

Sensing in Coin Discriminators

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Abstract— This paper describes the technologies used in coin discriminator devices, stressing the improvements and novel mechanisms introduced by the authors in the past few years as a result of the cooperation with one leading company in the vending sector. Emphasis is put on how low-cost sensors are used to characterize coins (or tokens) and discriminate them from their counterfeits.

Index Terms—Coin Discriminators, Acoustic Sensors, Impact Sensors, Electromagnetic Sensors, Data Fusion

I. INTRODUCTION

COIN discriminators, also called selectors, are present in any coin operated machine, such as vending, public phone or slot machines. Their role is to discriminate valid coins (or tokens) from their possible counterfeits. This must be done in a very short time frame such that the user does not appreciate any delay between the introduction of the coins and the operation of the device. The problem is particularly difficult in places where a number of different coins and even currencies must be accepted (e.g. some airports), where coins of very different nominal value may have very close physical dimensions and properties. Fraud in coin operated machines has also had an important economic impact in Europe, where it is common to have high value (more than a dollar) coins circulating (e.g. 2 Euro or 2 Sterling Pound).

Unlike note discriminators, coin discriminators must be low-cost devices (around \$30), which makes it impossible to use sophisticated technologies. This means that both low-cost electronic components and sensors should be employed. Microcontrollers are routinely used as processing units, in combination with analog conditioning circuits for the sensor signals. Imaginative procedures to process and combine the information coming from several sensors are the key to achieve good discrimination features. A simple search for coin discriminators in patent databases results in an overwhelming number of matches, which proves the economic relevance of the subject. However, this contrasts with the practical inexistence of literature in technical journals.

In this paper, we review the basic physical mechanisms and sensor related technologies used to achieve a good discrimination of coins, which are in the core of most discriminators available in the market. Then, we describe the improvements introduced by the authors that have led to a major breakthrough in the design of such discriminators. The

improvements are mainly based on synergically exploiting the information obtained by the different sensors and by making use of digital signal processing techniques. The use of low-cost, yet powerful DSPs has been essential in this development, which has been a long-term joint project involving universities, research centers and the funding company: AZKOYEN. The results of this research project have been incorporated in the last generation of coin discriminators marketed by AZKOYEN.

II. COIN DISCRIMINATORS IN A NUTSHELL

When a coin is introduced into the slot (see Fig. 1), it falls vertically and first hits an anvil, rolling down a short ramp of about ten centimeters. The sensors are located along this path, and their signals have to be processed to decide if the coin is good or a fake before it reaches the end of the ramp, where the coin is driven to the storage or returned to the customer.

The role of the sensors is to measure physical properties of the coins, such as dimensions, conductivity, magnetic permeability, elasticity, etc., and even the existence or not of relief. Only the diameter of the coin, actually its secant, can be directly measured, while for the remaining parameters only indirect information is obtained. This is not a limitation, since what is really needed is to have for each coin a set of parameters, sufficiently large so that, even considering their drifts (due to aging, sensor accuracy, coin trajectory, etc.),

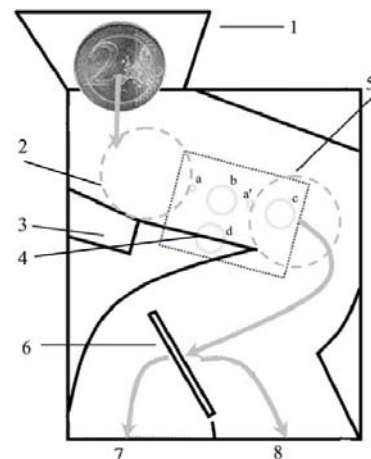


Figure 1. Schematic of a coin discriminator: 1) Coin entry, 2) Coin rolling, 3) Anvil, 4) Coin rolling ramp 5) Optical (a-a') and Electromagnetic sensors (b-c-d), 6) Acceptation gate, 7) Coin acceptance chute, 8) Coin rejection chute

allows for a clear discrimination among coins and frauds. In the next paragraphs, a brief description of the sensors most commonly used and the magnitudes measured, is given.

