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ULTRASONIC SIGNAL PROCESSING USING CONFIGURABLE SYSTEMS

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Abstract: The application of multi-mode techniques, in order to determine the times of flight of the ultrasounds, gives solution to the main problems of this kind of sensorial system (little precision and low speed of acquisition), but also presents certain constraints to perform its processing in real time. In this way, the application of the principles of the logical reconfiguration implies more optimal and efficient systems in the use of resources assigned initially to each task of the process, obtaining significant improvements in the developed platforms compared with other possible processing architectures more frequently used. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Ultrasonic transducers are normally based on measurement of the time of flight of the emitted waves, in order to determine the distance between transducer and reflector. The multi-mode techniques suppose an improvement in the problems associated to any ultrasonic sensorial system: low precision and low speed of acquisition. These techniques remarkably increase the precision in the determination of the times of flight, and it also makes possible to accelerate the acquisition process, using different sequences for each ultrasonic emitter. Therefore, a simultaneous emission and reception can be carried out in all the transducers of a system. It is only necessary to select carefully the sequences, searching the orthogonal ones. In this way, assigning to each emitter a different sequence, the receiver can discriminate at any moment to which emitter the captured pulse corresponds (Klaus-Werner, *et al.*, 1998) (Ureña, *et al.*, 1999).

If a system based on multi-mode techniques is analysed computationally, the receiver will consist of so many sequence detectors as emitters (or transducers), so each detector is assigned to a different sequence. Obviously, this fact imposes a new constraint to this type of systems, where the amount of necessary hardware resources is proportional to the number of existing emitters, and consequently to the acquisition speed of information from the environment.

Taking into account these questions, there are two different possibilities in the hardware design of the transducer reception stage:

- It is possible to determine all the features of the system a priori, so fixed and static hardware resources are assigned to each sequence detector. In this way, the type of emitted sequence, as well as the number of emitters in the system, must be known. This solution will be characterized by the development simplicity, although it will consume a considerable amount of resources, in addition to the fact that the reception stage will have not any flexibility or adaptability to new physical configurations with different number of transducers. Then, it takes place a space distribution of the algorithm in the resources available.

- On the other hand, it is possible to develop another possibility for the sequence detection, in which, the search of the different sequences is going to be multiplexed in time, using the same resources hardware. The result is a system with a rather more reduced cost, thanks to a smaller necessity of hardware resources. Now, they will be used more intensively in time. Also, a greater adaptation and flexibility is obtained, being possible to modify the emitted sequences at any moment or the number of transducers of the system, without any modification in the designed hardware platform.

The second option, developed in this work, provides more flexible systems, which are able to adapt to different transducer configurations, without requiring considerable modifications in the associated hardware.

2. TIMES OF FLIGHT DETERMINATION USING GOLAY SEQUENCES

The possibility of using pseudo-orthogonal complementary Golay sequences pairs to determine the times of flight in ultrasounds has been demonstrated in previous works (Díaz, *et al.*, 1999) (Díaz, *et al.*, 2000). These pairs are composed of two sequences, with values –1 and +1, whose independent auto-correlation, and following sum, provides an output signal according to the following expression:

$$C_{AA}[n]+C_{BB}[n]=\begin{cases}2N, & n=0\\ 0, & n\neq 0\end{cases} \quad (1)$$

Where A[n] and B[n] are the pair of complementary sequences Golay, and N is the number of bits or length of them.

For the simultaneous emission of the pair, a digital variant of a classic modulation QPSK has been implemented, so the components I and Q of the modulation has been associated to each one of the sequences of the pair. The expression (2) reflects the mathematical formulation corresponding to this transmission process of the signal e[n] for an emitter i. The signals $A_i[n]$ and $B_i[n]$ constitutes the Golay complementary pair, the first one associated to the component in phase I, and the second sequence B related to the component in quadrature Q. On the other hand, the signals $S_I[n]$ and $S_Q[n]$ are the carrier signals for each one of components I and Q, obtained from the same symbol S[n] with a corresponding phase. The symbol is chosen to centre the emission in the maximum frequency response of the ultrasonic transducer (50kHz).

$$\begin{aligned} e_i[n] &= A_i[n]*S_I[n]+B_i[n]*S_Q[n]= \\ &= \sum_{k=0}^{N\cdot M\cdot m-1} A_i\left[\frac{k}{M\cdot m}\right]\cdot S_I[n-k] \\ &+ \sum_{k=0}^{N\cdot M\cdot m-1} B_i\left[\frac{k}{M\cdot m}\right]\cdot S_I\left[\left(n-\frac{M}{4}\right)-k\right] \end{aligned} \quad (2)$$

Where M is the number of samples per period of the symbol; m is the number of periods per symbol; and N is the number of bits or length of the used Golay sequences.

