Considerations on Acoustic Source Localization

LUCIAN JURCA, AUREL GONTEAN, IOAN JIVET, BENIAMIN DRAGOI
Department of Applied Electronics
"Politehnica" University of Timisoara
B-dul Vasile Parvan nr.2, Timisoara
ROMANIA

Abstract: - This paper makes an analysis of the different methods of acoustic source localization and proposes a simple and versatile solution which can be very easily implemented in an urban environment. The electronic equipment advanced here will allow the fast detection and localization of powerful noises associated to violent accidents such as gunfire, explosion, collapse, collision, etc. which endanger human life or material goods. An assembly of minimum four acoustic sensors (for localization in small and medium urban area) allows the detection of the triggering of the same powerful sound at close time intervals. The absolute time differences sent by each detector on a dedicated frequency band to a central unit of data processing permit the determination of the coordinates of the noise source. The localization error will be analyzed for several configurations of the sensor network. Because the aim of this project is a civilian one, we will discuss the capability of the system to get the data and to announce as quickly as possible the police, firemen or rescue teams about the location where one of the above mentioned events started.

Keywords: Time delay of arrival, energy based source location, gunshot detection, target localization.

1 Introduction

In our world, there is an increasing preoccupation for the security of persons as well as material goods. The fast localization of violent noises associated with explosions, gunfire, etc. in big cities will allow a significant increase of the efficiency of intervention teams. The most telling example is the importance that the department of justice from the USA gives to this subject, as it can be seen on its web page - www.usdoj.gov, if we specify on the search engine of the page <gunshot detection system>.

In countries that have recently joined the EU, such as Hungary, there are such researches at the universities of Budapest, Szeged and Veszprem, financed through the Hungarian National Program of Research and Development [1], [2], [3], [4].

The equipments which are dedicated to this purpose are designed by well-known companies and institutions such as the Berkley University of California (the development platform MICA which operates a wireless network of low consume sensors [5]), Trilon Technology (the Shotspotter system [6]), Alliant Techsystems (the SECURES system [7]).

As far as the detection and localization of the noise source is concerned, there are mainly three methods of detection: DOA (direction of arrival), TDOA (time delay of arrival) and EBL (energy based source location). These methods and recent works in this direction will briefly be presented and discussed in section 2 of the paper.

In section 3 we present an experimental module which allowed us to localize the noise source by means of a small acoustic sensor network in an area of several hectares. A matlab program was conceived in order to calculate the coordinates of the source and to estimate the uncertainty of the localization for a given structure of the sensor network.

Section 4 deals with implementation possibilities and costs for a localization system which is based on the method presented in section 3 and creates a framework for further development.

Section 5 will conclude the paper.

2 Methods of acoustic source localization

The main methods used for the localization of a sudden and powerful acoustic source will be presented further.

1. DOA (direction of arrival). DOA is the localization by using areas of sensors with a narrow diagram of directivity, grouped in each junction of the sensor network. Kaplan and all present such a system in [8] and more recently in [9]. Although the precision of the localization can be high, this is possible with the cost of the excessive increase of the number of sensors and thus of the costs of implementation. It is the fastest localization system, but we think that a better speed/cost ratio can be

obtained through other method.

2. TDOA (time delay of arrival). TDOA is the localization by measuring the time of delay between the signals received by the sensors of the network. It is the most widely used method in recent years and it will be applied in our work. In 2002, Fodroczi and all obtained a data processing time for the localization in the space of the noise source in approximately 50ms, [1]. The performance was possible by using a PC with a 1GHz Pentium processor and of an auxiliary processor with high capabilities of parallel data processing. This allowed the calculation of the correlation functions between signals with a cyclical algorithm using sequences of approximately 600 samples, drawn with a frequency of 8 kHz. But the system was checked only for localization in a space of the size of a room and in conditions of low jamming.