A. Optical Sensors

They are normally used to measure a secant segment of the coin at a predefined height. The sensor is at least comprised of two optical barriers, which consist of pairs of high gain light emitting photodiodes and light receiving phototransistors placed along the coin's path. The time instants of the coin entering and leaving the barriers are detected when the voltage in the phototransistor exceeds a threshold value. It is assumed that the coin enters the barrier when the leading edge of the coin intercepts the beam of light between the photodiode and the phototransistor and that the coin leaves the barrier when the light beam is re-established as the trailing edge of the coin leaves the optic barrier. These time instants are stored in memory. If it is assumed that the coin rolling along the path describes a uniformly accelerated motion (which is not exactly true due to friction along the path), only two optical barriers placed at the same height are needed to calculate the secant segment of the coin. The position of the coin, x , at time t is given by: $x = \frac{1}{2} a t^2 + v_0 t + x_0$; where a is the acceleration of the coin, and v_0 and x_0 are its velocity and position, respectively, at time $t = 0$. Taking into account the measurements of the times at which the coin enters and leaves each of the optical barriers, and the distances the coin has rolled along the path with respect to a reference point, a system of four equations with the following unknowns can be set out: a , v_0 , x_0 and s , the secant segment of the coin. Coin discriminators using this type of sensors for measuring the diameter of the coin and for identifying whether the coin has a central orifice are described for instance in [1] and [2], respectively.

B. Electromagnetic (EM) sensors

Inductive sensors are based on inducing eddy currents in the coin and measuring them by analyzing the magnetic field they generate. They are usually constructed by coils encircling ferrite pot-cores in order to boost and concentrate the magnetic flux. The field detectors can also be made of magnetoresistances or Hall effect sensors. The coin is subjected to a variable magnetic field generated by an oscillating signal. In the case of inductor coils, the eddy currents induced inside the coin modify the electrical impedance of the coils, which results in variations of the amplitude and phase of the signal in the detection circuit. In the simplest approximation, amplitude variations are related to the coin conductivity whereas frequency variations relate to its magnetic permeability.

The simplest configuration is constituted by a single coil making both the excitation and measuring functions. The main drawback of this system is the strong dependence of the resistance and inductance of the coil on the distance between the coil and the coin (lift-off effect) [3]. The use of an inductive sensor placed on each side of the coin track partially

attenuates the effect, as the shift of the coin in one side along the common axis is compensated in the other side. There are many variations to this particular scheme, which mainly resort to the use of more than one pair of inductors and the way their magnetic fields are coupled (in "phase" when the fields are adding, in "counter-phase" when the fields are subtracting or in emitter-receiver mode), and the frequencies used (changing the penetration depth). The latter is particularly important in the so called bi-color coins (different materials in core and ring) and multilayer coins (sandwich of two materials).

Fig. 1 shows a configuration described in [4] where inductors b are in phase, c in counter-phase and d in emitter-receiver configurations. The envelope of the amplitude of the oscillating signal obtained in each of the inductive sensor pairs are depicted in Fig. 2. The two peaks in curves 1 and 3 correspond to the passing of the coin edges through the EM sensors. These curves are parameterized and values such as maxima, minima and averages of certain areas of the curve are extracted and related to the width and to the electromagnetic properties of the different parts of the coin.

This being the basic mechanism for coin discrimination, there are still some limitations that have precluded so far more efficient results. Basically, the method is limited by the air gap between the sensors and coins. On the one side the separation of opposite inductors in the channel, in a fabrication batch, present some variations. This can be corrected in part by calibration. On the other side, when the coin rolls down in the channel it also lifts-off in such a way that its separation from the two walls is not constant, affecting the accuracy of the measurement.

