THESIS ON INFORMATICS AND SYSTEM ENGINEERING C101

Coin Validation by Electromagnetic, Acoustic and Visual Features

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Alina Gavrijaševa

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INFORMAATIKA JA SÜSTEEMITEHNIKA C101

Mündi valideerimine elektromagnetiliste, akustiliste ja visuaalsete tunnuste järgi

ALINA GAVRIJAŠEVA

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KIRJASTUS

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LIST OF PUBLICATIONS

Listened in this section publications were presented and published to fulfill requirements for the PhD of Tallinn University of Technology.

Publications related to thesis topic, published

I. A. Gavrijaseva and O. Martens, “Image Based Counterfeit Coin Validation,“ in *Baltic Electronics Conference (BEC),* Tallinn, IEEE, 2014, pp. 153 - 156.

II. A. Gavrijaseva, O. Martens, R. Land and M. Reidla, “Coin Recognition Using Line Scan Camera,“ in *Baltic Electronics Conference,* Tallinn, IEEE, 2014, pp. 161 - 164.

III. R. Gordon, O. Märtens, R. Land, M. Min, M. Rist and A. Gavrijaseva, “Eddy-current validation of euro coins,“ in *Lecture Notes on Impedance Spectroscopy: Measurement, Modeling and Applications 3*, 2012, pp. 47 - 63.

IV. A. Gavrijaseva, A. Molder, O. Martens, C. Kyrkou and T. Theocharides, “Cross-Correlation-based Image Matching of Coins,“ in *Baltic Electronics Conference, 13th Biennial Baltic*, 2012, pp. 319 - 322.

V. O. Martens, T. Saar, A. Gavrijaseva and A. Molder, “Variable-resolution image processing for validation of coins,“ in *Intelligent Signal Processing (WISP), IEEE 7th International Symposium*, Floriana, Malta, 2011, pp. 176 - 179.

Publications related to thesis topic, accepted

VI. O. Martens, A. Gavrijaseva, R. Land and M. Min, “Simple acoustical signature based coin validation,“ in *Intelligent Signal Processing (WISP), IEEE 9th International Symposium*, Siena, Italy, 2015, May 15 - 17, 5p, accepted.

VII. A. Gavrijaseva, O. Martens and R. Land, “Acoustic Spectrum Analysis of Genuine and Counterfeit Euro Coins,“ *in Elektron. Ir Elektrotechnika*, 2015, 4p, accepted February.

Author’s contribution to the publications

Here is the list of author's contributions to the publications related to the current thesis according to the papers I - VII of the previous List of Publications.

Paper I. Development of the image based coin recognition algorithm by using optimised cross-correlation; matching pattern by extraction of the unique image segments creation (for coin recognition); optimisation of cross-correlation by created matching pattern; evaluation of diameter and thickness of the coins; extraction of symbols from edge of the coins; making of the experiments, analysis of the results; writing of the paper.

Paper II. Development, evaluation and testing of the simplified and low-cost line-scan camera based imaging algorithm for coin matching using the cross-correlation; evaluation and testing of proposed algorithm in Matlab; analysis of results: extraction of diameters of the authentic euro coins with denomination 2€, 1€, 50c and 20c in pixels; writing of the paper.

Paper III. Evaluation of described eddy current approach for coin validation; carrying out of the experiments on the authentic and counterfeit euro coin examples; analysis of the results.

Paper IV. Development and implementation of the cross-correlation based coin matching algorithm for visual recognition; experiments have been carried out on the genuine euro coins, the results of which were analysed and presented.

Paper V. Development and evaluation of the adaptively subsampled cross-correlation based algorithm for imaging solution; tests have been carried out on the genuine euro coins, the results of which were analysed and presented.

Paper VI. Carrying out of the experiments; collecting of the data, analysing and presenting of the results.

Paper VII. Carrying out of the tests on authentic and counterfeit coin metal based experiments using FFT and modal analysis; processing, analysis and presentation of the data; writing of the paper.

