Construction of a five bits Analog to Digital converter

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An Analog to Digital converter is a electronic device, which transforms an analog signal to a digital binary code. Different types of converters are described. The main scope of this project is to build two types of converters and analyse their properties and performances. As a final result, the two built converters had been able two digitalize correctly an analog alternate signal in a proper interval of frequencies.

I. INTRODUCTION

Nowadays most of the information is processed in digital format, this is due to the fact that it costs less, needs less space and normally the information remains intact longer. But actually, the great majority of the information that we want to save, in its natural state, is in the analog format. For this reason, digitalization is of capital importance in technology and it is always in constant development.

In this work we aim to study the general types of analog to digital converters and the different characteristics of each one, and finally build two different types to analyse their behaviour.

The main idea of a digitalizer is to transform an analog signal to the binary code, which is a discontinuous signal. Basically the inputs that we transform are electrical voltages variations. Consequently we need a sensor to translate the phenomena that we want to study to an electrical signal. For example, a microphone, a photoelectric sensor or a thermoelectric material will respectively transform the mechanical vibrations of the air, the variations of light or the temperature, into electrical stimulus(es).

Once the electrical signal is obtained, we have to evaluate which is the magnitude of the voltage. As we can not have an infinite number of values, the input range has to be discretized. The more divisions we make, the more precision we will have in the measure. There is the same problem with time, it is impossible to take measurements continuously, and save an infinite number of measurements. Therefore, time should also be discretized. Then the quality of the digitalizer depends on how many measure we can take and how many divisions of the voltage we can make.

After making a short research on the internet one quickly realizes that there are many types of digitalizers, but all of them are built of the same type of components. They combine both, the analog electric systems and the digital systems. They use the basic electronic elements like, resistors, capacitors, operational amplifiers (op-amp), digital gates... Depending on the components and the structure of the converter they have some different characteristics and uses. They could be faster, more accurate, more economic or easier to implement in an electronic system.

Next, we present a brief list of the most common digitalizers and their specifications.

Double Ramp digitalizers. These type of digitalizers are very accurate but are really slow and they are used to take measure of time independent magnitudes. They are based upon the discharging time of a capacitor. The capacitor is charged and the time of discharge is determined using a binary counter. The structure of their electronic circuit is represented in Fig.1a.

Successive Approximations digitalizers. These type of digitalizers have an intermediate precision and velocity. The digital system is their most fundamental part and the binary number is determined by making a trial and error decision in every one of the bits. Starting with the most significant bit, it compares if the calculated value is higher or lower than the signal, using a digital to analog converter and an op-amp as a comparator. It then fixes the bit as is necessary and jumps to the following bit. The structure of their electronic circuit is represented in Fig.1b.

Sigma-Delta digitalizers. These system are more sophisticated and their main part is analog. They works by taking small steps using an integrator, and comparing the obtained value with zero voltage. They give us a unique bit indicating if the voltage of the signal is increasing (the output bit is 1) or decreasing (the output bit is 0). Therefore, we can follow the signal with a delta (increment or decrement) of voltage. These digitalizers have a good resolution and velocity, they are basically used to transform signals that change their magnitude continuously, for example sound. The structure of their electronic circuit is represented in Fig.1c.

Flash Digitalizer (parallel comparator). The Flash type is the fastest of all the digitalizers. Unlike the others digitalizers the Flash converter does not use a clock, it is a asynchronous so we can almost consider it instantaneous. That means that it does not discretizes time. The discratization of time will be made at the moment that the measurements are processed, or saved, or analysed for us or another component. The main problem is that if we wont to increase the accuracy, the complexity of the circuits would be largely incremented. It is subdivided in two parts: the first, the analog part, is made with op-amp as comparators, that compares the signal with different voltages; and the second, the digital part that contains a priority encoder which provides the binary number of the corresponding value of the comparators. The structure of its electronic circuit is represented in Fig.2a.