The demodulator performs a correlation to obtain the components I[n] and Q[n] of the received signal r[n] in a receiver i according to the mathematical expression (3). The signal S[n] is still the symbol of the modulation.

$$\begin{aligned} I_i[n] &= C_{rS_I}[n]=r_i[n]\cdot S_I[n]=\sum_{k=0}^{M\cdot m-1} r_i[k+n]\cdot S_I[k] \\ Q_i[n] &= C_{rS_Q}[n]=r_i[n]\cdot S_Q[n]=\sum_{k=0}^{M\cdot m-1} r_i[k+n]\cdot S_I\left[k-\frac{M}{4}\right] \end{aligned} \quad (3)$$

And once obtained the two components of the modulation, the search of the sequences Golay is carried out, each one in its corresponding component, I or Q, performing a second correlation. This second correlation is described mathematically in the expression (4) for the search of the sequence A in component I. The expression is similar for the detection of sequence B in the component Q.

$$\begin{aligned} S_{IA_i}[n] &= C_{IA}[n]=I_i[n\cdot(m\cdot M)]\cdot A_i[n]= \\ &= \sum_{k=0}^{N-1} I_i[k\cdot(m\cdot M)+n]\cdot A_i[k] \end{aligned} \quad (4)$$

Finally the result of both correlations is added and a peak detector is used to determine the instant of the arrival of an echo.

The process, that has been described mathematically in the previous paragraphs, and whose block diagram is shown in figure 1, also has a general sequencer module, that allows to synchronize the operation between the different tasks in the algorithm, managing the use of common resources, and the interchange of intermediate results.

2.1. Efficient Golay Correlator algorithm

In (Popovic, 1999) a method is demonstrated to obtain pairs of Golay sequences whose length is $N=2^s$, where s is the number of bits of the seed of the sequence (w_1, w_2, … w_s). With this seed, it is possible to generate a pair of Golay sequences and, also, an Efficient Golay Correlator (EGC) can be designed. This correlator allows to simplify the detection process of Golay complementary sequences A and B. Figure 2 shows the block diagram of EGC.

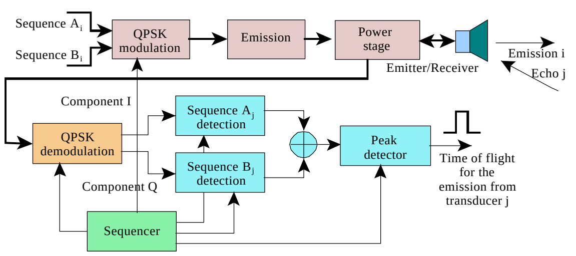

Fig. 1. Simplified scheme of emitter i, configured for the reception of the emission from transducer j (such that j= 1,2,…i,…k) in a system composed of k transducers.

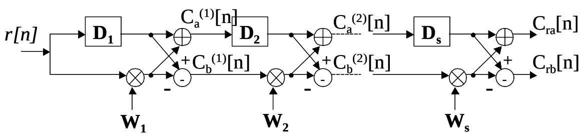

Fig. 2. Efficient Golay correlator.

In this figure, D_s means a delay $D_s=2^{Ps}$; Ps is any permutation of numbers {0, 1, …, s-1}; and $C_{ra}[n]$ and $C_{rb}[n]$ are the correlation results between the received signal r[n] and the searched sequences A and B. Obviously, in this block diagram there is no mention to the necessary demodulation process.