Author's other publications

1. O. Martens, R. Land, **A. Gavrijaseva** and A. Molder, "Adaptive-Rate Inductive Impedance Based Coin Validation", *Intelligent Signal Processing (WISP), IEEE 7th International Symposium*, 2011, Floriana, Malta, 19-21 September, pp. 122 - 125.
2. **A. Duhnik**, "Külgvaatlussonari sondeeriva signaali modelleerimine", in *Elektroonika 2003*, *X rahvusvahelise telekommunikatsioonipäeva materjalid,* Tallinna, 2003, pp. 84 - 89.
3. I. Arro, **A. Duhnik** and V. Kozevnikov, "Sidescan Sonar with high Resolution", *in: UDT Europe 2003, Conference Proceedings*, June 2003, Malmö, Sweden, pp. 23 - 25.
4. **A. Duhnik** and V. Kozhevnikov, "Formation and processing of the orthogonal sounding signals in multichannel sonars", in: *Baltic Electronics Conference,* Tallinn, IEEE, 2002, pp. 191 - 194.
5. I. Arro, **A. Duhnik** and J. Derkatsh, "Interaction of the PSK signal with a phase array", *Elektron. Ir Elektrotechnika*, Kaunas, pp. 50 - 52.

6. I. Arro, J. Derkatsh and **A. Duhnik**, “Multichannel Multibeam Sonar System“, in *UDT Europe 2002,* LaSpezia, Italy, 17 - 20 June, 2002, pp. 5.
7. V. Kozhevnikov and **A. Duhnik**, “Sonari töösageduse programne juhtimine“, in *Elektroonika 2001*, Tallinn, pp. 104 - 107.

ABBREVIATIONS

AC – Alternating Current
ANN – Artificial Neural Networks
DAQ – Data Acquisition Box
DC – Direct Current
DFT – Discrete Fourier Transform
OLAF – European Anti-Fraud Office
ECB – European Central Bank
EFSI – Estonian Forensic Science Institute
EM – Electromagnetic
EU – Europe Union
FIR – Finite Impulse Response
FFT – Fast Fourier Transform
FRF – Frequency Response Functions
GLOH – Gradient Location and Orientation Histogram method
JPG – Joint Photographic Experts Group
LoG – Laplacian of Gaussian
MS/m – Mega Siemens per Metre
ML-CPNN – Multi-Level Counter Propagation Neural Network
NI – National Instruments
PC – Personal Computer
RFP – Rational Fraction Polynomials
RGB – Red Green Blue
SIFT – Scale-Invariant Feature Transform
SURF – Speeded-Up Robust Features Transform
USB – Universal Serial Bus

INTRODUCTION

Nowadays millions of people use currency handling machines every day for various purposes. Currency handling machines are widely implemented in parking, self-services, gaming machines, public phones, markets, banks, exchange machines, money-box etc. [1-4]. Considering that industries are usually creating more efficient and cheaper products, in the typical handling machines the low-cost, fast and simple in realisation approaches have been implemented. Validation process of these machines 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. Therefore, a major part of them have limitations, such as: limited number of coins to be validated; accept tokens; does not accept new types of currencies.

In 2014 the OLAF has reported, that counterfeiting industry has estimated to have cost at least 500 million EUR in EU [5]. According to recently published by European Commission statistics, the total number of counterfeit euros withdrawn from circulation last year was about 175 900 euro coins. More than 80 classes of counterfeit euro coins and corresponding tooling and working methods have been discovered by European Technical and Scientific Centre [6].

The goal of this thesis, which has been related to the FP7-SME project “Safemetal”, and is focused on the research, development, evaluation and testing of the innovative, efficient, reasonable speed advanced applications for coin validation, recognition and classification [7]. Three various approaches: electromagnetic, acoustic and visual have been investigated during the work.

Precise, low-cost, high-speed eddy current based solution for AC conductivity measurements is applied for investigation of the metal alloys of the coins. The estimated conductivities of the euro coins are presented. FFT and optimised modal analysis are implemented for acoustic signal investigation of the metal of the coin. Sub-sampled cross-correlation and developed “pattern matching“ has been proposed, evaluated and tested in image based solution.

The corresponding solutions with practical experiments carried out on the authentic and counterfeit euro coins are described, analysed and presented.