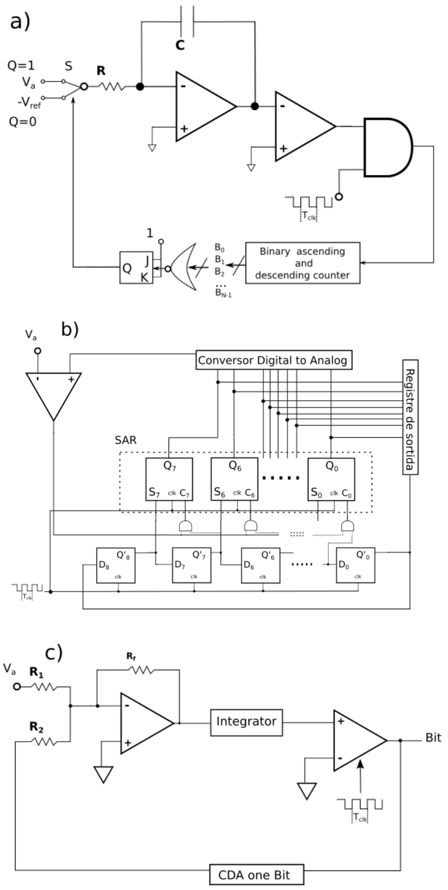

FIG. 1: Schemes of: (a) Double Ramp digitalizer ; (b)Successive Aproximations DIgitalizer; (c) Sigma-Delta Digitalizer.

Tracking digitalizers. In this case most of the system is digital; there is an ascending and descending binary counter that works with a clock. Using a digital to analog converter , an op-amp compares the signal with the value of the counter, then the digitalizer knows if it has to put the counter in the descending or ascending mode. Finally, it oscillates between the two most approximated values. This one is very useful to digitalize small variations in continuous signals. It is very accurate because it is easy to increase the bits of the counter. However, it is not a fast digitalizer because it is limited by the velocity of the counter. The structure of its electronic circuit is represented in Fig.2b.

After analysing the different digitalizers, we decided to build the Flash and the Tracking types. The decision of choosing these two digitalizers was because they represent two very different models: the first one is basically analog and uses comparators; the second one is essentially digital, and uses an ascending and descending counter. Moreover, this two types of digitalizers have different characteristics of quality and velocity so it merits evaluating them.

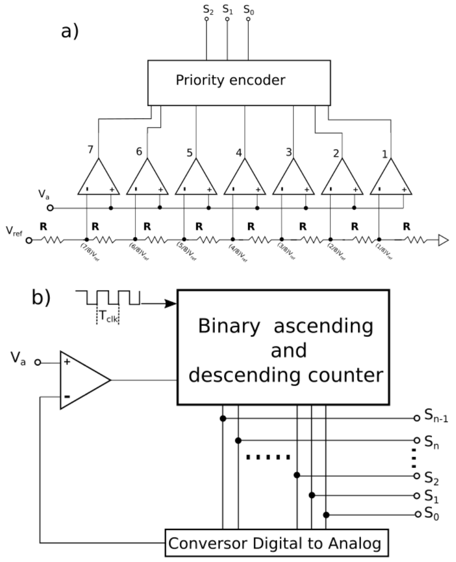

FIG. 2: Schemes of: (a) Flash digitalizer; (b) Tracking digitalizer.

II. PRACTICAL PART, DESIGN AND CONSTRUCTION,

First of all, we made a simulation of the two elected digitalizers circuits in the computer using the LTspice program, which allows us to simulate analog and digital circuits. The objective of building these virtual circuits is to understand their theoretical performance, and to use them as a guide to construct the real ones.

Flash digitalizer

First of all, we made a Flash digitalizer of 3 bits. As with 3 bits 8 binary numbers can be made, the Flash digitalizer will be able to make 8 subdivisions of the input. To simplify subdivisions of 1 V were defined, so the input voltage was between 0-8 V.

