24th COBEM - 2017

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0316
TIME OF FLIGHT ULTRASOUND INDOOR NAVIGATION SYSTEM

Ernani Melo de Sousa Reis
Cairo Lúcio Nascimento Júnior
Neusa Maria Franco de Oliveira
Instituto Tecnológico de Aeronáutica, Praça Marechal Eduardo Gomes, 50, São José dos Campos, SP, 12228-900
ernani.reis@gmail.com, cairo@ita.br, neusa@ita.br.

Abstract. *This work describes the development of a navigation system, to determine and provide fixes data to a flotilla of autonomous vehicles. To accommodate for lightweight vehicles, the emitter is light, small and have low power consumption. The intended use is in closed environments, where no satellite line of sight is available. The precision is adequate for flights at close range, in limited spaces, specially for the relative position of the members of the flotilla.*

Keywords: *Ultrasound, indoor navigation, uav cluster*

1. INTRODUCTION

The problem faced was the need for means to determine navigation fixes in constrained environments, for small aerial vehicles operating collaboratively in a group, possibly in close proximity to each other. The system operates by determining time of flight of a ultrasound pulse emitted by the rovers and received by multiple transducers precisely arranged in a well known pattern on the base.

Other principles of solutions to similar problems exist, and will be discussed below.

The main requirements that drove the development were: fast setup, low complexity, minimum weight and power consumption on the rover side. The initially intended rover has a nominal mass of 55g, ready to fly.

2. AVAILABLE TECHNOLOGY

Existing solutions to the same problem include a self discovering network of receivers (Robotics, 2016). The system has obvious strong points, specially precision and coverage of large target areas. The inconveniences to our application were the large master processor, a PC and a laborious setup.

Other similar system is found in (Yayan *et al.*, 2015), another solid development, with similar expectations of precision from (Robotics, 2016). The arrangement consists of receivers on the rover, that could result on a much larger weight. The arrangement will require many transducers on the receiver side, that and the many receiver amplifiers would be big and heavy, and require multiple processing tasks on the rover computer.

Other solutions are based on cameras on the rover, like in (Shen *et al.*, 2011), (Biswas and Veloso, 2012), (Gini and Marchi, 2002) and (Hile and Borriello, 2008). The solution requires cameras and image processing, and more, on the rover side, that will require power and present weight.

3. SELECTED SOLUTION

The selected solution was a rover transmitter cluster, four transmitters, evenly distributed on all directions on the horizontal plane, to assure maximum coverage with no blind regions. The system has a time reference, synchronized between all rovers and the base. The rovers, one at a time, emit an ultrasound burst, that is received by the transducers on the base. The time in witch the burst is detected in the base by each transducer allows the base microprocessor to compute the time of flight between the rover each base transducer. Then calculates X, Y and Z coordinates of the emitting rover in relation to the base origin. The position information is, then, sent to the rovers, that proceed accordingly.

The receiving transducers arrangement in the base is in a triangle of precise and well known dimensions, as in figure 1. The triangle side has the length L_{ref} between transducers, chosen arbitrarily (longer the arms, more precise the measurement, and more difficult to assure precision in the assembly - the compromise chosen was $L_{ref} \approx 500mm$).

In the initial arrangement, the synchronization is accomplished by a flexible cable connecting the base microprocessor and one rover, with the result sent to a portable computer, to be read by a human. The final arrangement has radio modules linking the rovers and base. The radio module offers a serial port to each end, working transparently. The module works with a frequency around 433MHz, an ISM band as per local regulations. The system transports the burst data to the base, synchronizes the clocks across the system components, and transports the rovers' fixes data back to the rovers.