In 2004, Liu and Albert presented an original technique, [10], with which the surveyed environment is reproduced on the computer on the scale of the PC monitor and they simulate the emission of sound waves from each acoustic sensor, but in a reversed order from that of their stimulation and at the same time intervals. In this way the graphic interface highlights a so-called hot spot, where all the waves from the simulation arrive at the same time. However, the process has high costs and it necessitates a very elaborate model, which increases the duration of the localization of the noise source.

A more sophisticate system was elaborated by a research team led by A. Ledeczi from the Vanderbilt University of Nashville USA, [2], [11]. Using the MICA development platform which administrates a wireless network of low-cost sensors and a 3-GHz PC, they obtained the localization and detection of the direction of a shock wave coming from a gunshot in 4 seconds. But they used a very dense network of sensors, located at distances of roughly 40m one from the other. We can also notice the mostly military character of the application, less interesting for the civilian applications.

3. EBL (energy based source location). EBL is the localization based on the different attenuation of the waves that arrive at each sensor, attenuation proportional with the distance square from the incidental noise source. This is the latest method that appeared in international publications (2003), [12], [13]. It is to be remarked that this method was implemented and described by one of the authors of this paper in 1996 [14]. It can also be used for validation and increase of the detection certainty. Unfortunately, the method implies the presence of an acquisition system in each node of the sensor network and the transmitted data can be too rich.

3 Experimental module for acoustic source localization

In this section we will present an experimental module which can localize a violent acoustic source in an area of several hectares with a given accuracy. We suppose that the propagation medium (air, water) is homogeneous, isotropic and static.

First, for simplicity, we consider the case in which three acoustic sensors are collinear, at equal distance from each other (see fig.1), and the origin of the system is superposed on the microphone M_2. Mathematically it is proven that the coordinates x and y of the source are univocally determinates in half-plane by the distance differences p and q (from now, called parameters p and q), where p=a-b and q=c-a. Because the propagation speed of the sound is known, the above mentioned parameters can be measured by means of the time intervals between the moments when the sound arrives at each microphone.

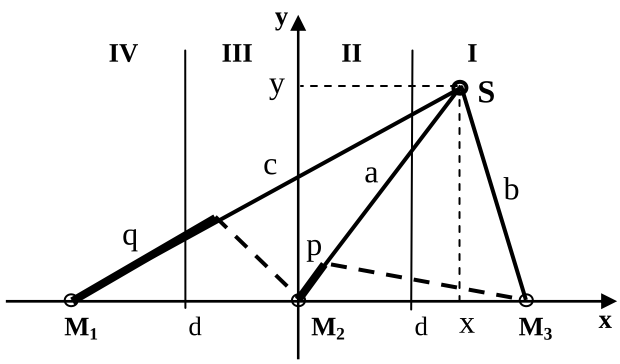

Fig.1 Principle of source localization

Depending on the order in which the signals are generated by microphones we can distinguish four adjacent zones (I, II, III and IV) in the surveyed area. So, the signal processing path must be able to identify the zone and to count the first time interval proportional with p and the second, proportional with q. Because the resolution of the time measuring is finite (on the one hand because of the response time of the analog part and on the other hand to avoid to manipulate too big digital data), there will be some uncertainty regarding the localization. This aspect will be discussed later.

At the same time the system must present immunity for signals which are not generated by all sensors or for signals produced by echoes. The rejection method is based on the fact that the incident wave is always the first detected and, after this, the digital input controlled by the sensor will be disabled until the last microphone will be excited. In addition, the signals which are generated through the three paths which appear at time intervals bigger then the theoretical propagation time, t_T, from one acoustic sensor to the next will also be rejected. In fact, not all the possible pairs (p, q), are compatible with a real position (x, y) of the noise source.

Adjusting the sensitivity threshold of the analog paths will separate the common noises of the city from the violent ones.