Therefore our Flash converter was based on a chain of op-amp used as comparators (with no feedback), polarized between 0-8 V. These op-amp were connected to a chain of resistors, so each comparator compares the signal voltage with a reference voltage that decreases for each one comparators in the chain. As a result, if the signal voltage is lower than the reference, the comparator returns 0 V in the output line. By contrast, if the signal voltage is bigger than the reference voltage, the comparator returns 8 V in the output line. Consequently, all the comparators that have the reference voltage lower than the signal return a high output voltage of 8 V. Therefore, reading the last comparator before the one that is in the down level (output voltage 0 V), we are able to know the magnitude of the input signal. Next, a priority codifier translates this magnitude to binary output. The priority codifier was designed with OR and XOR digital gates. The LTspice scheme of a Flash digitalizer is shown in Fig. 3.

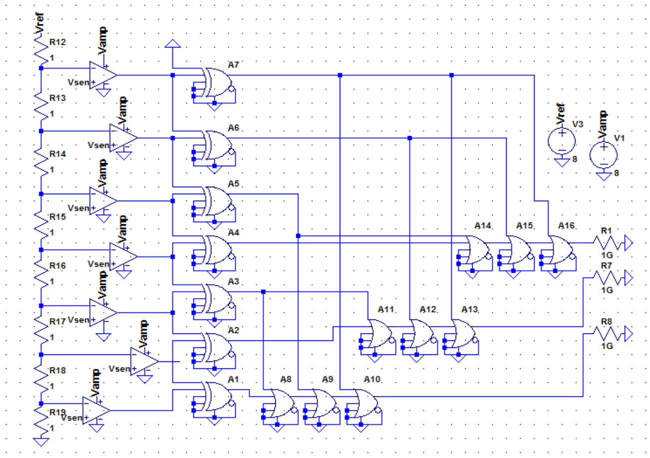

FIG. 3: Image of the LTspice schematics for a Flash of 3 bits. From left to right: chain of resistors and comparators, priority codifier, and the three resistors representing the digital outputs of three bits. The input signal is connected in the positive input of each comparator (Vsen).

Then we built the converter in a protoboard plate, and immediately we realized the complexity of making the circuit, as every component needs to have a polarization. That means that each component needs an input voltage and a ground voltage, consequently the number of electrical wires was higher than it was initially thought. Additionally, it implied that three voltage suppliers were needed: one for the digital components, a second one for the chain of resistors and op-amp, and a third one for the input signal.

After building the converter in the protoboart and fixing some of the connections that were incorrect, we checked its correct functionality. In order to visualize the final binary output, one LED to each digital output is added. We observed that after giving a continuous input voltage, the digitalizer returned the correct binary number, according to the magnitude of the voltage.

Because a converter of only 3 bits (8 grades) has a rather low precision, we found interesting to increase the number of bits. The problem was that to add only one additional bit to this model, it was necessary to duplicate all the structures shown in Fig 3. Thus, it is needed the double quantity of resistors and comparators and to build two priority codifiers. So we decided to design a different extension of the Flash converter to increase the number of bits with a less sophisticated procedure .

If one bit more is added (total of 4), the converter will be able to make 16 subdivisions of the input signal, and if two more bits are added (total of 5) 32 subdivisions will result. To simplify, as before, we will make each subdivision of 1 V and the input signal will be between 0-32 V.

Each extension will add one additional bit to the Flash converter , and contains two op-amp; one as a comparator and the other one as a subtracter. In this new design the signal will arrive to the extensions, prior to the Flash converter of 3 bits. The role of the first extension (total of 4 bits) is to compare if the signal voltage before entering the Flash is higher than the voltage that this can analyse (8 V). If the voltage is higher, the fourth bit will be activated and then 8 volts will be subtracted from the input signal that will be sent to the Flash converter . By contrast, if the input signal is lower than 8 V, it will be directly sent to the Flash, and the forth converter bit will remain Off. With the second extension (total of 5 bits) the same will be performed in the case that the input voltage is bigger than 16 V, which is the top of the next component. In this case, 16 V will be subtracted to the input signal, and will be send to the next component. The structure of the two extensions are shown in the Fig. 4.