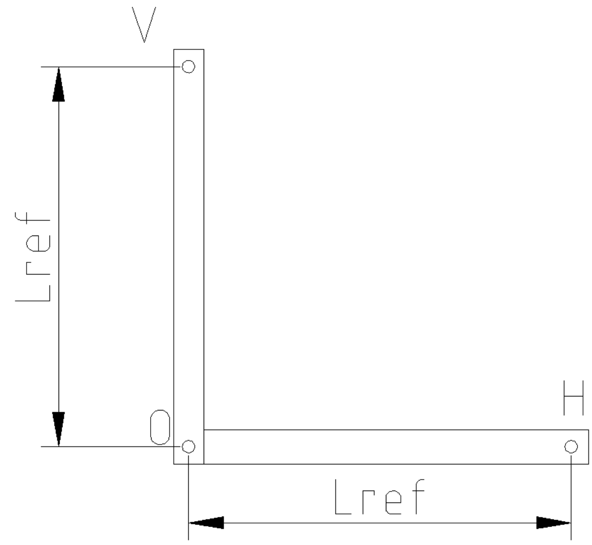

Figure 1. Base Geometry

4. IMPLEMENTATION

The system was implemented by developing transmitters, receivers, microprocessor code.

The transmitters consist of ultrasonic piezoelectric transducers, each driven by a MAX232, that generates, with its charge pumps, $\pm 10V$. The arrangement was based on (Dany, 2011) The transducer is connected to the microprocessor's output pins, which drives the input pins to a $20V$ peak-top-peak excitation.

The receivers consist of a filter, tuned to the burst frequency of 40KHz, amplifier and a level detector, figure 2. Figure 3 shows the filter's response (gain - solid; and phase - dotted) at the point "OUTPUT" against the excitation at point "INPUT".

The measured distance to each receiver was determined empirically, disposing the transmitter and receiver at different distances, sending a pulse, measuring the elapsed time until detection. With distances known and times measured, it was adjusted a function $L = f(elapsed\ time)$ for each receiver transducer. The $f(elapsed\ time)$ accommodates for latency in the microprocessor, filter and transducer, or other contributions to time delays.

The time of flight is measured by a timing loop running in the base microprocessor, with a resolution of $21\mu s$, with the burst frequency at 40KHz, the period is of $25\mu s$, the time measurement resolution should not degrade the overall precision noticeably. The expected resolution for this range meter arrangement is something slightly larger than the wavelength, 8.5mm, considering all error contributions, around 1cm.

The chosen microprocessor for this implementation was an Arduino micro, that has the resources compatible with the required tasks.

