IMPACT POINT DETERMINATION FOR THE AIR-DROPPED BOMBS BY MEANS OF ACUSTIC METHODS. PART 1: CASE ANALYSE AND NUMERICAL SIMULATION

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Abstract **– This paper is a study on the determination systems for the impact points of the air-dropped bombs. We analyse an acoustic variant which uses a Marquardt-Levenberg algorithm to estimate position and wind speed. This system's architecture supposes the usage of six acoustic sensors disposed in a hexagon shape. As a method to determine the delay of the signal received by two sensors, we chose cross-correlation. At first, the method is validated by numerical simulation.**

Keywords: *impact point, air - dropped bombs, acoustic method, numerical algorithm, numerical simulation.*

1. INTRODUCTION

To monitor the bombs' impact position is an activity of great interest and importance during the training of the military pilots, for the precision evaluation of the new avionics systems as well as for the testing – evaluation and the development of the similar products.

At present, this monitoring process is a part of the larger series of research conducted world – wide both in the military and civilian field. For the military field, there are various applications, extremely important for the successful development of military operations in real war zones: systems to determine the shooter's position for urban conflicts, systems to determine the location of the artillery pieces and of the explosions, etc. For the civilian field, the most important application is the determination of the trajectory and of the type of aircraft which is engaged in taking – off/ landing procedures on an airport.

2. THE COMPARATIVE ANALYSIS OF THE POSITIONING METHODS IS USE AT PRESENT

As the analysis methods are concerned, world – wide, a series of systems were developed. Generally, these systems are based on the examination of the video images or of the acoustic signals. Further on, in short, the functioning principles of such systems will be presented.

The functioning principle of the video systems consists in image acquisitions by two video or FLIR cameras, generally synchronised, and the analysis of the images transmitted by them. The architecture of such a system is presented in Fig. 1.

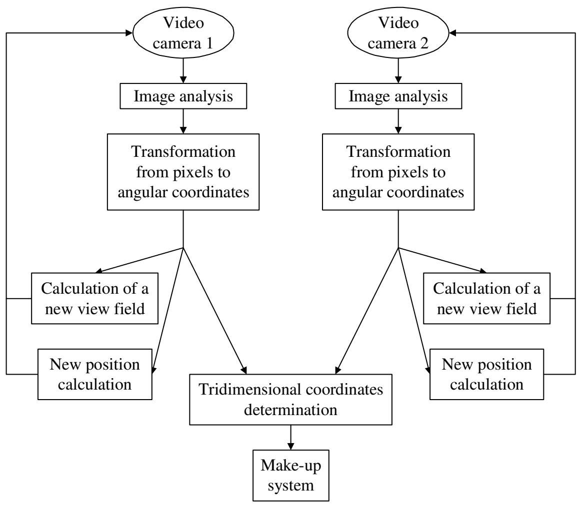

Figure 1: A video system architecture for the determination of the impact point position

The identification algorithm for such a system supposes ([1], [2]):

- Primary image examination (segmentation):
- Margins' detection;
- Colour grouping;
- Horizon detection;
- Image analysis for different resolutions to identify the object to be found;
- Object centre calculation as well as object dimensions calculation, all measured in pixels;
- 3-D position determination of the located object, using the data obtained, previously, from the two cameras.

Considering the somehow small dimensions and the low speed of the bombs, to put up such a system to ensure an acceptable precision to determine object position video cameras are necessary, (located close enough from the target area). These cameras need to perform a very accurate image resolution and a very high filming speed (fps). As a first consequence, the data quantity increases sensibly.

Considering a real bombing, as an order one priority, there appears the necessity to protect the staff from the monitoring system and to transmit the data to a monitoring station, safely located from the explosions' site.
At present, there are two ways to transmit the data to the monitoring point: data telemetry and cable or optical fibre transmission.
For cable or optical fibre transmission, the area has to be wired on a relatively large surface; the wires are exposed to explosion - resulted materials thus there are high chances for major deterioration. This could prevent the cables to reach the purpose they were put up for.
For radio transmission, the majority of the market systems do not ensure the transmission of such a large volume of information. The ones that are capable of performing such a task have very high market costs.
Another shortcoming of the video solution is the calculus power necessary to examine the acquisitioned data in real time; a multiprocessor processing system must be used.
Considering all the above, the conclusion is the putting up of such a monitoring system supposes very high costs.
As an alternative to the video systems, the acoustic monitoring systems present some advantages, such as a relatively small amount of necessary data.
The acoustic monitoring systems' implementation is generally based on the measurement of time differences among the signals received by several microphones whose spatial position is precisely determined. Also, it can be used the measurement of the time interval elapsed between the sound wave emission and its receiving by the receptors.
Further on, we present several aspects of the impact point determination of air – dropped bombs and the corresponding results.

