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LOW-COST IMPROVEMENT OF AN ULTRASONIC SENSOR AND ITS CHARACTERIZATION FOR MAP-BUILDING

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Abstract: Ultrasonic sensors have often been used as rangefinders in mobile robots. In many cases their use has been reduced to the measurement of distances to the closest object in front of each transducer, in isolation of the rest of the transducers. This paper describes the design, implementation and application of an ultrasonic sensor made up of four transducers suitably set up. Each transducer is equipped with a low cost electronic system, improved as compared with basic versions, so it may be used in conjunction with the rest and provide accurate Time of Flight (TOF) readings. This makes it possible to use triangulation techniques. The new sensor has been characterised for use in map building by means of certainty grids.

Keywords: intelligent instrumentation, ultrasonic transducer, enhancement, rangefinders, mobile robots.

1. INTRODUCTION

When ultrasonic transducers are used in mobile robots (MRs), these are distributed evenly around the robot's periphery. The distance readings are obtained by determining the times of flight (TOFs) of the ultrasounds from the moment they are emitted to when they are reflected back by surrounding objects. The readings obtained are processed in the light of one or several of the following objectives:

a) Direct implementation of an algorithm for guidance of the MR. The readings obtained are sometimes introduced directly and processed into high level algorithms, whose outputs directly provide the robot's guidance speeds (reactive control). This research work normally lays greater stress on the techniques and algorithms used than on the use and problems of the ultrasounds *per se*. They therefore deal with the use of fuzzy techniques, neural network learning (Song & Sheen, 1995), etc.

b) Map building of the MR's environment: Although some attempts at map building have been made using "adaptive" models (visibility graphs, free regions, etc), errors and lack of precision in the ultrasound readings are more suited to "rigid" models (for example the use of certainty grids and probability functions for post-reading updating (Elfes, 1987)). Along the same lines, some authors have proposed simplified updating models following heuristic rules for their implementation in real time (Borenstein & Koren, 1991a) (Song & Chen, 1996). The algorithms for the MR guidance are built up from the maps in environments with fixed or mobile objects.

c) Locating the MR. Determining the position of the MR in relation to its environment involves identifying some of the environment's objects, whose position is known a priori. Normally the objects detected are classified into three types: planes, corners and edges. For the identification of this type of reflectors, using TOF readings, an active perception of the environment is necessary (i.e., different "points of view"). This is done either by taking advantage of successive readings as the robot moves along (Leonard & Durrant-White, 1991) or by using more than one ultrasound receiver for each emitter. Kleeman and Kuc (1995) showed that the classification of the three reflector types (planes, corners, edges) calls for at least two emitters, their pulses also being received by at least two receivers. For classification algorithms it is essential to have transducers capable of measuring distances with sub-millimetre accuracy. This involves the use of echo signal processing techniques such as optimum filtering and the compression of pulses (Audenhart *et al.*, 1992, Hamadene & Colle, 1997).

This paper will show, firstly, the improvements made in the basic transducer, such as that of Polaroid (POLAROID, 1991), geared towards achieving the following objectives with a low-cost electronic system:

1. Ease of combining one transducer with another, so they may make up more complex sensory modules.
2. High sensitivity, enabling the detection of echoes from small objects or those apart from transducer axis.
3. Ability to detect multiple echoes in a single reading.
4. High accuracy in the determination of the TOFs, (distances determined with sub-millimetre accuracy).

Four improved transducers can be arranged to form a sensor module. The study of a sensor of these characteristics, its possibilities of measuring bearing angles and classifying edges or walls/corners, plus the arrangement of several of them on an industrial vehicle, may be seen in (Ureña *et al.*, 1998).

Lastly, in light of the possibilities of a sensor module of these characteristics, a description is given of an algorithm for map building, using a gridded environment. The translation of the readings obtained into certainty values on the corresponding cells is a costly, computer-intensive process (especially if the number of cells is high). To solve this problem a previous, *off-line* processing is made of the different solutions that may arise, once the parameters to be used in the map building have been reduced to some discrete values. After each pre-processing, templates have been generated (*predetermined templates)* with the certainty values to be updated on the cells remaining in the influence zone of the sensor. These templates are first stored in memory and thereafter used in updating the map as readings are taken (*on-line* processing).