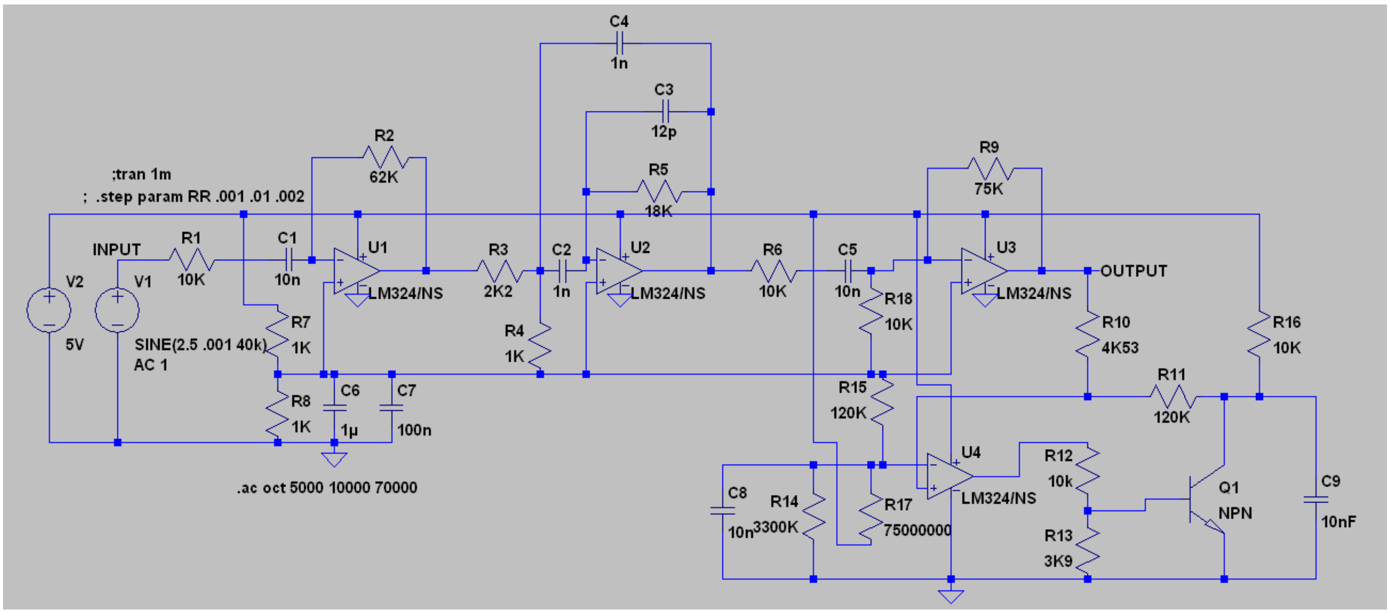

Figure 2. Receiver SPICE Schematic

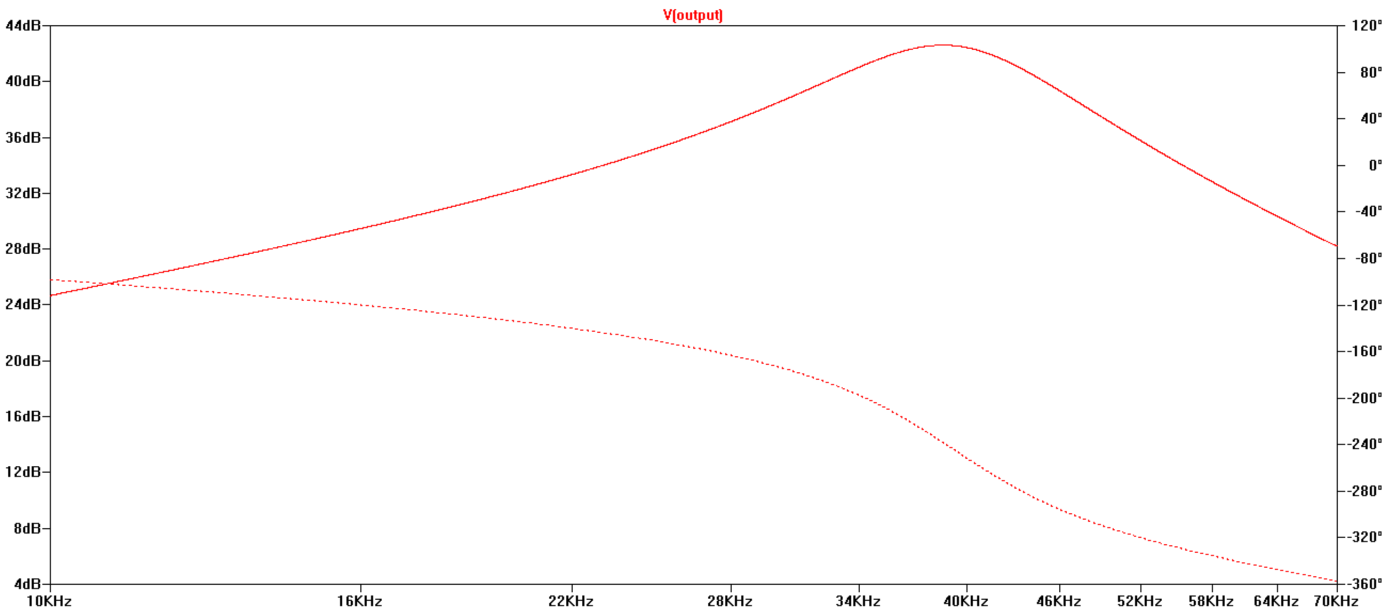

Figure 3. Receiver SPICE Simulation

5. ALGORITHMS

The general case is represented in the figure 4, the points were named: central transducer, the O; the transducer on the vertical arm V; the transducer on the horizontal arm H; the rover position R.