This new possibility presents several advantages, compared to traditional algorithm, reducing the necessary computations to perform the mentioned detection. First, in traditional correlation it is necessary to perform N multiplications (N is still the length of the sequence), while, with the EGC block, only $\log_2 N$ multiplications are performed. In this way, classic method needs N-1 additions, and ECG only needs $2\cdot \log_2 N$. Finally, the number of memory access is also reduced from N accesses to $2\cdot \log_2 N$ in EGC. This is an important point, because the access to memory is usually the bottleneck of systems.

3. HARDWARE IMPLEMENTATION

The general system is structured around a global sequencer, which organizes the execution of the different tasks in the algorithm, in transmission and in reception.

3.1. Emitter

The emitter has been designed for the use of 32 bits Golay sequences (N=32) modulated at 50KHz, because this is the excitation frequency of the Polaroid electrostatic transducer (Polaroid, 1991). A symbol formed by two periods of the carrier signal has been chosen (m=2). The block diagram corresponding to a possible emitter can be observed in figure 3. The pair of complementary sequences is stored in a FIFO memory, so the control module, or sequencer, extracts the corresponding bits to perform the emission. Each set of 2 bits, one from the signal A and another one of signal B, is called dibit, and it allows to obtain the phase that will be applied to the symbol to make QPSK modulation. An adder and an OR-exclusive gate are used to implement the modulation.

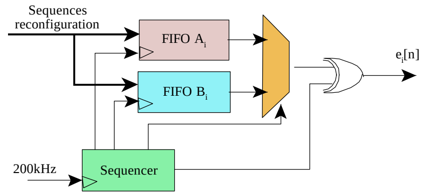

Fig. 3. Block diagram of the ultrasonic emitter i based on a Golay sequence pair.

3.2. Receiver

Once configured the transducer in reception mode, this must implement some processes in order to detect the times of flight from the different emissions performed. It is remarkable that all the computations described in this point can be reduced to additions and subtractions, due to the use of binary signals with values –1 and +1. Now, each one of these phases is described:

- The received signal is digitalised at 400kHz, frequency greater enough than the emission one. This frequency implies that a new sample will be available every 2.5µs. This is the period to analyse the contribution of a determined sample in the algorithm.

- Once captured a new sample, it is necessary to perform a demodulation of the acquired signal r[n] to obtain the components in phase I[n] and in quadrature Q[n] (see figure 4). Because the symbol used in the modulation corresponds with 2 periods of the carrier signal (m=2) and, on the other hand, 8 samples are acquired by every period of the carrier signal, the implementation of this demodulation requires to have the last $m\cdot M=16$ samples. To simplify the design, only the component Q[n] is demodulated, according to expression (3). The component I[n] can be obtained from Q[n], delaying this one two samples in next correlation.

- Once obtained the components in phase I and in quadrature Q, the detection of the Golay sequence A will be performed on component I, while the sequence B will be correlated with Q. The block diagram of this process has been simplified, according to ECG's algorithm shown in figure 2. An operation basic unit (OP) has been defined, containing the basic computations of the process (see figure 5).

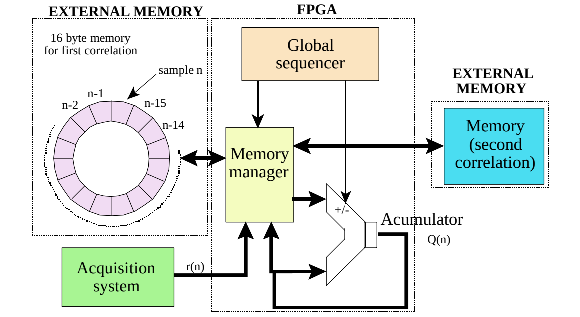

Fig. 4. Block diagram of demodulation (first correlation of the algorithm).

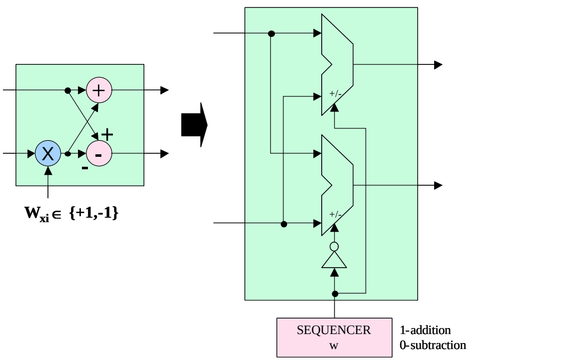

Fig. 5. Block diagram of the operation basic unit (OP).