The block diagram of the experimental module is presented in fig.2. In our experiment we imposed the resolution of measurement for the parameters p and q to be 1m and we placed the sensors at 50m from each other. The clock period resulted approximately 3ms and CounterP and CounterQ are 6-b counters. The maximum value of p and q resulted 50m also. So, each memory address is a 14-b word in which the most significant two bits X and Y codify the zone (I, II, III and IV from fig.1).

The digital part including the blocks: 3-input time-instance detector, excitation-order encoder, immunity logic and conditioning circuits is presented in detail in fig.3 and simulated (fig.4). The schematic was minimized for our particular case (in which the sensor M2 can never be the last excited one), but it can very easily be extended for a more general case.

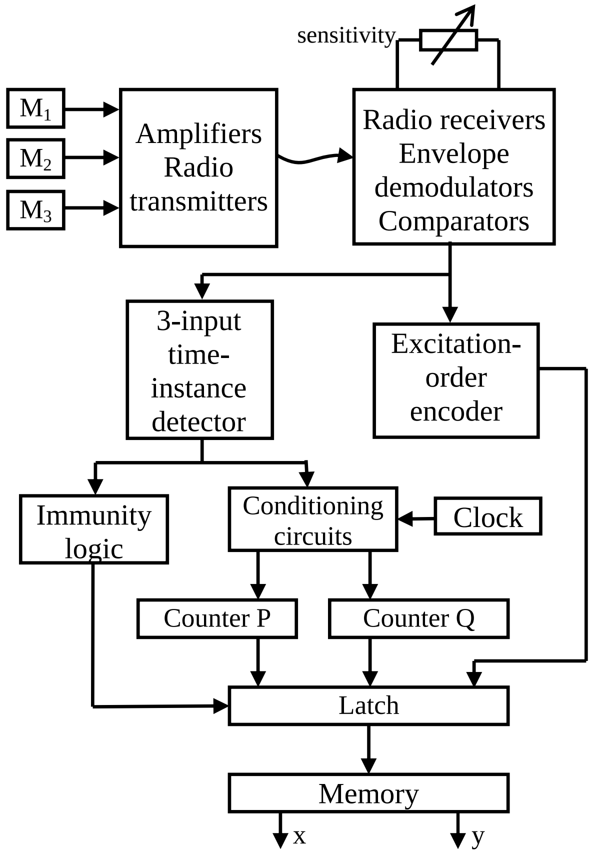

Fig.2 Block diagram of the experimental module

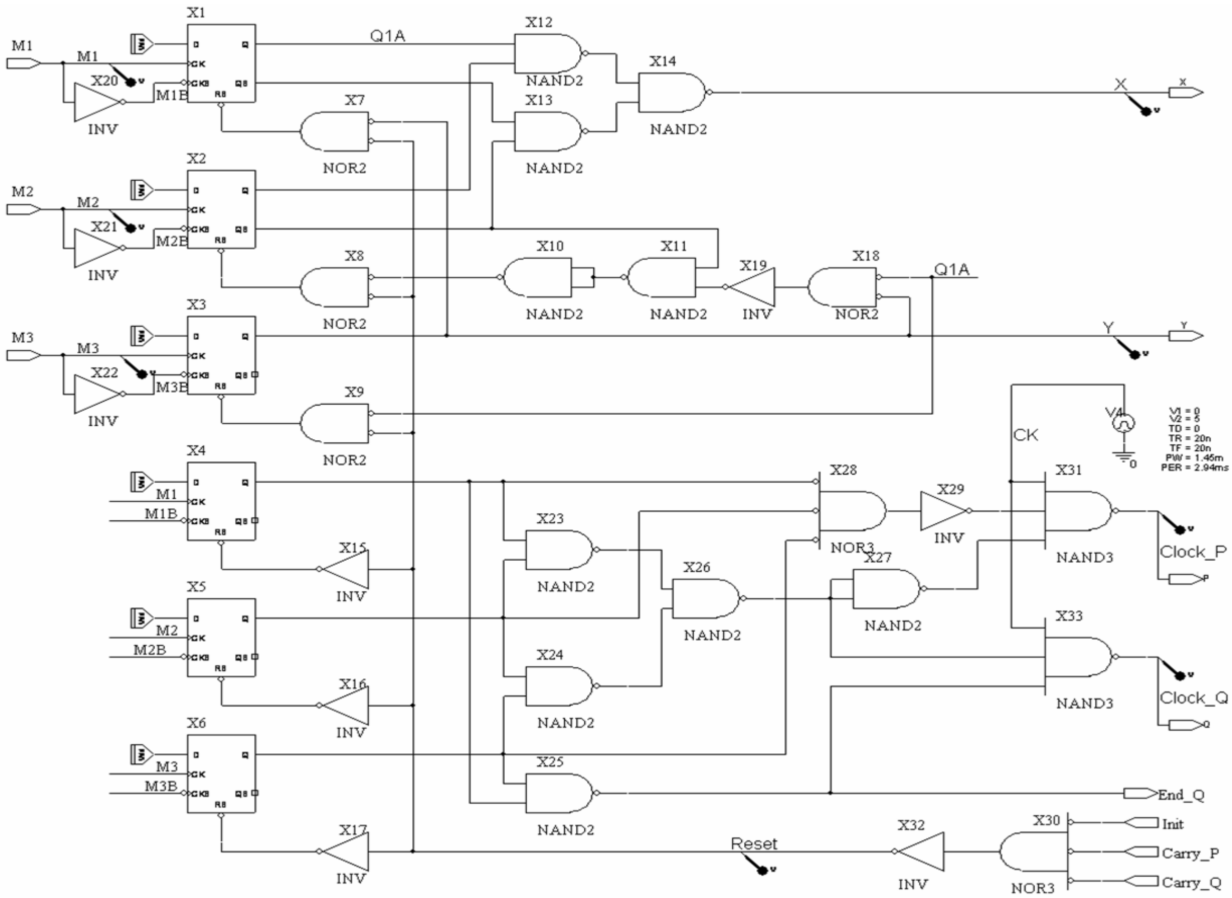

Fig.3 3-input time-instance detector, excitation-order encoder, immunity logic and conditioning circuits

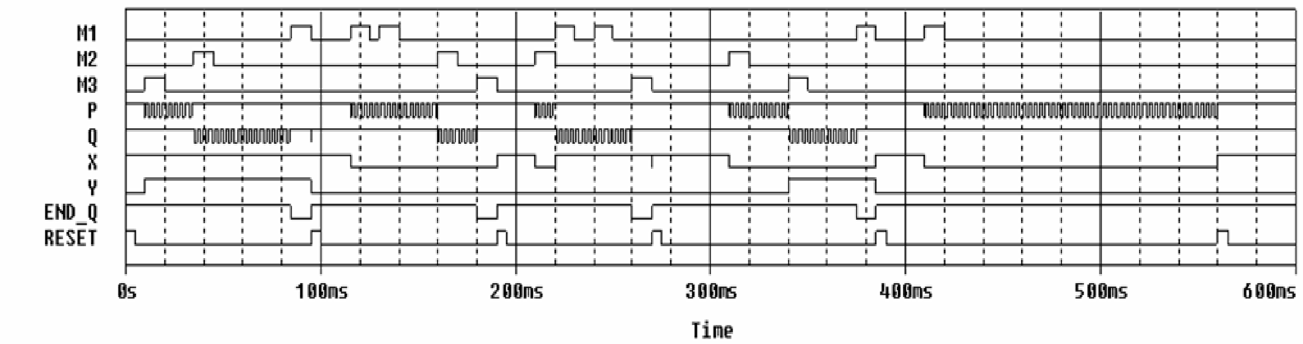

Fig.4 Simulation results for the circuit presented in fig.3

As we can see from fig.4, 10ms after the counter Q is stopped, a new measurement process is initialized. While the signal End_Q is low, the content of the counters P and Q, as well as the bits X and Y, are latched. These logical values of X and Y are obtained according to the content of the Table 1.