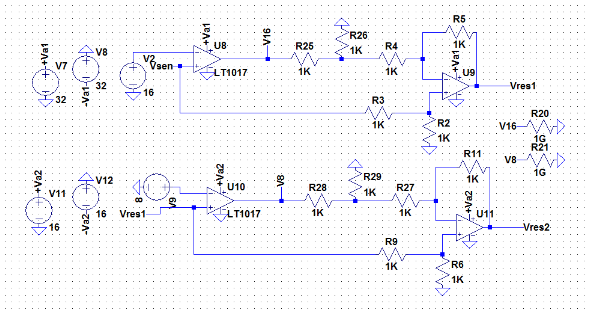

FIG. 4: Image of the Ltspice schematics for the to new extensions and the new two bits added to the Flash.

As mentioned above, the voltages used in the simulation are the ones which make easier to understand the converter . But in the real digitalizer there is a limitation the polarization of the components. To avoid putting excessive voltages, the components were polarized with 2.5, 5 and 10 V (keeping the same proportionality as between 8, 16 and 32 V) for the 3, 4 and 5 bits Flash designs.

When building and checking the extended circuit in the protoboard, new problems emerged. Firstly, the real comparators did not work like the ideal one in the simulations. When polarizing them to 10 V or 5 V they were only able to return a high output of 8 V and 4 V respectively. Therefore it was necessary to polarize them with a higher voltage to have an output 10V or 5V, in each case. The real values were 11.8 V and 6.8 V. Additionally, some of the op-amp used needed to be polarised with positive and negative voltages. Consequently, 6 voltage suppliers were used.

Furthermore, even after correcting these problems the Flash was jumping some bits. The problem was that the resistors had the same magnitudes of the impedances of the op-amp. It was crucial for the correct work to adapt the impedances of the op-amp and the resistors. After substituting the resistors for the appropriated ones, the extended Flash of 5 bits worked properly.

Tracking Digitalizer

The key component part of this digitalizer is digital. It is based on a chain of JK Flip-flops, connected by

"AND" and "OR" digital gates. This chain of JK and logical doors are connected to make a binary counter, both ascending and descending.

The counter gives a binary number of five bites that we will be able to increase or decrease. Then this digital number is transformed to an analog voltage using an adder constructed as follows: op-amp and resistors are connected to each bit of the counter considering the significance of the bit. Thus, the less significant bits are connected to a higher number of resistors than the more significant bits. Since the adder is also an inverter, the addition of the digital number needs to be inverted again by an op-amp. This calculated value of voltage is compared with the input voltage, in this case using a op-amp as a comparator. If the voltage of the input signal is higher than the value of the binary number, the counter of binary numbers needs to increase the value, so have to stay in the ascending mode. In the other case, the counter needs to decrease, so it has to stay in the descending mode. The final result is that the converter is jumping between the two digital numbers that are closest to the value of the input signal.

Last but not least, as this is a synchronous converter , the counter has to be connected to a clock that controls the beat of the cycles. As will be showed, it will be very important to have the correct frequency of the clock, depending on the frequency or the speed of change of the input voltage.

Based on these facts, we made a simulation of a Tracking digitalizer of 5 bits, using the LTspice simulator, as indicated in Fig. 5.