With this basic unit, a new block diagram can be constructed for the process of detection of Golay sequences. In figure 6 it has been represented the detection process of two different emissions in the same transducer. Notice that it is really easy to expand the algorithm to systems where the number of emitters can be configured.

Also the memory necessary to implement the second correlation is modified according to the number of transducer in the system. Figure 7 explains how data is sequentially manipulated by the basic unit, first for an emission i, and second for an emission j. Exactly, this memory bank must have a size of N· m· M=512 positions for every emission to detect.

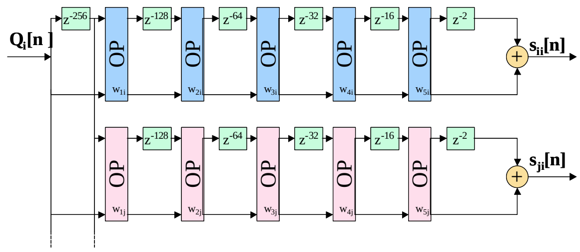

Fig. 6. Scheme of detection of two Golay sequences in a transducer.

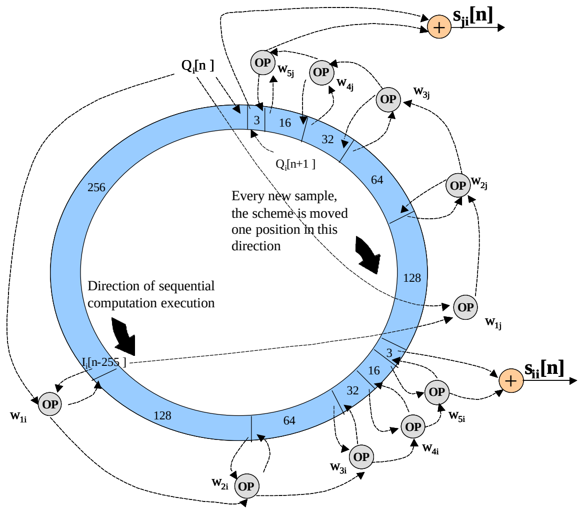

Fig. 7. Operation scheme of the second correlation memory in a transducer for two different emissions.

All the design, corresponding to the reception process explained before, has been implemented on a FPGA XC4006 (Xilinx, 1999). This design can be seen in figure 8. It can be observed the resources used for the first correlation, for the second correlation (including the OP unit), and also the memory manager (right side of the figure).

- Finally, the result of sequences detection should be analysed to detect possible peaks, which can be understood as echoes from reflectors. The block

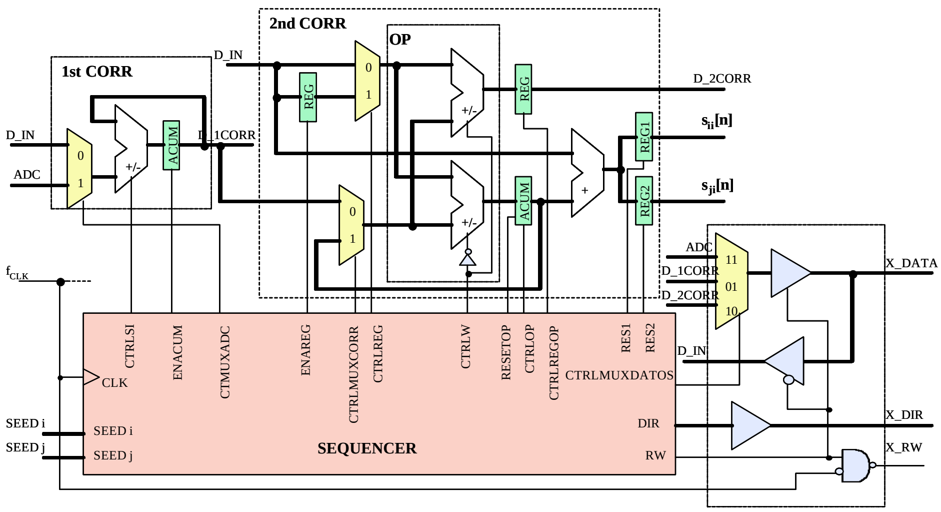

Fig. 8. Implementation of Golay sequences detection.

diagram of this peak detector can be observed in figure 9.

