the accuracy of positioning of the helicopter is more than satisfactory.

Thus the basic components of the system seem to be correctly designed. Nevertheless, some particular problems require development or improvement to make the system more reliable and easily applicable. Among others, construction improvements are necessary to assure visibility of all accessible satellites irrespective of the helicopter orientation, and the helicopter pilot should be liberated from the burden of releasing the water-capsule thanks to development of a relevant computer-controlled bag release subsystem.

ACKNOWLEDGMENTS

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