Motivation

In EU, there are 19 euro area countries and more than 130 types of euro coins. It is clear that euro coins have the highest security features of all world currencies, but the volume of counterfeit euro coins is still growing annually.

According to EU regulation 1210/2010, the control for withdrawing of counterfeit and “unfit” coin from circulation should be provided by the national authorities [8]. “Unfit” coins are deformed and/or damaged authentic coins, physical properties of which are altered through usage, by corrosion or due to physical damage. Such coins should be discovered and withdrawn from circulation.

So, the issue of coin validation, recognition and classification is becoming critically important for every euro area country. Therefore, the output of FP7-SME has great importance for coin validation industry over EU. This dissertation was motivated by described project and contains the authors contribution to the development, evaluation and testing of the proposed solutions. The results of this work were presented in eight publications, at the following conferences: IEEE 7th International Symposium on Intelligent Signal Processing (WISP), 2011; 13th Biennial Baltic Electronics Conference, 2012; 5th International Workshop on Impedance Spectroscopy: Measurement, Modelling and Applications 3, 2012; 14th Biennial Baltic Electronics Conference, 2014. The publications are included to Appendix.

Research tasks

The idea of the doctoral thesis is to develop the secure, cost-efficient, accurate applications for euro coin validation, recognition and classification based on eddy current, acoustic wave and visual processing approaches.

The criteria of the beneficial coin validator, based on the requirements of the project FP7-SME are the following:

- Matching of the security features all coins with high accuracy;
- Counterfeit coin detection;
- Unfit coin detection;
- Low level of the computational resources;
- Real or reasonable speed of validation;
- Small dimensions of the end-device;
- Low price of the end-device;
- Programmability – opportunity for adding new coin types to the databases;
- Possibility for validation of all coin types in euro area.

The minimization of computational cost allows decreasing the price of end-device and the system components in particular. The optimization of the parameters of coin recognition and validation algorithm makes the coin validation fast and accurate.

The requirement of low price of the end-device makes it impractical to use sophisticated technologies. This means that low-cost components and sensors as well as computationally efficient methods of data processing should be employed to achieve good discrimination features and satisfy criteria mentioned above. Therefore, the implementation of the simple, smart and reasonably fast coin validation and recognition solution is highly important.

The research tasks of the dissertation are:

1) Evaluation and testing of the electrical conductivity based solution; determination of the metal alloy conductivities of all euro coins for coin validation and classification;
2) Investigation of FFT and modal analysis based acoustic coin validation, recognition and classification with high accuracy; optimization of the modal analysis parameters;
3) Feasibility study of autonomous using of acoustic method for euro coin validation and/or recognition;
4) Development, evaluation and testing of image based algorithms for authentic and counterfeit euro coin recognition, as well as authentic coin classification:
    a) Optimisation of the cross-correlation method by subsampling and pyramid methods;
    b) Design and testing of the "matching pattern" for coin recognition using cross-correlation method;
    c) Investigation of the euro coin edge for thickness measurement, pattern examination and roughness detection.

Therefore, the implementation of simple, smart with reasonable speed coin validation and recognition solution is highly important.

Overview of the thesis

This dissertation is focused on the validation, recognition and classification issue of the authentic and counterfeit coins. The introduction section of the current work contains overview of the problem, motivations and research tasks.

Chapter one gives a brief overview of the sensors, corresponding signal processing and historical remarks of the coin validation field. The description of the advantages and limitations, presented in this chapter, allows to analyse and highlight the more efficient techniques and use or test them for further developments.

Chapters 2-4 consist of the author's contribution in the euro coin validation, recognition and classification area.

In chapter two and paper [III (14)], the eddy current based AC electrical conductivity measurement for validation of the alloys of the euro coins is presented. Experiments of described approach has been carried out on the authentic and counterfeit euro coin examples, based on the simulation model and corresponding software. Evaluated conductivities of coins under test have been presented and analysed.