2. IMPROVEMENT OF A TRANSDUCER ELECTRONIC SYSTEM

A basic transducer, such as that of Polaroid [1], employing integration and thresholding techniques of the echo signal, gives an accuracy (see figure 1) that may suffice for many MR applications requiring only

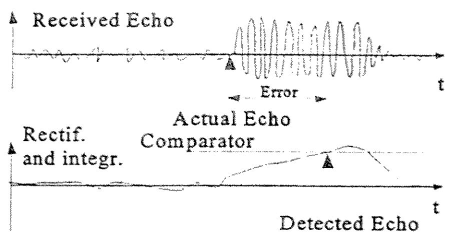

Figure 1.- Echo detected after rectification, integration and thresholding.

distance measurement but not for the determination of reception angles nor for a correct classification of the detected reflectors.

2.1. Proposed electronic system

To improve the transducer's capacity of measuring TOFs accurately, the echo signal is processed along similar lines to those used in radar. The great drawback is that each transducer must necessarily be equipped with a processing system for carrying out all necessary operations. This may significantly increase the complexity of the total system, making its assembly more difficult and cutting down some of the great advantages of ultrasonic sensory systems: their relatively low cost and simplicity. To avoid this, the algorithms have been implemented into a specific digital system, based on an FPGA 4005E of Xilinx, the block diagram of which is shown in figure 2. From an external point of view the working of the transducer may be controlled by a micro-controller system, through an interface circuit, using only four digital lines, namely: *a) mode signal (E-R/R)*; this digital line indicates whether the transducer has to function in EMITTER-RECEIVER mode (E-R) or as RECEIVER only (R), b) *Initiating signal (INIT)*; this signal indicates the moment when the measuring process starts, c) *CLOCK signal*: the functioning of the whole system, in its digital processing facet, calls for a single

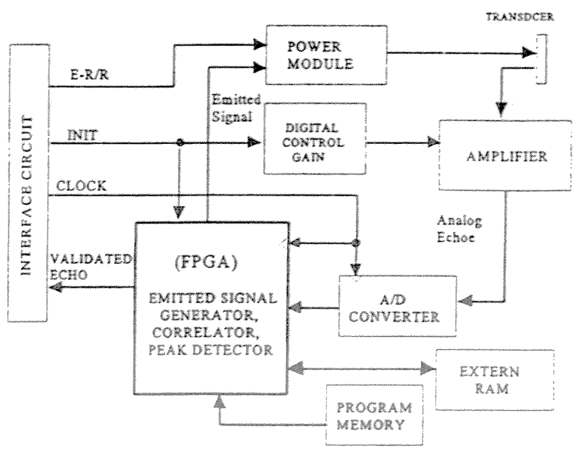

Figure 2.- Electronic system for every transducer.

[1] "Probably the single most significant sensor development from the stanpoint of its catalytic influence on the robotics research community" H.R. Everett *"Sensors for mobile robots"*. Ed. A K Peters. Pag. 144 .(1995)

clock synchronising signal and d) *Echo reception signal* (VALIDATED ECHO): as the echo signal is received it is processed to determine the arrival times of the various echoes detected. Each time one of the echoes is validated the ECHO VALIDATED signal is turned on for 32 µs. The system resolution has been established with a minimum TOF difference of 64 µs (a distance resolution of about 1 cm).

2.2. Implemented algorithm

A practical approach to an optimum filtering (Hamadane et al, 1997) involves taking the emitted signal as reference and making a cross-correlation between this and the signal received (see figure 3). A peak search is made at the correlator output, the peaks coinciding with the arrival of the echoes.

From a digital point of view, if N is the sample number of the emitted signal, y(n) will be:

$$y[n] = \sum_{k=0}^{N} x_e[k] \cdot x_r[n+k] \qquad (1)$$

The ultrasonic transducer used requires binary excitation, so the signal emitted has to be of this type. A binary sequence whose autocorrelation function has a straight lobe is the 13-bit Barker code (Hovanessian, 1984). The main lobe has a width of one bit and an amplitude 13 times higher than the side lobes.