The two kinds of sensors mentioned so far have been fundamental for coin discrimination for a long time, and even they are the only ones included in low-end discriminators. In cases where important fraud or coin confusion is present, more elaborated sensing mechanisms need to be included. Other sophisticated techniques have been described to even obtain a magnetic profile of the coin [5], but however they are far from being amenable for its introduction in low-cost discriminators.

C. Acoustic Sensors

It is known that when a coin is mechanically excited, for instance by dropping it against a hard surface, the sound it

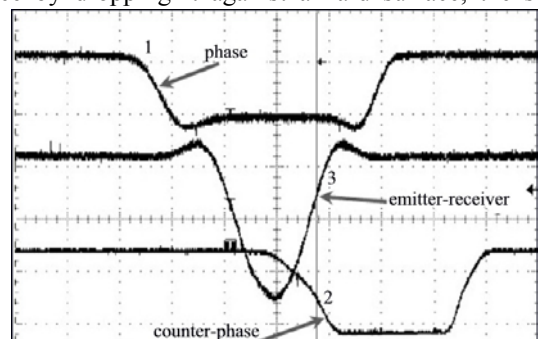


Figure 2. Envelope signals acquired with sensor pairs b , c , and d configured in phase, counter-phase and emitter-receiver modes, respectively.

produces relates to their mechanical properties (physical dimensions, stiffness and density). Since these properties are not related to the electromagnetic properties, an acoustic measurement looks at first sight an excellent complement to the EM sensors. This is the reason why some coin selectors include a microphone in the wall of the vertical channel, to measure the sound when the coin hits the anvil. Then, acoustic signal is spectrally analyzed to obtain its energy in some prescribed bands. This is typically accomplished by analog filtering, since digital methods (namely FFT) are not easy to implement in very low-cost microcontrollers. The potential of the technique has been hampered by the impossibility to acquire a clean coin signal. Coin hits selector walls before and after it hits the anvil, resulting in an inappropriate excitation (walls are plastic and softer than the anvil), sound emissions by the casing, and false triggers. Consequently, the value of the information obtained by microphones has been, so far, limited to very specific frauds.

D. Impact Sensors

The same properties the sound depends on can be also indirectly measured by obtaining information of the very impact, by measuring vibration or acceleration of the body where the coin impacts. This is a subtle measurement since the signal obtained strongly depends not only on the coin properties but also in the way it hits (edge flat or corner) and the way the sensor is mechanically coupled to the impact body. This latter aspect is difficult to control in a fabrication process. Sensors typically used are piezoelectric materials (ceramics or piezofilms) configured as accelerometers, pressure sensors or in embodiments which are difficult to qualify. All these mentioned difficulties have in practice reduced the use of these sensors to detect frauds made with soft alloys such as those made of lead and tin, which are easy to manipulate, and may have magnetic properties close to those of many valid coins.

III. A NEW GENERATION OF COIN SELECTORS

The goal of the project mentioned above was the design of a novel selector that should be a major breakthrough in the field. A global approach was undertaken, taking into account in an integrated manner mechanics, electronics, sensors and data integration and processing. Several groups worked together trying different approaches. Besides aspects related to the modularity of the design (which are important to adapt the selector to different sizes), we will concentrate here on the technologies related to the sensors. Following a scheme similar to the previous section, we will describe here, yet in a very simplified way, the most significant advances. Patents that we will refer to in the next paragraph contain more details.

A. Optical Sensors:

The limited dimensions of the coin discriminator make a stable rolling of the coin inside the selector impossible due to the following factors:

- The entrance of the coin into the first optical barrier (a in Fig. 1) takes place when the coin has not been stabilized yet.

-The coin leaves the second barrier (a' in Fig. 1) when it has already passed the whole coin path, and it is falling, describing a parabolic trajectory. The coin's trajectory at this instant depends on the velocity of the coin, the length of the ramp and the possible different inclinations of the coin discriminator placed in the vending device.