3. HOW TO ESTABLISH THE SYSTEM'S ARCHITECTURE

To sustain the chosen architecture, several introductory data must be presented:

– Time of Flight (TOF) – defines the time interval comprised between the wave emission and its receiving by the sensor;
– Reference delay – the time interval comprised between the wave receiving by the closest sensor to the source and the next sensor;
– Direction of Arrival (DOA) – the calculated direction from which the system source issued the wave.

It is clear that, to measure TOF we need a supplementary synchronising signal. Because obtaining such a signal is a difficult task, in order to calculate position and DOA, reference delay is used for practical purposes.
Considering the distance among sensors reported to the distance of the signal source, the acoustic systems are classified, as follows, in two main categories [3]:

– far field, the distance among sensors is smaller than the distance to the signal source;
– near field, the distance among sensors is larger or equals the distance to the signal source.

For near field systems, the position of the signal source can be determined, while for far field systems, only the direction of the signal source (DOA).
To determine the impact point of air – dropped bombs supposes the monitoring of a relatively small area (approximately 500 metres, circularly) to the target centre.
It is possible to use a far field system, but thus the system becomes more complex. It is necessary to use a minimum two clusters of sensors to determine two directions; the intersection of these two directions determines the impact point position.
For each cluster of sensors a local unit to process data is needed. It supposes:

– a high sampling rate, because the distance among sensors is relatively small as compared to the distance to the signal source;
– a high performance data processing unit, because the volume of information to be processed is very large;
– a meteo center, DOA thus determined needs corrections with the wind speed and direction, temperature etc.;
– time basis to synchronise the clusters;
– a unit to transmit the processed data.

The link among the sensors and the unit for processing the data is made by cable or optical fibre.
In addition to the two mini – systems, the monitoring center, located to a safe distance, is necessary to have another unit to process the information: the intersection of the two DOAs and the presentation of the results.
Considering all the above, a near field architecture was chosen for the system which determines the impact point for air – dropped bombs.
The near field architecture supposes the location of the sensors in a convenient position, not at all complex, the data collected by the acoustic sensors are transmitted to the monitoring center. To process and analyse the signals and to present the location of the signal source supposes the use of a single processing unit.
The disadvantage of the method consists in the use of a data telemetry system which must not input delays while transmitting the signals to the monitoring center (or the delays must be of the same order for all the sensors).
The basic diagram of such a system is presented in Fig. 2.

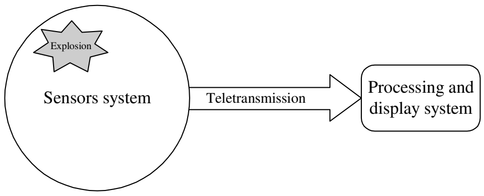

Figure 2: Basic block diagram of a near field acoustic system

4. MONITORING SYSTEM CONFIGURATION AND ITS VALIDATION BY MEANS OF NUMERICAL SIMULATION

Mathematically speaking, if we know the time t_i (TOF) between the emission and the reception for each sensor *i*, the distance d_i to the sensor can be determined by using the sound speed v_s, so

$$\left\{d_i^{\,2} = t_i^2 v_s^{\,2} = (x-x_i)^2 + (y-y_i)^2\right\}_{i=1,2}. \qquad (1)$$

where x_i, y_i are the coordinates of the *i* sensor.

To determine the coordinates of the signal emission source (x, y) supposes to solve the non – linear equation system given by the relations (1). Very good results to solve this system have the iterative methods, like Gauss-Newton or Marquardt-Levenberg ([4]). These are based on the minimalising of an expression with the form

$$\sum_{i=1}^{n}\left(t_i v_s - \sqrt{(x-x_i)^2} + \sqrt{(y-y_i)^2}\right)^2 . \qquad (2)$$

These methods give good results as long as, during calculation, there is a point of local minimum. To use the iterative methods shows a great advantage because TOF calculation is not always very accurate; in this case the analytical methods give wrong results.