The signal emitted by the transducer must be 50 Khz and last long enough for the energy emitted to allow the detection of echoes from reflectors at a considerable distance. For each bit of the Barker code a symbol has been emitted composed of two periods of the carrier signal (at 50 Khz). In total 13 x 40 µs = 520 µs. A two-phase modulation was used, emitting with phase zero if the code bit is 1, and complemented phase if it is -1. A separation time equal to the sampling time (2 µs) is set between consecutive samples, and the signal emitted can be obtained as the correlation between the symbol used (two periods) and the Barker code sequence (but in this case with consecutive samples separated by a symbol - 20 periods), as may be seen in figure 4, from which it follows :

$$x_e[n] = c[n] * b[n] \qquad (2)$$

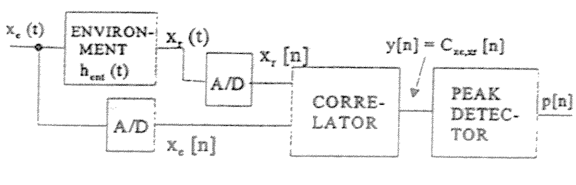

Figure 3.- Block diagam for the prccessing of the received signal.

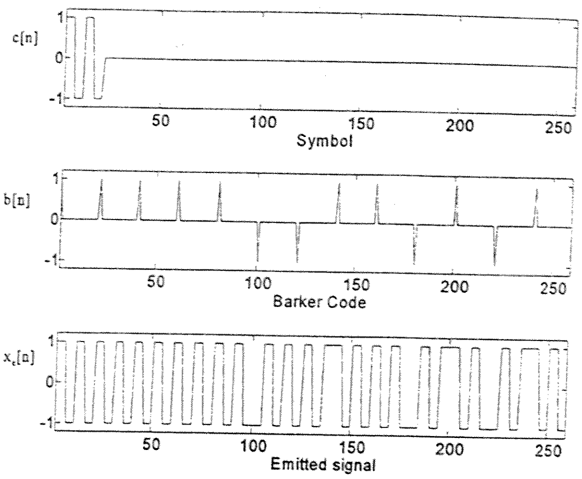

Figure 4.- Generation of the emitted signal.

2.3. Implementation of the correlation and detection of peaks

The sampling period used in the digitalisation of the signal received is 2 µs (sampling at 500 Khz). In other words, for each sequence emitted there will be 520/2 260 samples. The reception of the echo signal is maintained for 32 ms (to detect distant targets up to about 6m.) But the correlation is effected while the signal is being digitalised, maintaining only a reception memory capacity of 260 samples (equal to the duration of the signal emitted). The total correlation between the signal emitted and received may be broken down into two successive correlations:

$$y[n] = x_r[n] * x_e[n] = x_r[n] * (c[n] * b[n]) = \\ = (x_r[n] * c[n]) * b[n] \qquad (3)$$

* *First correlation*: Between the signal received, once digitialised, and the sequence corresponding to a symbol (20 samples). As the latter only takes on the values +1 and -1, the correlation is simplified since only additions and subtractions are necessary (not products). The process will involve taking twenty samples of the signal received and, in units of five, adding or subtracting them according to the followingsequence: {+++++-----+++++-----}. Figure 5 shows a block diagram of the circuit for this process.

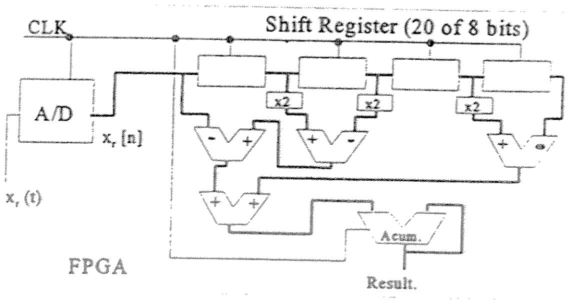

Figure 5. Block diagram for the first correlation.

* *Second correlation*: In each sampling period the result of the previous correlation is taken to an external RAM memory whose addresses are accessed by a pointer - counter- in cyclical mode. The capacity of this memory is 13x20 = 260 words. The block diagram is shown in figure 6. During the sampling period (2 µs) a 16-state sequential process is synchronised by a frequency clock 16 times higher (8 MHz)-. In these states the following operations are carried out:

State 1: While the value of the previous correlation is stored in the relevant memory address (picked out by the counter acting as pointer) , it is taken to an accumulator where it is added to the initial value.
States 2-13: It is added twenty to the pointer value of the previous state and the contents of the new direction are introduced by the relevant sign to the Barker code sequence in the accumulator.
States 14 to 16. These are used for peak detector operations with the last correlation result.

The combinational logic block performs the function shown in table 1:

Table 1.- Combinational function (in figure 6).