These unstable time measurements produce secant segment measurements with large deviations, which is an important weakness of the discriminator. The use of at least three optical sensors, allows for the selection of the four most stable time stamps of the coin trajectory, leading to a much more stable secant segment measurement parameter. With configurations of three and four barriers accuracies of $350\mu\text{m}$ and $200\mu\text{m}$, respectively, can be achieved. An accuracy of up to $60\mu\text{m}$ for a large coin (e.g. 2€) can be achieved with four barriers. As an example of the results obtained, Fig. 3-a shows that with the two barrier sensor the histograms of the 2€ coin and its token (the coin before being minted), with a difference between their diameters of $250\mu\text{m}$, clearly overlap, making the distinction between them impossible. The proposed four barrier sensor distinguishes them undoubtedly (Fig. 3-b).

Additionally, the set of at least three optical sensors provides with an accurate and stable measurement of the coin position with respect to time at any instant. This supplementary information is very useful to relate the measurements of any of the other sensors used in the discriminator with the position of the coin [6].

Apart from this, the temperature and the dirt accumulated on the internal walls of the coin discriminator (after large quantities of coins pass through it) are important factors affecting the performance of the photo-electric devices. On one hand, an increase in temperature diminishes the efficiency of the photodiodes and increases the sensitivity of the phototransistor. On the other hand, the time instant at which the voltage threshold in the phototransistor is exceeded corresponds to a defined relative position between the coin and the optical barrier. Any alteration of the coupling between the photodiode-phototransistor barrier, either by a change of temperature or by the accumulation of dirt shadowing the barrier, can modify the relative position between the coin and the barrier at which the threshold value is reached, and therefore, change the time values acquired by the sensors and

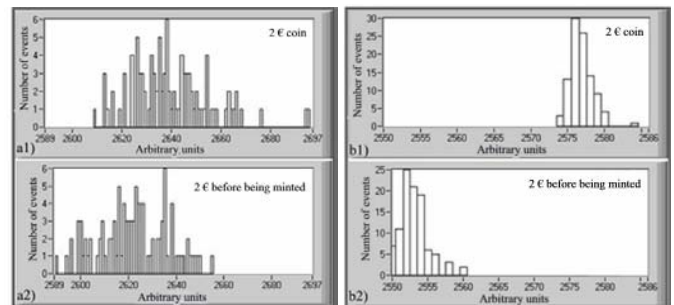


Figure 3 Histograms of a coin of 2€ (a1 and b1) and its token (a2 and b2) inserted in the selector 100 times with a) two barriers and b) four barriers optical sensor.

consequently modify its accuracy. In order to overcome these problems, for each pair of barriers in the new selector a control loop is established between the receiver and the emitter that injects the required current to each photodiode, so that all phototransistors are maintained at a common and constant operating point, in the linear region, which increases the stability of the diameter and position measuring method.

B. Electromagnetic (EM) Sensors

Contrarily to what has been described in the case of the photo barriers, the increase in the number of coils would be impossible due to space restrictions and price constraints. Here the goal was to increase the efficiency of the sensor, by making use of the potential of signal processing techniques to compensate the coin's lift-off effect. Additionally, the result was that it was even possible to reduce the number of coils to just one pair with the same discrimination capability as the previously described with three pairs of coils (Fig. 1). We will briefly describe how this can be accomplished.

The resistance (R) and inductance (L) measurements of a pair of coils configured in phase and counter-phase modes can be described by: $Z = Z1 + Z2 \pm 2M12$, respectively, where Z represents the impedance of the coil pair, Z1 and Z2 the impedances of the coils separately and M12 the mutual impedance coefficient between the coils, and which represents the measurement of the emitter-receiver configuration.