Table 1

Order	X Y	Zone
M_3, M_2, M_1	1 1	I
M_1, M_2, M_3	0 0	IV
M_2, M_1, M_3	1 0	III
M_2, M_3, M_1	0 1	II

We can observe from the time diagrams that the signal provided through the path of the microphone M1 includes echoes, but the measurement process is not deranged. Furthermore, if one single sensor or only two are excited, then, after a time interval t_T the system is reinitialized and no data is latched.

Unfortunately, a fourth acoustic sensor M4 is needed to find out from what half-plane the sound comes. In our experiment it is located at 10m behind M2, at equal distance from M1 and M3. The order in which M2 and M4 are excited will tell us in which half-plane the noise is produced.

As far as the memory content is concerned, a matlab program was conceived to calculate x and y from p and q. In fact the program calculates p and q for all possible pairs x and y of the surveyed area and after that it rearranges the matrix with respect to p and q. The time measuring error imposed by the counters is transferred into a localization error, because many neighboring pairs (x, y) lead to the same measured result (p, q). The maximum distance between 2 positions of the source which don't change the localization information (p, q) is presented in fig.5.a and b in a 3D representation from two perspectives. The localization error is the half of the above mentioned distance, if each localized point is in the middle of the region with the same p and q. The coordinates of the sensors are (-50m, 0) for M1, (0, 0) for M2 and (50m, 0) for M3 and the computation was made for zones I and II for a square of 50m×50m with a step of 0.2m.

We can observe that a reasonable error (less then 3.5m) can be obtained if the source is not located too close of the extreme sensors M1 and M3.

A better result (fig.5.c) was obtained for a triangular arrangement of the sensors where the position of M2 was changed at (0, 50m). Unfortunately, as in the case of the collinear arrangement, without the fourth microphone, a given pair (p, q) can lead to equivoque results (x, y) inside the triangle and outside the triangle beyond each vertex.

Further we extended the surveyed area for both collinear and triangular arrangements and the results are presented in fig.6.a and b. In fact, for the triangular network, we took into account a square with the opposite corners at (50m, 50m) and (100m,

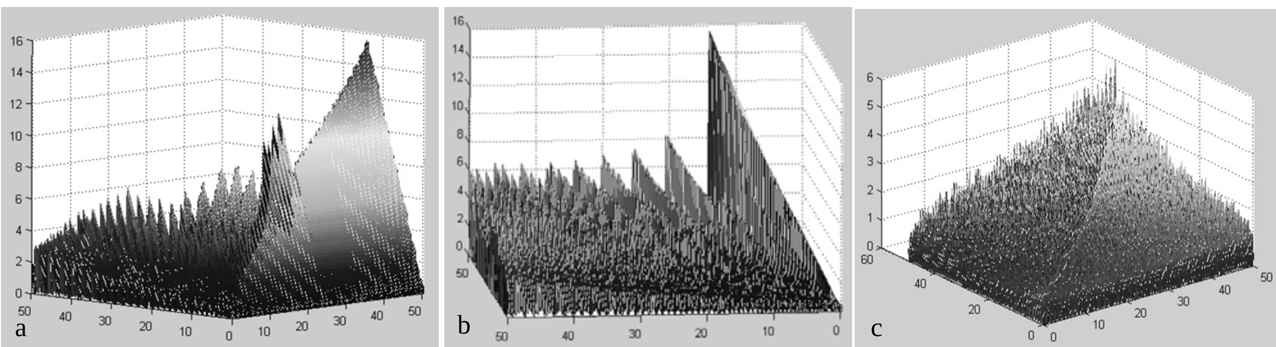

Fig.5 The trend of the localization-error variation for collinear case (a, b) and triangular case (c)