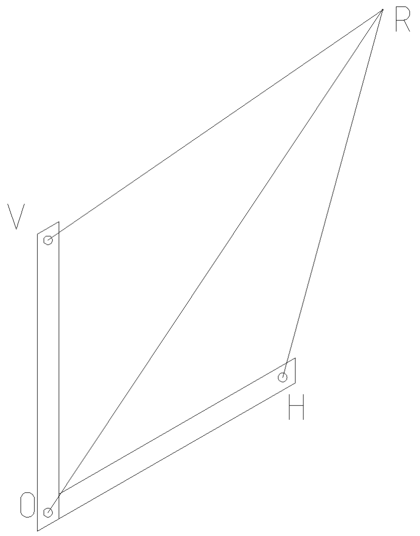

Figure 4. General Case Measurement

The range is determined by applying $L_O = f_O(T_O)$, being L_O equal to the desired range. The central transducer is the system origin.

Considering the triangle formed by O, H and R, figure 5, the distance OH is known by construction L_{ref}; the distance OR is L_O, determined above; the distance RH is determined by $L_H = f_H(T_H)$. This defines the triangle. The angle A_H can be calculated by the law of cosines (Anton and Rorres, 2005), in equation 1. The projection of OR over the OH line is easily calculated by $L_Y = L_O * COS(AH)$, and that is the rover's Y coordinate.

$$COS(AH) = \frac{L_H^2 - L_{ref}^2 - L_O^2}{2 * L_{ref} * L_O} \tag{1}$$

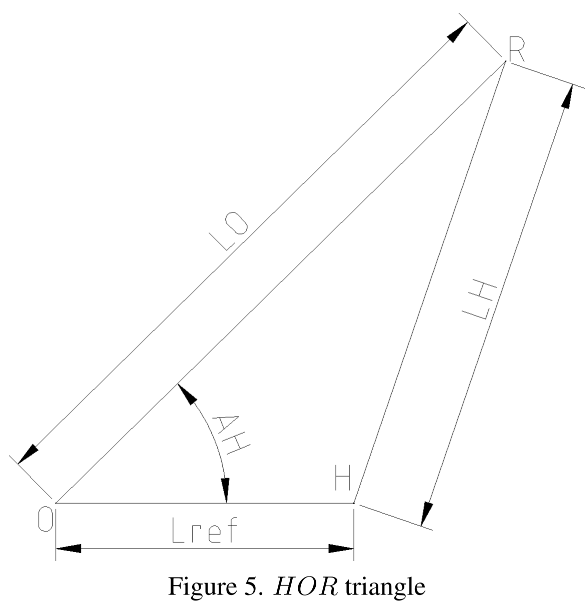

Figure 5. HOR triangle

The triangle VOR, in figure 6, is treated similarly. The angle A_V can be calculated in equation 2. The projection of OR over the OV line is calculated by $L_Y = L_O * COS(AV)$, and that is the rover's Z coordinate.

$$COS(AV) = \frac{L_V^2 - L_{ref}^2 - L_O^2}{2 * L_{ref} * L_O} \tag{2}$$

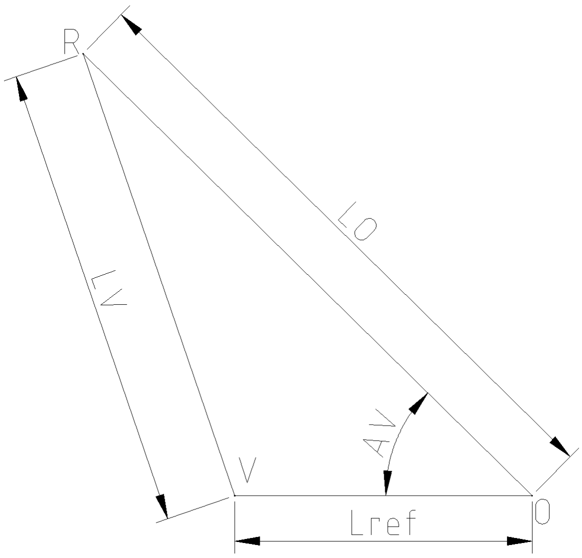

Figure 6. VOR triangle

Considering the line segment between O and the projection of R over the plane containing O, V and H. We call the projected point R_{proj}, figure 7. The segment has length $L_{YX} = \sqrt{L_Y^2 + L_Z^2}$. Considering the triangle defined by O, R and R_{proj}, the distance between R and R_{proj} is $L_X = \sqrt{L_O^2 - L_{YZ}^2}$. Rearranging the equations, we have $L_X = \sqrt{L_O^2 - L_Y^2 + L_Z^2}$.