Alternatively, the impedances corresponding to the three configurations can be calculated by directly measuring only two of the following four modes of operation: exciting only coil 1, exciting only coil 2, exciting both coils in phase, exciting both coils in counter-phase. On one hand, the coil pair has to be excited sequentially in the two modes (generically called A and B). On the other hand, in order to be able to apply the previous equations the impedance measurements should be simultaneous. To overcome these two incompatible aspects, the two modes are cyclically excited fast enough not to lose any relevant information as the coin is constantly rolling. The missing modes at any instant, i.e. the data of mode A when the coils are excited in mode B and vice versa, are obtained by a second order polynomial interpolation. For the present design the two modes chosen were the ones which excite each one of the two coils individually. These are achieved by exciting the coils using the circuit shown in Fig. 4. The switches SW1 and SW2 are implemented by using general purpose analogue multiplexer/demultiplexer driving high impedance amplifiers. The synchronous generation of the exciting signals and the switching of SW1 and SW2, together with the direct measurement of the voltages in the coils and the computation of the impedances are made by the DSP.

Additionally, a mathematical procedure to compensate for the effect of changing the distance between the coin and the coils was developed. On one hand, the instability of the coin alters the distance between the coin and each of the coils from one coin insertion to another and also while the coin is rolling in the channel. On the other hand, manufacturing tolerances

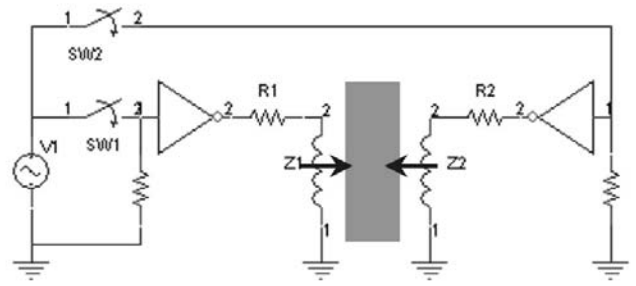


Figure 4. Schematic of the electronic circuit used to excite the pair of coils of the electromagnetic sensor.

and aging in the discriminator may change the distance between the coils which also affects to each of the individual distances from the coils to the coin. The procedure compensates the lift-off effect of the phase and counter-phase measurements by using non-linear compensation terms calculated using the measurements obtained from the two excitation modes described previously, without measuring the distance between the coin and the coils [7]. Fig. 5 shows the result of the application of the lift-off compensation algorithm on the resistance of the coils in counter-phase configuration, which clearly improves the discrimination capability of the selector.

C. Acoustic Sensor

Taking into account the limitations described above for this kind of sensors, it was obvious that acoustic measurement, to be of relevance within the discriminator, should fulfill some basic requirements, namely:

- Coins should always impact in similar conditions, regardless of the way (speed, orientation,...) they come into the slot. This means that impact point must be moved as far as possible from the input.
- It is important to make sure when the coin is exactly tapping the hard body.
- It is important to avoid sound induced by the casing vibration when the coin hits the hard body.

The first condition seems in contradiction with the

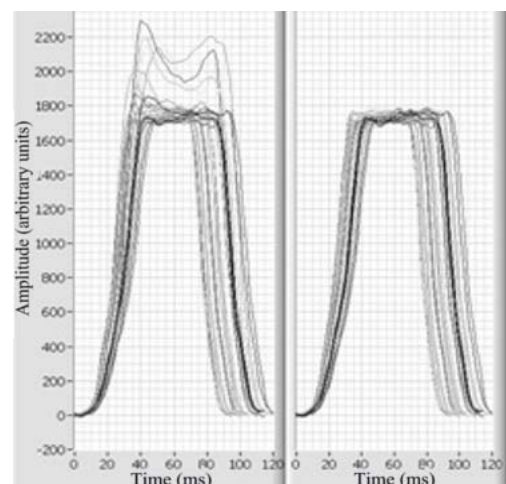


Figure 5 Counter-phase resistance measurements of 30 insertions of a 50c (€) coin: a) before and b) after lift-off compensation.

possibility to make a sophisticated analysis of the sound signal: if the acoustic signal is acquired at the end of the slope, there are just a few milliseconds left to analyze it and combine with other sensors' information to take a decision. Fortunately, low cost DSPs with the required capabilities were available at the end of the project, making the problem solvable.