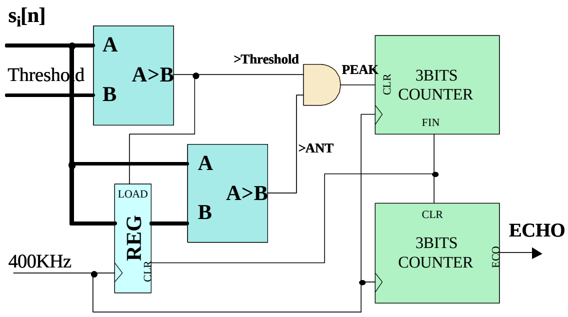

Fig. 9. Block diagram of the peak detector.

4. CONFIGURABLE SYSTEMS

Although the system described before was designed mainly for the detection of an echo, from only one emitter, the great advantage of multi-mode systems is the possibility of simultaneous emission with several emitters. Obviously, it is necessary to assign an unequivocal Golay sequence pair, in order to detect correctly where a determined echo comes from.

Because of this, the initial design shown in figure 1 has to be extended to search for echoes from other emitters. This extension can be solved from two different points of view. The first possibility consists of a spatial distribution of the algorithm, so the different blocks used in detection have to be replicated and adapted to each possible emitter existing in the system. This approach is easy to design and it performs a parallel computation.

On the other hand, it has to be taken into account that there are 2.5µs to compute every sample. If hardware is not used all the time between consecutive samples, it would be better to process the algorithm for searching a determined emission, and then to use the same hardware resources to process this sample for searching another sequence (related to another possible emitter) in the system. This implies a temporal distribution of the algorithm, and presents some advantages. First, there is a reduction of necessary hardware resources, because design is adapted to algorithm; and second, a more efficient use of them, because they are stalled less time in a cycle.

Because of that, configurable computing appears as a new platform to process information from ultrasonic transducer, making possible to adapt the hardware system to the necessities of the algorithm at any moment in order to obtain better performances and a reduction in costs.

5. DEVELOPED PLATFORM

The viability of this kind of implementation has been tested in a developed platform based on a family XC4000 device from Xilinx (Xilinx, 1999). Exactly, the used device is a XC4006, which it is connected to memory bank of 2Kb (see figure 10). This bank is used by the FPGA to store the intermediate results of the process. The main constraint in the system comes from the connection between FGPA and memory, due to the reduced number of pins in this FPGA family, so it is crucial to determine and minimise the number of accesses to establish the feasibility of it. Figure 11 shows the accesses performed in every part of the process, and the spent time, supposing the best access time to memory (20ns).

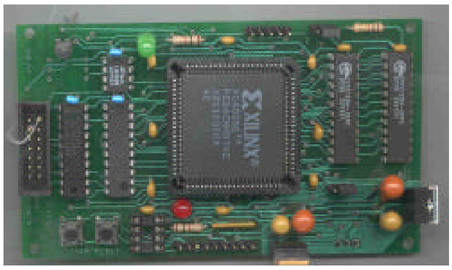

Fig. 10. Developed hardware platform.

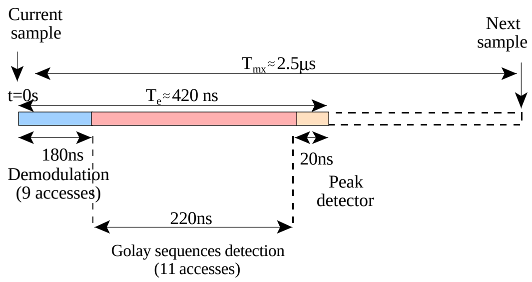

Fig. 11. Timing for the detection of only one emission.