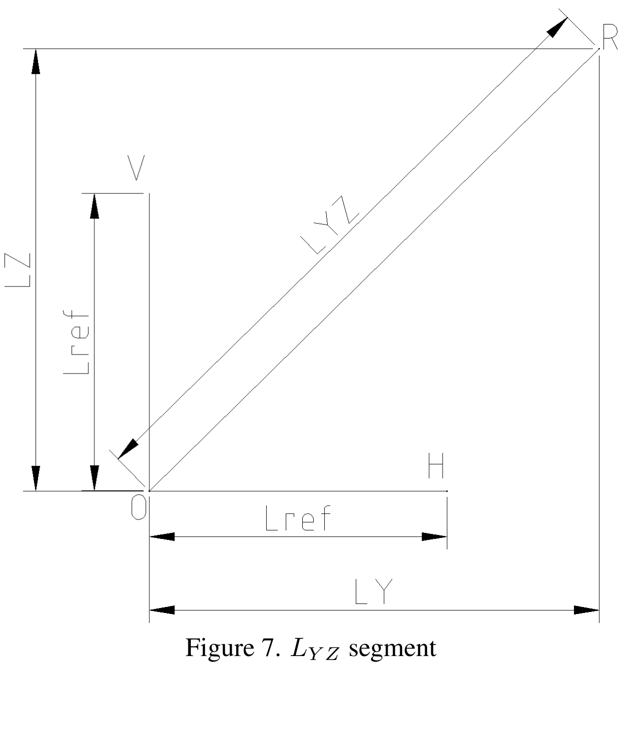

Figure 7. L_{YZ} segment

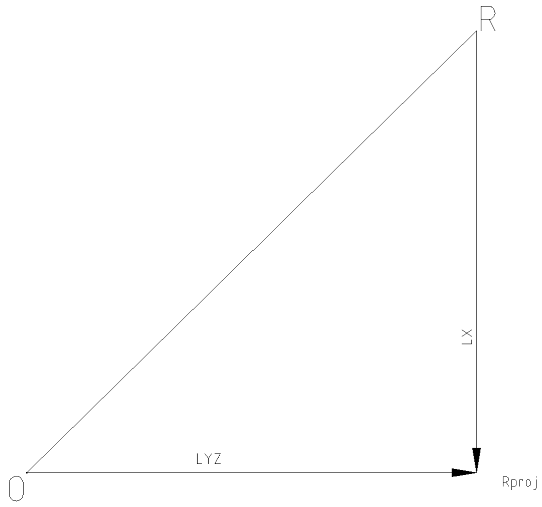

Figure 8. L_X segment

6. RESULTS

The system was tested with 1,200 fixes, with the rover sliding over a 2 metre long bar, marked in points with known location. The components were aligned with a laser level, assuring known positions. The bar was not parallel to any of the axes, so all three coordinates changed as the rover was sled over the bar. The bar was installed in various different positions. The observed data presented errors shown in table 1, with occasional spikes, when the direct path between rover and receiving transducer was blocked, resulting in detection by a reflection, that were manually removed from the data considered.

The principle demonstrator, used for calibration and initial tests was built in a flexible frame, to be attached to a wall, and serve as base and reference origin figure 9. Once attached to a flat surface, assures the transducers relative position precision compatible with system requirements.