The solution adopted is shown in Fig. 6. It represents a floating cylinder placed on one of the walls at the end of the ramp, and perpendicular to the movement of the coin. The reasons for the cylindrical shape will be explained later. The cylinder stands out partially from the wall, and has one degree of freedom in such a way that it hides when the coin impacts (allowing the coin to keep rolling), and releases when the coin has passed. A low cost microphone is placed in the opposite wall in a position, which is intended to be the closest of the coin's center when impacting. The sound captured is crystal clear with negligible influence of noise induced by the casing.

The signal acquired in this way is digitized and then spectrally analyzed (see [8]). Sound harmonics have been found to be close to the theoretically predicted [9,10] for a metal disc. According to classical theory of vibration, the first harmonics of the vibration modes for an unsupported disc shaped plate are related to the fundamental by factors shown in Table I. In the same table we show the experimentally measured ratios for some coins (old Spanish Pesetas and Euros), which match very well with these numbers. The differences are mainly based on the minting, which separates a coin from an ideal discoid form. The positive consequence of this is that, if the spectral analysis has fine enough frequency resolution a non minted coin (legally not a fraud), can be even

distinguished from the minted one.

Bicolor coins require a separate analysis, since they are composed of a central disc embedded in a disc of different material. Modes of vibration associate separately to both pieces, but they may strongly depend on the way they are joined. It is important to note that while fundamental sound harmonic is within the audible range, high order harmonics are mostly out of this range. This is particularly true for coins of small diameter which, fortunately, tend to be of low value.

D. Impact Sensor

Impact sensing was actually designed in parallel with the acoustic sensor. This is not surprising in the sense that a "good" impact produces an optimum excitation of coin vibration modes and therefore a good sound. Therefore, an accelerometer was also placed on the internal side of the cylinder to measure the acceleration it suffers when impacted by the coin. This is also shown in Fig. 6. Again, it is mandatory that the cylinder has freedom to move in the direction of the impact, to avoid any reaction force from the casing that would affect the measurement. Also, it has to be made of a material stiffer than any possible coin (steel in our case), and it was even coated with nickel to increase surface hardness. This is required so that acceleration depends mainly on coin properties (elasticity, and mass) and not on those of the cylinder. The shape, dimensions and exact placing of the cylinder are calculated to assure that impact is on one of the coin's corners and its effective surface is about punctual. We made sure that vibration modes of the cylinder are beyond impact bandwidth [11]. Sensing the impact can be used, if needed, to time stamp the exact instant the sound commences.

The accelerometer used was a very low-cost shock sensor (from Murata PKGS family), typically used for hard-disk protection under falls or shocks, which is basically a beam of bimorph material clamped at its two ends. It is obvious that such sensor is not intended to give an accurate acceleration measurement. According to basic impact theory, the acceleration (force) history of an elastic impact follows a semi-sinusoidal shape [12-13], that is somehow distorted if there is a plastic interaction. Actually, impact bandwidth is so high that it excites sensor resonance, masking the impact form and showing a highly underdamped response, as shown in Fig. 7 (blue curve). It is therefore not surprising that this kind of sensors have been only used to detect soft (plastic) materials that are those unable to excite the resonance. In our case, we have heavily relied on signal processing techniques to extract the usable information. Some possible ways to do that, based

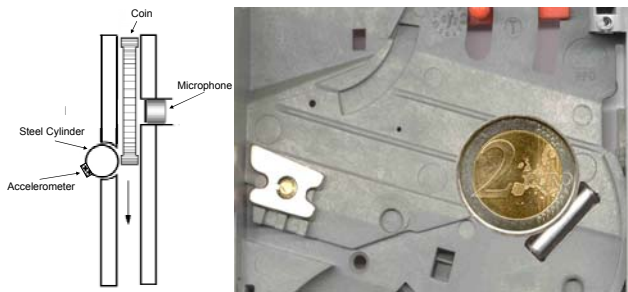


Figure 6 Cylinder and sensors (microphone and accelerometer) views

Table I- Theoretical and experimental ratios between vibration modes in discs (coins)