STATES	A	B	C	D	E
0	0	1	1	0	0
1,2,3,4,5,8,9,11	0	0	1	0	0
6,7,10	0	0	0	0	0
12	0	0	0	0	1
13	1	0	x	0	x
14,15	0	0	x	1	x

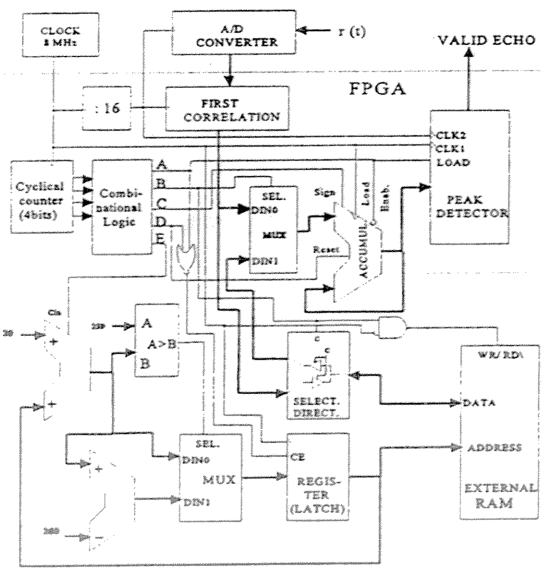

Figure 6.- Circuit for the second correlation.

Peak detector: A comparator is used so that only output values of the second correlation higher than a certain threshold are taken into account. When this obtains, this instant is stored and is definitely validated as an echo reception moment if there is no higher value in the 16 following samples (and at the end of same). In other words two echoes separated (in flight time) by less than 32 x 2 µs = 64 µs (tantamount to about 10 mm of reflector separation) will never be distinguished.

When a valid peak is detected the VALID ECHO output is activated (at a high level) during 32 µs (guaranteeing that during at least 32 µs it will not again be activated). It should be pointed out that from the moment an echo is received until it is actually validated with the corresponding signal there is a systematic processing time of 260 periods for both correlations and 32 periods for the echo validation, i.e., 292 x 2 µs = 584 µs. The external system must subtracting this time from the value actually measured. Figure 7 shows the block diagram of the peak detector.

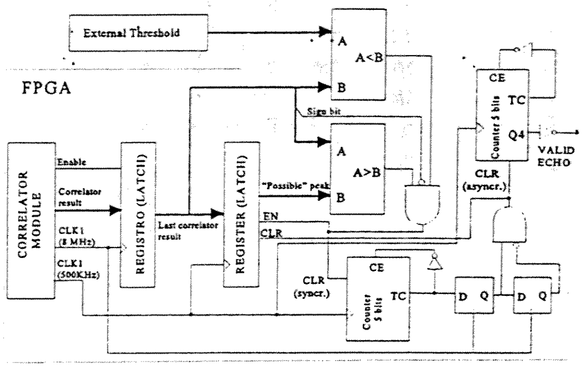

Figura 7.- Block diagram for the peak detector.

2.4 Results

The experimental results have proved the enhacement of the system obtaining a time-of-fly precission of 2µs. Figure 8 shows the analog signal recived and the pulse of validation of the echo for a isolated reflector (note that this pulse is 584 µs delayed since the begining of the echo). In figure 9 can be observed the case of multiple echoes (even with matching beetwen them).

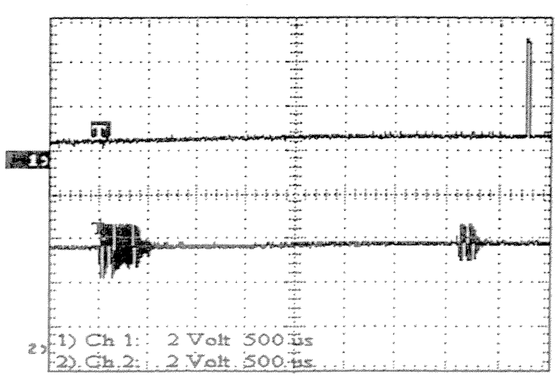

Figure 8. Detection of a echo (one isolated reflector).