Because, as we have previously mentioned, it is not possible to use TOF, the reference delay can be used

$$\begin{array}{l} v_s t_{12} = \sqrt{(x-x_1)^2 + (y-y_1)^2} - \sqrt{(x-x_2)^2 + (y-y_2)^2} \\ v_s t_{13} = \sqrt{(x-x_1)^2 + (y-y_1)^2} - \sqrt{(x-x_3)^2 + (y-y_3)^2} \end{array} ,(3)$$

where, t_{ij} are the references delays (*i* and respectively *j* sensors). For this particular situation, the architecture of the detection system must have a minimum of 3 acoustic sensors to obtain at least two equations in the system.

To estimate the delays between two signals of two acoustic sensors (t_{ij}) techniques to estimate this delay can be used. A largely used method is cross correlation ([3], [5], [6]), when we consider the sample signal with a corresponding acquisition rate. Practically, for this situation, the precision to estimate position, is clearly determined by the sampling rate. A high sampling rate allows a resolution increase for the number of samples between the signals received by the two sensors.

This minimum configuration of three acoustic sensors works for closed environments. For this particular situation, the wind speed is zero, thus there are no parasite influences on the necessary signal received by the sensors. In out – doors applications, the wind must be considered as a factor with important effects to establish the delays for the sensors received signals; this directly influences the sound speed v_s.

The change of the environment where the measurements are performed influences the sound speed both by the longitudinal component of its speed and by its transversal component too. A relation which connects the final signal speed within moving environments by the respective environment speed is the following ([4])

$$v_{sp} = v_{al} + v_s\sqrt{1-\left(\frac{v_{at}}{v_s}\right)^2} . \qquad (4)$$

v_{al} is the longitudinal component of the environment speed, and v_{at} is its transversal component. For our particular situation the environment change is linked to the wind. For wind speed under 10÷15m/s it can be considered that the wind speed v_a is much lower than sound speed and relation (4) can be approximated by

$$v_{sp} = v_{al} + v_s - \frac{1}{2}\frac{v_{at}^2}{v_s}. \qquad (5)$$

Thus, the transversal component of the wind speed can be neglected, the present system uses only its longitudinal component (v_{al})

$$v_{sp} = v_{al} + v_s . \qquad (6)$$

This has the components v_{alx}, v_{aly} on the two reference axes of the position system.

Under these circumstances the number of unknown variables increased to 4: two positions(x, y)and two speed values (v_{alx}, v_{aly}). As a consequence, the minimum number of equations necessary to determine these unknown variables will be 4, which implies a minimum configuration of 5 acoustic sensors.

Considering the wind speed, TOF from the equations (1), for sensor i, can be expressed by the relation ([4])

$$t_i = \frac{(x-x_i)^2 + (y-y_i)^2}{v_s\sqrt{(x-x_i)^2 + (y-y_i)^2} - v_{alx}(x-x_i) - v_{aly}(y-y_i)}, \qquad (7)$$

And for sensor j, by the relation ([4])

$$t_j = \frac{(x-x_j)^2+(y-y_j)^2}{v_s\sqrt{(x-x_j)^2+(y-y_j)^2}-v_{alx}(x-x_j)-v_{aly}(y-y_j)}. \quad (8)$$

So, the delay in the signal receiving by the two sensors (sensor i and sensor j) can be expressed by the relation

$$t_{ij} = t_i - t_j, \quad (9)$$

meaning

$$t_{ij} = \frac{(x-x_i)^2+(y-y_i)^2}{v_s\sqrt{(x-x_i)^2+(y-y_i)^2}-v_{alx}(x-x_i)-v_{aly}(y-y_i)} -$$

$$-\frac{(x-x_j)^2+(y-y_j)^2}{v_s\sqrt{(x-x_j)^2+(y-y_j)^2}-v_{alx}(x-x_j)-v_{aly}(y-y_j)}. \quad (10)$$

For the iterative methods, to use a number of equations equal to the number of unknown values reflects in an unstable behaviour, the incorrect estimation of a single difference leads to the incorrect position determination or even to a non – convergence of the entire system.