Ideal Factor	1,73	2,33	3,91	6,71
200 Pta	1,66	2,21		
100 Pta	1,73	2,21		
500 Pta	1,74	2,28	3,69	
500 Pta (fake)	1,63	2,25	3,63	
1 Euro	1,75	2,21		
1 Euro (cospel)		2,66	3,26	4,22
50 cents	1,74	2,27	3,67	
50 cent (cospel)	1,75	2,25		
20 cents	1,71	2,22		

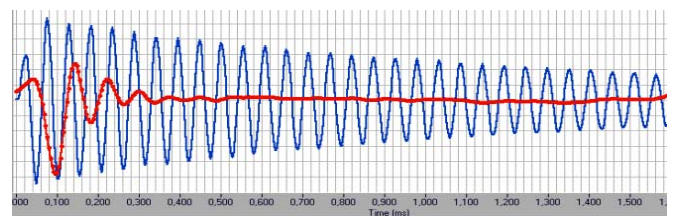


Figure 7 Impact signal from the accelerometer (blue) and its deconvolved version (red)

on deconvolving the obtained signal by a suitable model of the mechanical system, are described in [14]. No further details can be given for confidentiality reasons. In Fig. 7 (red curve) we show the result of the deconvolution process. This signal is further parameterized in a set of significant parameters to characterize every coin.

Another problem we had to face was the presence of Electro Static Discharge (ESD) which severely corrupted the signal from the accelerometer. The coin, on its way thru a plastic casing, acquires electrical charge that is transmitted to the metallic cylinder upon contact. This in turn produces a common mode signal to the sensor that makes its signal unusable. To avoid this problem, two strategies were combined: on one side proper isolation between cylinder and sensor was introduced, and on the other side a differential charge amplifier, with very high common mode charge rejection was designed [15].

As a final point it is worth to comment that in spite of the close relation between impact and sound, it was not possible to find any correlation between the information we obtain from the accelerometer and the microphone. This observation has been also made in the context of structural analysis [16].

IV. SENSOR INTEGRATION

Though, for space limitations, it is not the goal of this paper to describe how the information from all of the sensors is gathered and used to take a final decision, we would like to give some comments about the process. Basically, and for each sensor, an internal table with typical parameters for each coin and sensor is stored, together with a tolerance window. The window can be opened, by the programmer, or closed depending on the potential existence of frauds for such coin. Closing the window results in a higher rejection ratio of fake coins, but may bring together an increased number of rejected good coins. Each sensor labels the introduced coin with an unconditionally good, unconditionally fake, or dubious. A variety of algorithms to combine the information from all sensors is then possible ranging from a plain hierarchical analysis to fuzzy logic. This is the topic of a number of patents.

Another interesting aspect is that signals coming from the different sensors are acquired and, to some extent processed, in an overlapping way. Selector channel is very short, and while coins are passing thru the optic barriers, they are affected by the fields generated by the inductors, and are about to impact the cylinder. This is particularly true for high valued coins, which are obviously the most important to measure. This means that most of the relevant information is only available at the end of the running. In addition each signal bandwidth is different and so with its required sampling frequency. Therefore, a careful strategy has to be designed for the implementation, in order to properly interleave of all acquisition processes, and their subsequent processing. Moreover, and in a low-cost DSP, memory management can be an issue and it is mandatory to reduce signal records as much

as possible and erase them as soon as they are not needed.

V. CONCLUSION

This paper has described the sensorization of a coin discriminator. The emphasis has been put on showing how very low cost sensors and electronics can be combined to obtain an accurate discrimination of valid coins from their fakes. This has been accomplished by carefully considering all mechanical aspects that influence the measurement and an extensive use of signal processing techniques. The techniques here described have been implemented in the so called Modular Series (A;X or Z) fabricated and marketed worldwide by AZKOYEN MEDIOS DE PAGO S.A. [17].

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