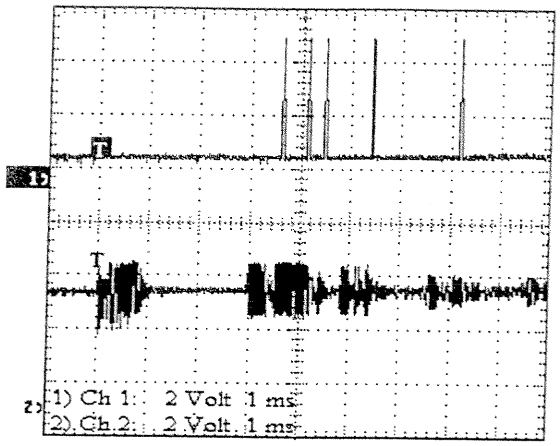

Figure 9. Detection of several echoes (five reflectors)

3. SENSOR MODULE

A single sensor (see figure 10) has been assembled from four transducers with the electronic system indicated in the above section, plus one microcontroller Intel 87C51FB to configure, synchronise and collect the readings of the whole system. The possibilities of measuring distances, reception angles and even discrimination between reflector types (edge or plane) has been described in Ureña et al., 1998. Five sensors of these characteristics were fitted on an industrial vehicle, constituting one of the sensory nodes thereof, together with a CCD colour vision camera and a laser rangefinder (Mazo et al., 1997).

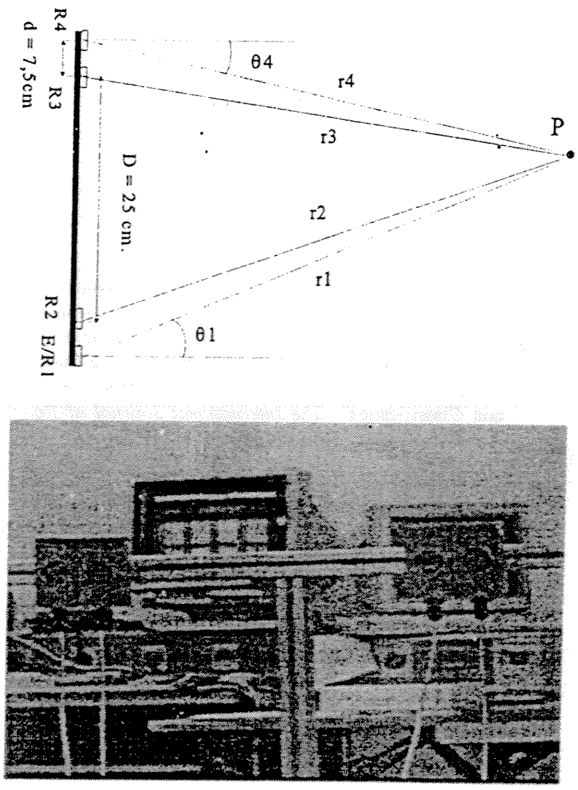

Figure 10. Four-transducer sensor (diagram and prototype).

4. CHARACTERISTICS OF THE SENSOR FOR MAP BUILDING

When one of the sensor's end transducers is emitting, the possible echo signals are received separated by the four transducer, obtaining four TOFs (t_1, t_2 t_3, and t_4). A general rule such as that shown in table 2 is derived from the analysis of the correspondence of the echoes between themselves (verification of whether the transducers have detected the same reflector or another nearby one (Ureña *et al.*, 1998). The sensor has been simplified, each end transducer pair being considered sufficiently close to take in the same "viewing" angle (see figure 11).

Table 2.- Possible data obteined after one reading.

Correspondence: R1-R2	R3-R4	R1-R4	It can be obtained:
No	No	Indiferent	r_A y r_B
No	Yes	Indiferent	r_A, r_B y θ_B
Yes	No	Indiferent	r_A, θ_A y r_B
Yes	Yes	No	r_A, θ_A, r_B y θ_B
Yes	Yes	Yes	r_A, θ_A, r_B, θ_B, type

Once points A and B have been located and the orientation of the transducers is known, the values resulting from a reading determine which zones in front of the sensor can be considered "empty" of obstacles and which "full". A function (variable between 0 and 1) will also be assigned to indicate the degree of certainty involved in both cases. Several algorithms have been proposed for the case of a transducer. Basically, a zone is considered to be "full" when it comes within the opening angle of the transducer at a distance equal to the reading, more or less the degree of accuracy with which said reading is taken. The "empty" zone is that existing between the transducer and the aforementioned "full" zone. Algorithms for a single transducer, such as the HPF (Elfes, 1987), the HIMM (Borestein and Koren, 1991b) or the HAM