In chapter three and papers [VI (44), VII (15)], FFT and modal analysis based methods for investigation of the acoustic signal of euro coin metal are described. The optimisation of the modal analysis method has been proposed and tested. The experiments with FFT and modal analysis on the authentic and counterfeit euro coin examples have been carried out, results of which are submitted and analysed.

Chapter four and papers [I (87), IV (85), V (88)] present two imaging solutions for coin recognition and classification based on sub-sampled cross-correlation. In the first solution, development and implementation of the “matching pattern“ for authentic and counterfeit euro coin detection, which reduces the computational complexity of the cross-correlation significantly, is presented. Extracting of the diameter and thickness of the coin and investigation of the edge of the coin providing coin recognition and classification precisely.

In paper [II (81)] the low-cost and simple in realisation line-scan camera based solution for coin recognition by diameter has been proposed as alternative (second) approach. Proposed visual solutions have been evaluated and tested with Matlab tools. The experiments have been carried out on the authentic and counterfeit euro coins, the results of which are presented.

In chapter five, the conclusion of experimental results and analysis of proposed in chapters 2-4 solutions, novelty and future works are given.

1. SOLUTIONS IN COIN VALIDATION AREA

In this chapter the overview of specific features of all euro coins are given. The historical remarks and state of art in coin validation area are presented. Three main aspects for investigation of the features of the coins are described: electromagnetic, acoustic and visual. The main features of available commercial solutions are presented and analysed.

1.1. Key features of the euro coin

All euro coins can be distinguished by physical, electromagnetic and visual features, the description of which are presented in Table 1.

TABLE 1. Characteristics of euro coins [6].

Coin	Diameter (mm)	Thickness (mm)	Weight (g)	Colour	Edge
2€	25.75	2.20	8.5	external part white, internal part yellow	edge lettering, fine milled
1€	23.25	2.33	7.5	external part yellow, internal part white	interrupted milled
50c	24.25	2.38	7.8	yellow	fine scallops
20c	22.25	2.14	5.7	yellow	plain
10c	19.7	1.93	4.1	yellow	fine scallops
5c	21.25	1.67	3.9	red	smooth
2c	18.75	1.67	3	red	smooth with a groove
1c	16.25	1.67	2.3	red	smooth

The images of the common and national side of euro coins in circulation can be found from the ECB site [6]. In Figure 1.1, the images of euro coin edges are shown, where the coins from 2€ to 1c are shown in decreasing order from left to right accordingly.

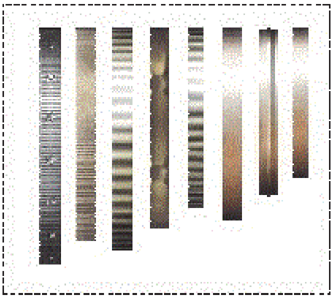


Figure 1.1. Edges of all euro coins [6].

The electromagnetic properties of euro coins are unique, because they have high-security features due to distinct composition of the alloy and so-called "sandwich" composition for 1€ and 2€ euro coins [6]:

- 1€ and 2€ coins are slightly magnetic; only the central area of these coins is magnetic. 1€ coin has a golden coloured outer ring made of an alloy called nickel brass; this is 75% copper, 20% zinc and 5% nickel. The centre is silver coloured made from nickel coated with an alloy of 75% copper and 25% nickel;
- The metal of 10c, 20c and 50c coins is special alloy (Nordic Gold), which contains 89% copper and is difficult to melt;
- Genuine 1c, 2c and 5c coins are made of copper-coated steel and are highly magnetic.

The ECB, being responsible for monitoring of detection, analysis and withdrawal of counterfeit euro coins, reports that the number of euro coins with denomination 50c, 1€ and 2€ coins in circulation (all over the EU) in 2014 was about 17 millions. In Table 2 the number of counterfeit euro coins detected in circulation all over EU is given, where the total number of counterfeit euro coins withdrawn from circulation in 2012 was about 184 000 units [6].

TABLE 2. Counterfeit euro coin detected in circulation all over EU [6].