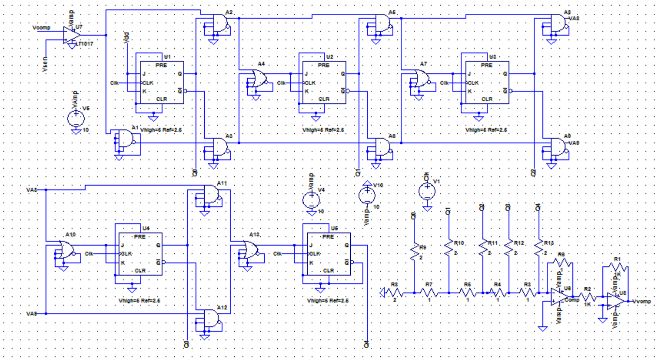

FIG. 5: Image of the LTspice schematics for a Tracking digitalizer of 5 bits. From left to right: the comparator, the counter (made with JK and logical doors). Below the adder and the inverter. All the components work betwen 0 and 5 V.

Then we built a real circuit in the protoboard plate with the scope to digitalize an input signal between 0 and 10 V (as with the Flash converter). The first problem was that the JK Flip-Flop did not return high-value (corresponding to the logical number 1) of 10 V, this is because, like most of the common digital components, they have to be polarized between 0 and 5 V.

The problem was solved by putting five op-amp as comparators that were polarized to give us 0 V if the output voltage of the JK was in the Zero digital (less than 0.8 volts) and 10 V if the JK is in the One digital (more than 3.5 V). Again, as with the Flash digitalizer, to have and output of 10 V in the op-amp, it was necessary to polarize them between 0 and 11.8 V.

After resolving some problems with the resistors and the impedances of the op-amp, the Tracking digitalizer worked properly with a continuous input signal. To visualize the final binary number, we put five LED in the outputs of the JK flip-flop, each one representing an individual bit.

III. RESULTS

Once checked, the correct functioning of the converters using a continuous voltage, we studied their limits with an alternate signal. The objective was to compare the input signal and the output signal. To this end, the binary code of the result of the digitalizer has to be transformed again to an analog signal, which could be visualised using an oscilloscope. Actually, for the Tracking digitalizer converter it is already made this using the op-amp and the chain of resistors to make the adder. Using the same structure, the binary output of the Flash converter is transformed to an analog signal.

With the help of a wave generator, we generated an oscillating sinusoidal wave with the appropriated values for our digitalizers: a mean value of approx 5 volts, a minimum value of 0.1 V and a maximum value of 9.9 V. Then just by altering the frequency, we were able to study the behaviour of the digitalizers. The two analysed parameters were the resolution and the speed.

In theory, both converters should have the same resolution, 5 bits, and the Flash converter has to be faster than the other. But, the addition of two extensions to the Flash digitalizer could have a negative impact in its speed.

We first studied a wave of 1 Hz of frequency as an input signal, and both of the digitalizers responded well and returned the wave perfectly. Of course, for the Tracking digitalizer, we needed to take care of the clock, and adjust it to the correct frequency.

As it can be seen in the Fig. 6a the Flash converter , correctly followed the input signal of 1 Hz, according to the resolution of 32 subdivicions. This can be clearly observed when representing the function of the differences between the input and output signal, which is a toothed function with values between 0 and 0.3 V (10 V / 32 subdivisions).

Regarding the Tracking converter , it only properly followed the input signal if the clock had the appropriated beat. A shown in Fig. 6b, the output signal does not follow the input one because the clock is too slow. In contrast, the output correctly follows the input signal when using a faster clock (Fig. 6c). Notably, the function of differences of the Tracking converter has a range of values higher than 0.3 V. We believe that this may be due to difficulties in adjusting the clock properly or that the counter does not function perfectly at the speed at which we need to work.