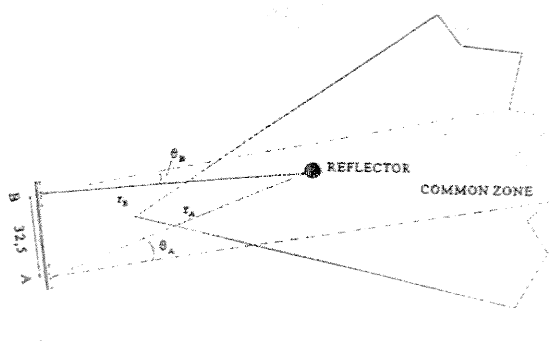

Figure 11.- Simplified model of the sensor.

(Song & Chen, 1996) assign maximum certainty (for both zones) along the whole axis, decreasing as the angles grow therefrom. Greater confidence is also granted to short than long readings.

The algorithm herein proposed takes into account not only the distance measured but also the following: whether the distance reading is confirmed by two transducers on one end (double confirmation) - in the event of any discrepancy the lower distance is chosen - whether the reception angle has been obtained (maximum certainty is assigned there to) and whether the reflector type has been determined (if it is a wall its inclination angle is taken into account to determine the "full" area) For both zones the following updating function is used (f):

$$f = \left[1 - \frac{r - d_{min}}{2 \cdot (d_{max} - d_{min})}\right] \cdot e^{-\left[\frac{(\theta - \theta_c)^2}{2 \cdot \sigma^2}\right]} \qquad (4)$$

where (r, θ) is the point of the "empty" or "full" zone considered (with respect to A or B), d_{min} and d_{max} are the maximum and minimum distances processed, Q is the reception angle detected and σ is a value that varies as the function decreases from its maximum (fixed at 5° of the full zone if it is not a wall and 30° if it is a wall; for the empty zone it will in any case be 10°). This function is applied to the central point of each cell of the gridded environment, and the value obtained is used to update the certainly value (CV) thereof. If CV(k-1) is the previous value, after updating the new one, CV(k), will take the value:

$$CV(k) = m \cdot f + (1 - m) \cdot CV(k-1) \qquad (5)$$

where m is a factor between 0 and 1 that weighs up the influence of past history of the map updating. Following the empirical considerations of the HAM method, 0.4 has been fixed for the "full" zone and 0.2 for the "empty" zone.

The evaluation of the *f* function, mentioned above, has been carried out *off-line* for all existing cells in an octant of the co-ordinate system centred on the position of the transducer. For remaining octants an easy extrapolation can be made thereafter in terms of symmetry. A first template for each measurement has therefore been generated that assumes an orientation - according to the axis - and distance coinciding with the cell in question. For each cell additional templates have also been considered, taking into account the angles measured (for the values -12, -9, -6, -3, 0, +3, +6 , +9, +12). Figure 12 shows a template generated for one side of the sensor with an orientation of 60°, after a reading giving a value of r_A = 500cm and θ_C = 5° with a cell width of 20 cm, d_{min} = 30 cm and d_{max} = 600 cm for the case of an edge. Negatives values are for the "empty" zone and positives for the "full" one.

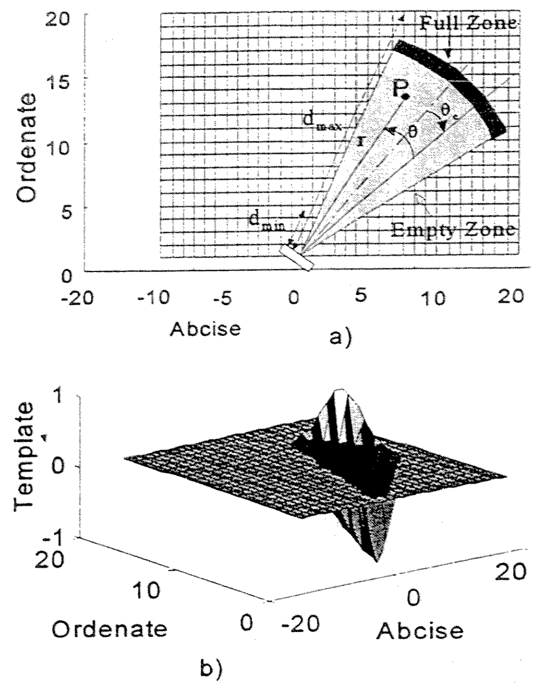

Figure 12.- a) Full and empty zones, b) Template.