Year	50c	1€	2€	Total	Value
2009	18 100	26 500	127 500	172 100	290 550
2010	25 100	31 000	129 700	185 800	302 950
2011	28 400	32 800	96 300	157 500	239 600
2012	32 700	29 500	121 000	183 200	288 000

According to the statistics of EFSI, the total number of counterfeit euro coins removed from circulation in Estonia in period 2011-2013 was 417 units, as presented in Table 3 [9].

TABLE 3. The number of counterfeit euro coins removed from circulation in Estonia [9].

Year	50c	1€	2€	Total
2011	1	26	77	104
2012	4	39	118	161
2013	0	21	131	152
Total	5	86	326	417

In 2014, the number removed from circulation counterfeit euro coins increases. The national bank is the only trusted institution in Estonia, who deals with removing of the counterfeit coins from the circulation. As has been reported in FP7, there are around 17 illegal mints discovered to date. There are identified more than 80 classes of counterfeit coins and corresponding tooling and working methods [7]. Some EU countries have reported that they have not appropriate coin validation and recognition equipment. These facts demonstrate the great importance of developing advanced coin validation, recognition and classification device.

The issue of counterfeit and unfit coin validation is highly important in the area where coin handling machines should be able not only to validate the denomination of various euro coins but also provide identification of euro coins from all Europe Union countries, especially at such places as airports or tourist places.

Modern validators need to determine and estimate the security features of euro coins and to ensure fast, accurate with low consumption validation, sorting and counting solution.

1.2. Coin validation: Historical and general remarks

The first simplest mechanical coin-operating machines were established in 1615 in England for tobacco dispensing. Next, in 1822 self-service newspaper dispensing machine was built. Only in 1857 the first fully automatic vending machine was patented by Simeon Denham, British Patent number 706, for stamp dispensing [10].

After 400 years of development, the modern coin validation systems are much more advanced. The evolution of coin industry has reached a great progress today due to continuous growing of the self-services area and technical progress. More and more self-service machines with new objectives are invented and implemented into human life every year. So, various types of coin handling machines are applied for special purposes: discriminating, selecting, sorting, counting, accepting, changing and wrapping. From technical point of view, systems for coin operations can be divided into three types: mechanical, electromagnetic and visual based solutions.

Mechanical validators usually provide measuring of the physical properties (Table 1) of the coin by mechanical means, for example, by having holes according to each coin diameter. Permanent magnet is the regular part of such mechanical solutions [11, 12] often. Typically, mechanical validation is applied for validation of the low denomination coins, because of high magnetic features of these coins. Since the magnetic features of 1€ and 2€ coins are low, the validation is made mainly by diameter of coin that does ensure metal and pattern matching. The limitation of such validator is low security level. Thus, implementation this method is insufficient for sophisticated modern euro coin validation.

The electromagnetic validators are analysing the properties of the coin alloy [13]. Implementation of the electromagnetic sensorics allows inducing and measuring electrical currents in the coins. Eddy current sensors are used for electrical conductivity measurements in most promising solutions for coin validation process, because of high-speed, accuracy, cost–efficiency and simplicity [III (14)]. This method uses distinct electromagnetic features of euro coins for various denomination to be differentiated. The principle of this approach is to store the electromagnetic properties of coins as validation criteria and then compare with the properties of the coin under test. In this work, the eddy current based validation solution is proposed and tested, providing discovering of special electromagnetic properties of alloys in euro coins.

It is well known, that when a coin is mechanically excited, for instance by dropping it against a hard surface, the sound it produces relates to its mechanical properties (physical dimensions, stiffness and density). Since these properties are not related to the electromagnetic properties, an acoustic measurement could be an excellent complement to the electromagnetic 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. The distinct features like natural frequencies, their amplitudes or damping ratios of acoustic signal spectra could be used for coin classification and validation [VI (44), VII (15)].

The common and/or national side of coin can be investigated using visual sensor and corresponding image processing. The great progress of the IT-technology makes it possible using of smart, reasonably fast and complicated methods/algorithms in imaging solutions. However, sophisticated methods based on image processing leads to increase of the price of the end-system, because of required computational complexity [16, 17]. The main contribution of this work is the development of the smart efficient, reasonably fast and low-cost image based algorithm for recognition and classification of euro coins.