Analysing the figure before, it is possible to observe that there is enough time to process the detection of other emissions using those same hardware resources. The demodulation is common for any emission, and it is also possible to overlap the peak detector process with next phase, because this has a set of resources not shared. So if there is a period about 2.3 ms to implement the different detections, and each detection takes 220ns, it is possible to perform up to 10 detections. Summing it up, it is possible to use up to ten emitters in the system without any modification in the electronic platform associated to every transducer.

However, in this analysis, no mention has been made to the time that reconfiguration takes. It is obvious that if the detection for different sequences is desired, it is necessary to configure the modules for each one, and this process takes a time that it is not negligible. There are several methodologies to make reconfiguration trying to minimise time costs, but, due to the used family, XC4000, almost none is available. Nevertheless, the most suitable possibility is to design a memory area inside the FPGA to store the sequences, so configuring the system is so easy as writing a new sequence in this area. Obviously, this writing has to be performed through the same 8-bit bus used to access external memory, so if the sequence length is 32 bits, four new accesses are necessary to perform reconfiguration.

With this new conclusion, the Golay sequence detection takes 300ns, so, with the platform developed, it is possible to detect up to 7 emissions. Anyway, the methodology developed allows to perform simultaneous emission and reception with a variable number of transducers (up to 7), so the system can be configured to different situations.

Figure 12 shows some experimental results obtained in the developed platform. The system was formed by two ultrasonic emitters/receivers, and, in front of it, it was placed a cylindrical reflector at 70 cm. In the first graph, it can be observed the emitted signal, and, then, in the second graph, it appears the detected echo for the emission of one transducer.

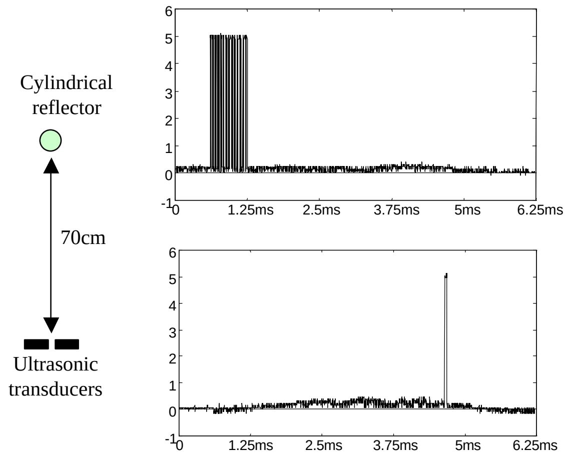

Fig. 12. Experimental results.

6. ADAPTATION TO ENVIRONMENT

As it has been mentioned in the early points, configurable computing offers the opportunity of obtaining a processing system for ultrasonic information able to adapt to the presence of different number of emitters.

Configurable computing also allows a second improvement in the design. As it has been mentioned, sensorial systems based on ultrasounds are influenced by noise from the environment. A solution to improve the signal-noise relation and eliminate this influence is to use longer sequences, so the process gain is increased. However, the use of long sequences implies more computations and a more restrictive constraint to perform algorithm in real time. A possibility is to adapt the length of the sequences to any environment, performing a configuration of the system to change sequence characteristics. This allows to reduce resources in environments with not too much noise and, on the other hand, to implement more complicate computations when the environment is noisy, because it is necessary to improve the signal-noise relation.

7. CONCLUSIONS

The proposed and developed system supposes an improvement in the ultrasonic signal processing. Using the Golay sequences in the emitted modulation, two features have been obtained. The sequence length can be as long as it is desired, to obtain a suitable signal-noise relation in any situation. And, also, it is possible to obtain different pseudo-orthogonal sequences, in order to associate a sequence to a transducer, allowing to emit and to receive simultaneously with all of them, with not crossed interference.

Configurable computing is the philosophy used for its implementation. It provides several advantages over other possibilities. The developed hardware is more adapted to the implemented algorithm, so the final results are more efficient. Furthermore, the system can be configured to different conditions; in this way, it is possible to perform the detection for a number of emissions not fixed a priori, so any transducer can take part of any association. Also, the precision of a transducer can be adapted to the presence of noise, so it is possible to configure the length of the Golay sequences used. Because of this, the final obtained system results very efficient, flexible and adapted to any operation conditions.

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