In the specialised literature there are recommendations to use redundant references, generally it is chosen a number larger by three units than the number of the variables to be estimated. Considering that the chosen system is a near field like system, the main arguments to choose its architecture are:

– the distance between the sensors must be chosen so that it is larger or equal to the distance to the signal source;
– the mathematic model previously presented recommends the choice of a symmetrical structure when disposing the sensors;
– the monitoring area – a circle with a radius of a maximum 500 metres;
– the number of equations necessary to the iterative method.

That is why it was chosen an architecture including a network of 6 acoustic sensors with a hexagonal disposition (Fig. 3). The hexagon line was chosen of 500 m, but the numerical simulations can be performed for any value of the radius.

So, there resulted a system of 5 equations with 4 unknown values, which means that the chosen system is based on a single redundant reference. The choice of a single redundant reference was made mainly considering the costs of equipment used to detect acoustic signals and the data telemetry system.

The relation to be minimised by means of the Marquardt-Levenberg method, has the form

$$\sum_{j=2}^{6}\{t_{1j}v_s^2[\sqrt{(x-x_1)^2+(y-y_1)^2}-v_{alx}(x-x_1)-v_{aly}(y-y_1)]\cdot$$

$$\cdot[\sqrt{(x-x_j)^2+(y-y_j)^2}-v_{alx}(x-x_j)-v_{aly}(y-y_j)]-$$

$$-[\sqrt{(x-x_j)^2+(y-y_j)^2}-v_{alx}(x-x_j)-v_{aly}(y-y_j)]\cdot$$

$$\cdot[(x-x_1)^2+(y-y_1)^2]-$$

$$-[\sqrt{(x-x_1)^2+(y-y_1)^2}-v_{alx}(x-x_1)-v_{aly}(y-y_1)]\cdot$$

$$\cdot[(x-x_j)^2+(y-y_j)^2]\}^2. \quad (11)$$

Number 1 sensor was chosen as a reference sensor.

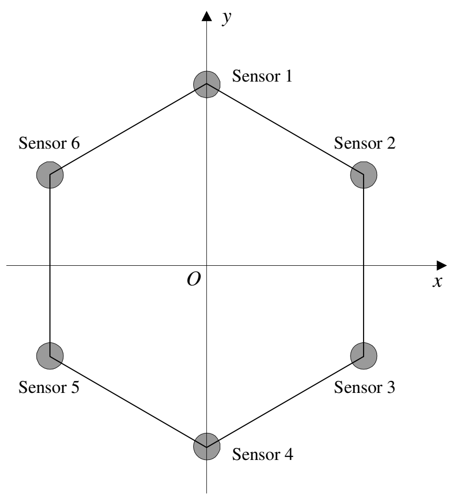

Figure 3: Hexagonal configuration of the sensors system

To validate the chosen architecture it was used a *Matlab* analysis and simulation software 6R13 version ([6]).

The theoretical validation of the model supposed a large number of numerical simulations. In Table 1 we present, as an example, a number of test points, (the position of the blast), for different simulation conditions (with or without wind). In Fig.4 we present the test points positions within the hexagonal system of the acoustic sensors, analytically calculated.

No.	Test point (TP) position		Wind speed		Obs.
	x coordinate [m]	*y* coordinate [m]	X axis [m/s]	Y axis [m/s]	
1	0	0	0	0	Centre point
2	0	250	0	0	
3	-433.012	-250	0	0	Sensor 5
4	0	250	20	30	
5	0	-250	20	-30	
6	-433.012	250	20	30	Sensor 6

Table 1: Test points positions and simulation conditions

The results of the simulations are presented in table 2. The location of the estimates for the testing points within the hexagonal system of the acoustic sensors is also given in Fig. 5.

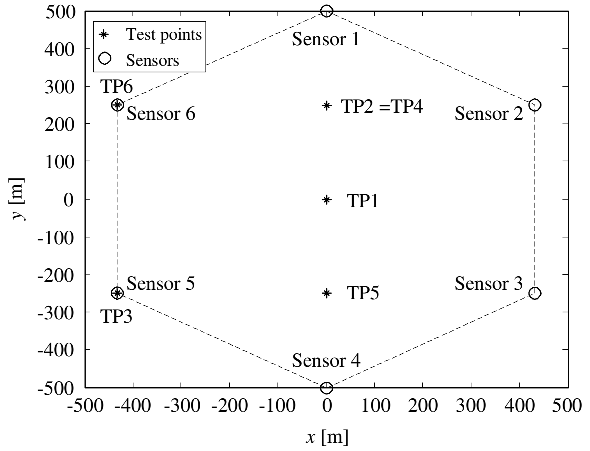

Figure 4: The analytic determined positions of test points inside of the sensors network

The simulations were performed on Pentium 4 system, CPU 3.2 MHz, 512 MB RAM and the maximum time to estimate the values was of 1.5 s.
To be noticed that 6 test points were simulated, three on a zero wind and three with a non – null wind. There were also considered several particular cases to validate the algorithm.