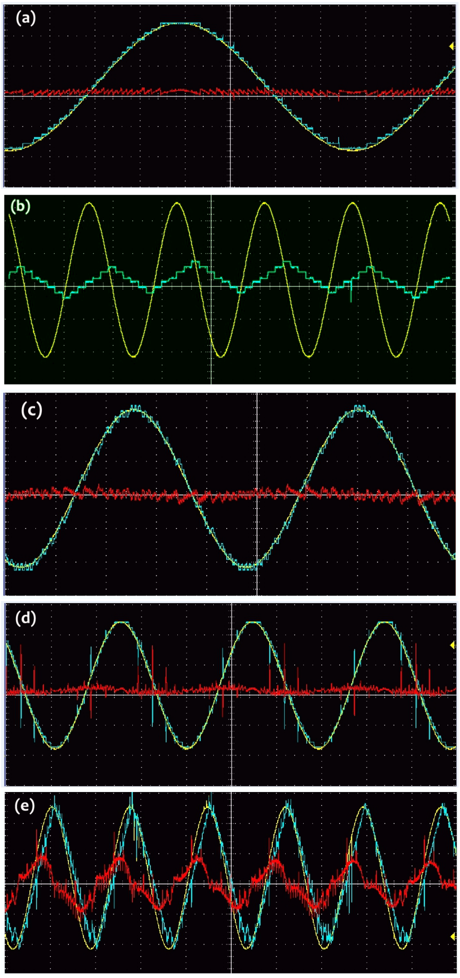

FIG. 6: Images of the oscilloscope, in yellow the input signal, in blue the output signal and in red the differences function. (a), (b) and (c) correspond to an input signal of the order of 1 Hz. (a) corresponds to the Flash converter , (b) to the Tracking converter for a clock of 20 Hz and (c) the Tracking one for a clock of 200 Hz. For the y axis (voltage) the scale for all them is 2 V and for the x axis (time) the scales are: 100 ms, 250 ms and 100 ms respectively. (d) and (e) correspond to an input signal of the order of 100 Hz (similar to an audio signal). (d) corresponds to the Flash converter , (e) to the Tracking converter for a clock of 20000 Hz. The scales of the y axis and the x axis are 2 V and 2.5 ms respectively.

Finally, we analysed the functionality at higher frequencies (Fig. 6d and 6e).

It is observed that the Flash digitalizer followed the input signal, but started to have some significant differences, and jumped some values, as can be observed in the function of differences (Fig. 6d). On the other hand, the Tracking converter is not able to follow correctly the signal of 100 Hz (Fig. 6e).

When considering the next order of magnitude, 1000 Hz, the Flash converter did not digitalize correctly the input signal. One possibility was that the first part of the Flash digitalizer, the extensions that we added, was slower than the second part of only 3 bits. But when the Flash converter was analysed using only the last 3 bits (without the extensions) the results were very similar.

IV. CONCLUSIONS

We have been able to design and build a Flash and a Tracking digitalizers. The main achievement is that both, the Flash and the Tracking (with the proper clock), can digitalize correctly an input signal of the order of 10Hz.

For frequencies higher than 100 Hz only the Flash digitalizer works properly. The extensions added to the device did not interfere with the velocity of the converter . Therefore, the Flash converter still could be considered instantaneous, and the problem of not digitalizing an input signal higher than 1000 Hz, can not be associated with being a slow converter . The reason is that the used op-amp star to have a bad behaviour for a frequency close to 1000 Hz, as can be read in their data-sheet. A way to improve the converter is to change all the op-amp, for other ones that can work at higher frequencies.

Regarding the Tracking converter , as it is slower, it can only take an input signal of the order of 10 Hz. This is due to the fact that the counter has to go through all the numbers before arriving to the right value. This is particularly evident if the input signal is a step function. In contrast, the Flash converter would mark immediately the new value.

According to the previous comments, the Tracking converter has to be used for continuous input signals of low frequencies, and the Flash converter could be used for continuous or discontinuous input signals with high frequencies, depending on the limits of the op-amp. In our case, the Flash converter may be used to digitalize an audio signal, which are between 20 Hz to 20000 Hz. However, a big range of frequencies can be lost affecting the quality of the sound.

Acknowledgements

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