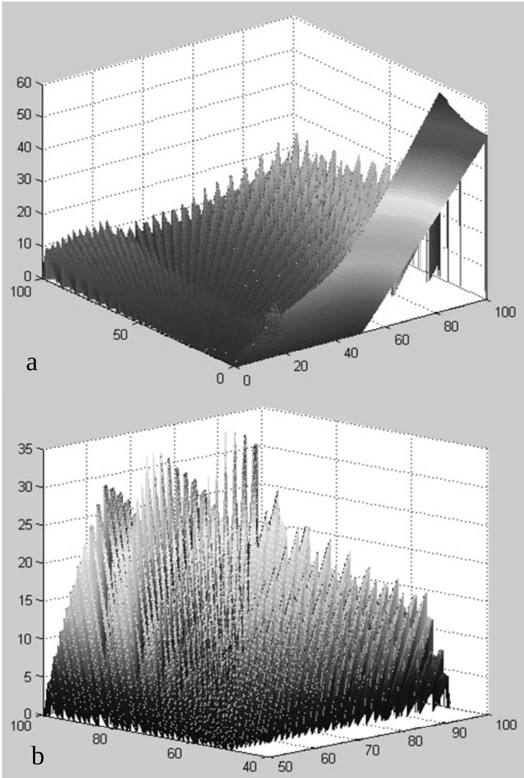

Fig.6 Localization error for extended areas for collinear case (a) and triangular case (b)

100m) only, to avoid equivoque results. As we can see, the behavior at medium and big distance from the sensor network in direction of y axis is better for the collinear case. We can conclude that the collinear arrangement covers a bigger area for a given localization error and a given distance between sensors. However, the triangular solution can be very attractive if we enlarge the triangular network so that we are sure that the expected violent acoustic source is kept inside the triangle. At the same time the localization error becomes smaller, as we can observe in fig.7 where we enlarged the triangular network so that the sensor coordinates are (-200m, 0)

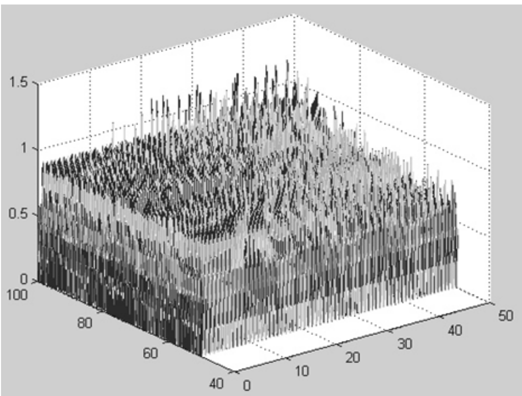

Fig.7 Localization error for extended triangular network

for M1, (0, 200m) for M2 and (200m, 0) for M3 and the analyzed area was a square with the opposite corners at (0m, 50m) and (50m, 100m).

4 Considerations on final implementation. Future work

A final implementation of the acoustic detector system supposes the use of data channels between the acoustic sensors which detect acoustic events and the central unit. These channels can use a physical support as a specific electric cable (advantages: independency, security, no crosstalk; drawback: high cost) or a telephone line rented from a local operator of fixed telephony (low cost but dependency on the stability of the operator's equipments, possible interferences and low security).

An alternative to these is the radio channel. But we need to occupy as many channels as the number of sensors we would have in the localization network and to get licenses for these. Furthermore, to cover the distance between the sensors and the central unit we need a lot of power for the radio transmitters and this will limit the autonomy on batteries in the case of an electrical power blackout.

The variant that we would choose is the use of GSM radio channels. Among the advantages we mention: a license is not necessary and nor are dedicated channels, it requires small emission power (this should only cover the distance to the nearest GSM cell). In the case of the damage of a GSM cell, the cell network can take over the emission of the sensor. The disadvantage of the GSM variant refers to the existence of an intermediate between the sensor and the central unit.