No.	Estimated test point (ETP) position		Estimated wind speed	
	x coordinate [m]	*y* coordinate [m]	X axis [m/s]	Y axis [m/s]
1	-0.0447	-0.113	0.030	0.077
2	$1.154 \cdot 10^{-6}$	249.999	$-6.84 \cdot 10^{-7}$	$6.304 \cdot 10^{-7}$
3	-433.009	-249.998	-0.0006	-0.0004
4	$-1.616 \cdot 10^{-7}$	249.999	20.000	30.000
5	$1.051 \cdot 10^{-5}$	-249.999	19.999	-30.000
6	-433.01	249.998	19.999	30.000

Table 2: Simulations results for 6 test points

For a first particular case, test point 2 and test point 4 are identical as a position, the differences in the testing conditions appeared because of the wind components. To be noticed that the estimates for the position of the two test points are identical on the Y axis and almost null on the X axis ($1.154 \cdot 10^{-6}$ m for TP2 and $-1.616 \cdot 10^{-7}$ m for TP4).
The maximum absolute error on the X axis, for simulated conditions is 0.0447 m, and for Y axis, 0.113m. The maximum absolute estimation error for the wind speed is 0.03 m/s for the component on the X axis and 0.077m for the component on the Y axis. To be noticed that these maximal values were obtained for the test point located in the centre of the sensor system.

For the other test points the errors can be neglected as they are situated under the limit of 10^{-3}, both for position estimates and for the wind speed estimates.
Other two particular cases place the test points on the maximum limit of the distance to be estimated with this system: TP3 in the location of sensor 5 (test without wind) and TP6 in the location of sensor 6 (test with wind). The results thus obtained are very good, the positioning errors have the order 10^{-3} m for the estimated distances of 433 m on the X axis and 250 m on the Y.

5. CONCLUSIONS

The paper presented the theoretical study and the validation by means of the numerical simulation of an acoustic system used to determine the impact point of the air – dropped bombs.
By the comparative analysis of the methods recently used to determine the position of the impact point we chose the variant which uses the reference delay (acoustic sensors). The calculus for the delay was made by means of the determination of the number of delay samples between the prints of the audio signals received by two sensors and based on a sampling rate set for the system. The method used was cross-correlation.
The method estimated both the impact point position in a horizontal plane, as well as the two components of the longitudinal wind speed within the testing area we established a 6 acoustic sensors architecture, in a hexagonal shape. To estimate the 4 unknown values we used Marquardt-Levenberg iterative method. 6 test points were simulated, three with zero wind, three with a non – null wind, the maximum absolute errors were obtained for the test point from the centre of the hexagon. For all the other test points the estimate errors were under the limit of 10^{-3}, both for the position as well as for the wind speed.

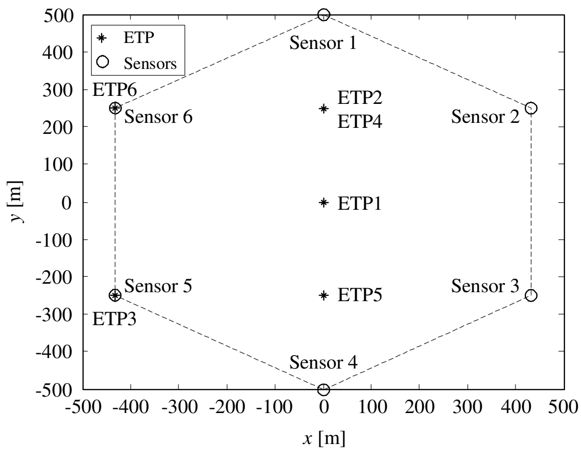

Figure 5: The estimated positions of test points (ETP) inside of the sensors network

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