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OUTDOOR NAVIGATION

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MARINE SYSTEMS

ULTRASONIC SENSORS

Integral System for Assisted Mobility

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Abstract

This paper presents the results of research work carried out in the Electronics Department of the University of Alcalá, in the field of electronic systems for the guidance of wheelchairs for the disabled and/or the elderly. These electronic systems have been designed to meet a wide range of needs experienced by the users of this type of wheelchair. One of their most important features is their modularity, making them adaptable to the particular needs of each user according to the type and degree of handicap involved. The overall system includes a complete user-machine interface, motor control modules and safety and autonomous guidance systems. The project is called: "Sistema Integral de Ayuda a la Movilidad -SIAMO-" (Integral System for Assisted Mobility).

1. Introduction

The need for artificial means to assist the mobility of people with some type of disability and/or the elderly is a question of great interest to many national and international organisations and institutions. The reasons for this interest are varied (to live an independent life, access to the media, etc) but without doubt the most important are those to do with the quality of life, the need for integration into the working world. All this explains why one of the growing research fields is precisely the adaptation of robotics techniques to the aid of the physically or even mentally handicapped [1] [3]. In terms of mobile robotics applications in this field, one of the most interesting research areas is assisted mobility.

Various alternatives have been mooted to solve this problem; some are based on more or less complex mechanical solutions, involving artificial legs or tracks [5] [6]. But the feasibility of these solutions is still limited for various reasons. Most solutions therefore aim at incorporating advanced control equipment on standard mobile platforms, i.e., on conventional powered wheelchairs [7] [8].

The research group on assisted mobility of the Electronics Department of the University of Alcalá has been working in this field for more than six years. As a result of this work various prototype wheelchairs have been developed including various guidance alternatives and different types of safety sensors and tracking aids [2] [4]. Current efforts are focussing on the design of modular systems, the incorporation of guidance alternatives for cases of severe disability (guidance by eye movement and expulsion of air, for example), autonomous guidance (passing through doors, multisensor integration, wall tracking, etc) and interface systems to optimise user-machine communication.

The following account presents the most important aspects of the work within the SIAMO project, starting with the architecture of the electronic system, then going on to operational modes and ending with a brief description of the most important modules.

2. Architecture of SIAMO System

SIAMO system prototypes have been designed with the aim of being versatile. They therefore allow for the incorporation or removal of various services by simply adding or removing the modules involved in each task. The modules making up this system (Figure 1) are: a) low level control, b) user-machine interface, c) safety and environment detection and d) navigation and multisensory integration.

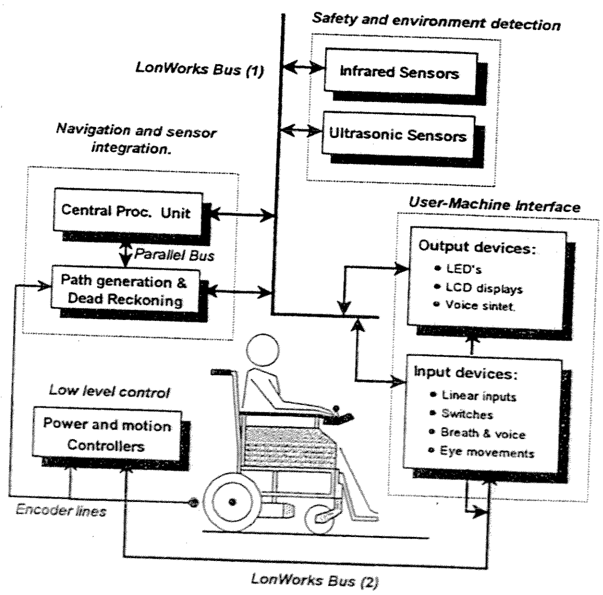

Figure 1.-SIAMO system, functional diagram.

Each module, in turn, is made up by several subsystems, some to implement the basic functions of the module and other optional ones to extend, adapt or change them. Thus, the user-machine-interface module, for example, comprises a display to show the state of the system and, optionally, the state of any manual control subsystem (joystick, etc), of a word-recognition guidance unit, of a breath-expulsion guidance unit, etc.