The system which we will develop is based on the use of GSM modules that operate with a sim prepay card. The data from the emitter are transmitted to the central unit through written messages of SMS type. The data which have to be transmitted from the sensor to the base contain little information and thus they can be transmitted in the form of a short SMS including the localization code of the emitter and the exact time when the acoustic event occurred. This essential information can be obtained with sufficient accuracy by means of GPS modules (e.g. absolute-time resolution of 1 ms). The data are transmitted through serial communication using the standard protocol to the GSM module and from the GSM module to the central unit, respectively. The advantages of using the SMS message are the low cost and the short time for transmission. The system would be very flexible because the sensors can be placed in the most favorable positions whose coordinates will be automatically known.

5 Conclusions

The paper presents specific aspects regarding the design of a localization system for violent acoustic sources. The electronic equipment advanced here as experimental module uses a TDOA localization method and ensures very good immunity to parasitic acoustic signals. The system is simpler and faster than other related works.

A framework is proposed for the final operational version of the system which will aim to minimize the cost of implementation and to raise the flexibility of the system.

References:

[1] Z. Fodroczi, A. Radvanyi, G. Takacs, Acoustic Source Localization Using Microphone Arrays Via CNN Algorithms, European Conference on Circuit Theory and Design, Krakow, Poland, vol. 2, September 2003, pp. 177-180.

[2] A. Ledeczi & all, Countersniper System for Urban Warfare, *ACM Transactions on Sensor Networks*, Vol. 1, Issue 2 , November 2005, pp: 153-177.

[3] G. Balogh, A. Ledeczi, M. Maroti, G. Simon, Time of arrival data fusion for source localization, Workshop on Information Fusion and Dissemination in Wireless Sensor Networks. Proceedings, Budapest, Hungary, July, 2005.

[4] G. Simon, L. Sujbert, Acoustic Source Localization in Sensor Networks with Low Communication Bandwidth, International Workshop on Intelligent Solutions in Embedded Systems. Proceedings, Vienna, June 2006, pp.1-9.

[5] J. Hill, D. Culler, Mica: A Wireless Platform for Deeply Embedded Networks. *IEEE Micro*, Vol. 22, No. 6, 2002, pp. 12–24.

[6] http://www.shotspotter.com/.

[7] E.A. Page, B. Sharkey, SECURES: System for Reporting Gunshots in Urban Environments, Proc. SPIE, Vol. 2497, May, 1995, pp. 160-172.

[8] L. M. Kaplan, L. Qiang, P. Molnar, Maximum likelihood methods for bearings-only target localization, Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, vol.5, 2001, pp. 3001-3004.

[9] L. M. Kaplan, L. Qiang, On exploiting propagation delays for passive target localization using bearings-only measurements, *Journal of Franklin Institute*, vol. 342, March 2005, pp. 193–211.

[10] L. Liu, D.G. Albert, A Shot in the City: Locating a sound source in an urban environment. 147th Meeting of Acoustical Society of America, May 28, 2004, http://www. acoustics.org/press/147th/liu-albert.html.

[11] A. Ledeczi & all, Multiple Simultaneous Acoustic Source Localization in Urban Terrain, Proceedings of the 4th International Symposium on Information Processing in Sensor Networks, Los Angeles, USA, 2005, pp.491- 496.

[12] X. Sheng, Y.H. Hu, Energy Based Acoustic Source Localization, IPSN, Palo Alto, USA, April, 2003. Proceedings, *Lecture Notes in Computer Science*, Vol. 2634, Springer Berlin/ Heidelberg, 2003, pp.551-555.

[13] T. Pham, B.M. Sadler, H. Papadopoulos, Energy-based source localization via ad-hoc acoustic sensor network, IEEE Workshop on Statistical Signal Processing, Saint-Louis, USA, Sept. 2003, pp. 387-390.

[14] L.Jurca, M. Dutu, Position Detector in Polar Coordinates, *Scientific Journal of Politehnica University of Timisoara*, Romania, Tome 41(55) vol.1, 1996, pp.125-128.