Table 1. Measured RMS Error (mm)

X_{ref}	X_{RMS}	Y_{RMS}	z_{RMS}
645	14	58	46
745	12	36	29
845	6	32	15
945	13	24	23
1045	8	15	22
1145	10	22	21
1245	9	22	20
1445	8	21	24
1545	9	22	35
1645	11	45	38
1745	5	33	50
1845	14	45	54
1945	15	52	92

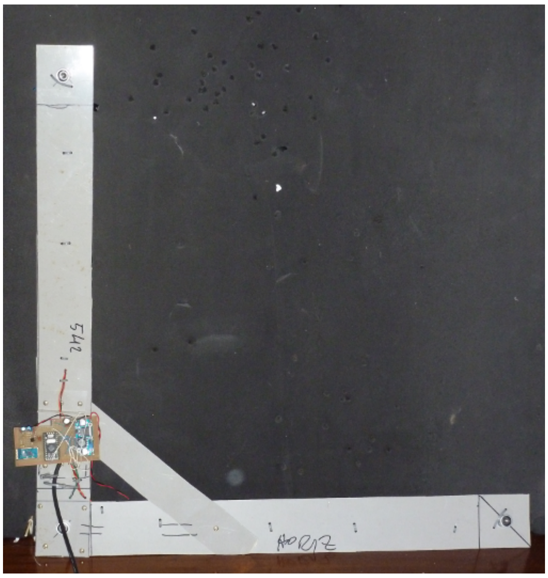

Figure 9. System Prototype Base

7. CONCLUSION

This paper shows a solution to the determination of navigation fixes in enclosed environments, with no line of sight to a navigation satellite constellation. The solution showed the desired precision, and a practical arrangement, easy to deploy, and fast to operate. The first intended use requires precision in the position of the rovers relative to one another, a case that the system proved well suited for.

The system is clearly applicable to many other applications, when satellite navigation is unavailable, inconvenient or unreliable.

The transmitter size, power consumption and weight were compatible with the small rovers intended.

The system was tested to the capability of the test setup, that had very limited range. The maximum range depends on the receiver sensibility. It is expected, for the current implementation, a usable range of about 10 metres. The precision is reasonable along the X axis, measurements along the other axes have larger expected errors. A arrangement with multiple receiving bases with their measurements fused together would expand the range and improved precision.

8. FUTURE WORK

The first planned improvement to the system is a better approach for rovers and base time synchronization. The main improvement is to fuse the position measurement with the rovers' AHRS (Attitude and Heading Reference System), using the read heading to align the rovers' stability axes with the base reference frame, then fuse the accelerations on the base reference frame with the read positions, by means of a linear observer. A Kalman filter would provide better error handling, but the system will have a large number of states, requiring the inversion of large matrices, that will require heavy processing on the rover side. The linear observer seems to be a better compromise between precision and processing burden. Investigation will be made in fusing the results of multiple receiving bases, for improved range and precision

9. REFERENCES

Anton, H. and Rorres, C., 2005. *Elementary linear algebra: applications version; 9th ed.* Wiley, Hoboken, NJ. URL `https:cds.cern.ch/record/882356`.

Biswas, J. and Veloso, M., 2012. "Depth camera based indoor mobile robot localization and navigation". In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*. pp. 1697–1702. doi:10.1109ICRA.2012.6224766.

Dany, 2011. *Ultrasonic Ranging Module HC-SR04*.

Gini, G.C. and Marchi, A., 2002. "Indoor robot navigation with single camera vision." *PRIS*, Vol. 2, pp. 67–76.

Hile, H. and Borriello, G., 2008. "Positioning and orientation in indoor environments using camera phones". *IEEE Computer Graphics and Applications*, Vol. 28, No. 4.

Robotics, M., 2016. *Marvelmind Indoor Navigation System manual*. 1111 W El Camino Real 109-365, Sunnyvale, CA ,94087, USA, v2016-05-21 edition.

Shen, S., Michael, N. and Kumar, V., 2011. "Autonomous multi-floor indoor navigation with a computationally constrained mav". In *Robotics and automation (ICRA), 2011 IEEE international conference on*. pp. 20–25. doi: 10.1109ICRA.2011.5980357.

Yayan, U., Yucel, H. and Yazici, A., 2015. "A low cost ultrasonic based positioning system for the indoor navigation of mobile robots". *Journal of Intelligent & Robotic Systems*, Vol. 78, No. 3-4, p. 541. doi:10.1007s10846-014-0060-7.

10. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.