A variety of coin discriminators have been developed and described in scientific literature and patents, where electromagnetic, physical and visual sensorics based solutions are presented. However, it has happened that some types of counterfeit and unfit for circulation euro coins are not rejected by coin-processing machine [18].

1.3. Electromagnetic sensorics

Various sizes, types, signals and configurations of EM sensors (coils) are used and often combined in the alternative solutions, which differ by shape, magnetic core types, construction, excitation frequencies and waveforms [19]. In some cases, separate transmission and reception coils are used, in contrast to use of a single coil. Also, some approaches are based on measuring either the transmitted or reflected fields resulting from presence of the coin. Eddy current sensors are used for measuring and analysis of the magnetic features of the coins, namely: conductivity, magnetic permeability, etc.

Since 1982, there are over 2000 patents that are related to coin detection, selection, control, counting and separation topic [20-24]. Electromagnetic, also commonly referred to as inductive or eddy current sensors, are usually constructed by coils encircling ferrite pot-cores, in order to boost and concentrate the magnetic flux. 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.

There are many variations for particular setup schemes, 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 summed or in "anti-phase" when the fields are subtracted from each other or in emitter-receiver mode), and the frequencies used (changing the penetration depth). The penetration depth of the signals is particularly important for the so-called bi-colour coins (having different materials in core and ring) and multilayer coins (sandwich of two materials) [25].

One of the most distinctive features of various metal alloys is electrical conductivity. So the electrical conductivity measurements of metal coins consisting of complicated alloys are widely used for coin discrimination and validations, as proposed in [26-28].

Conductivity measurements can be conducted with an utmost accuracy of better than 0.1% by using the direct current (DC) contact-method [29]. The DC method can be applied to determine the conductivity of a bulk material under stable temperature conditions.

Most of commercially available eddy current based conductivity meters are operated at frequencies up to 1 MHz. In order to provide constant accuracy of the conductivity meter readings, the devices need to be regularly calibrated. For this purpose, dedicated reference samples are used whose values of conductivity are measured either at the DC current or at the AC current with a frequency up to 100 kHz [30] with measurement uncertainties of less than 0.1% and 0.7%, respectively.

For materials with uniform properties throughout their thickness, the electrical conductivity of a conducting media does not depend on the measurement frequency. In practice, relative differences up to 0.5% between conductivity measurement results obtained by using DC and AC measurement technique are observed [31]. When this difference is not taken into account or measured, the manufacturing or inspection processes could lead to faulty decisions causing unjustified losses of resources. The output of DC measurements gives one constant value, what sometimes can be insufficient for validation due to overlapping possibility with random value of fake metal [31].

In 1968, Dodd and Deeds developed the analytical model for analysis of the impedance of the measurement coil placed above the metal plate [33]. In 1975, they published the numerical results of proposed method [34], where only active (real) part of the coil impedance (losses in the measurement coil) was considered in the calculations. In the [35] both eddy current and contact-based (ohmic) measurement theory for metal plates has been investigated and compared. More advanced numerical model for eddy current simulations has been developed and published [36]. This solution is most computationally efficient, simple and accurate.

By practical reasons, eddy current AC method is preferred due to opportunity to measure a number of parameters, which are investigated experimentally and used for matching with pre-defined tolerance. Typically, the AC conductivity is measured at frequencies 60, 120, 240 and 480 kHz that enables tracking the dynamic behaviour of metal alloy properties.

Modern conductivity meters operating are based on the eddy current method. The measurement of electrical conductivity using eddy current (electromagnetic induction) sensors is the most promising solution for validation of metal coins in coin handling devices, as the electrical conductivity is a very distinctive property of specific alloys. Low cost, simple and robust by nature, and also possibility for high-speed precise measurements are the advantages of electromagnetic sensors. Multi-frequency scanning of the coins under test at various field penetration depths is preferred due to the sophisticated "construction" of various alloys in nowadays coins. Air-core measurement coils have an additional advantage – a possibility to measure absolute values of conductivity without repetitive calibration of sensors and the measurement systems [19].

Principle of electromagnetic air-coil model

As it was noted above, the air-core coil implementation is beneficial solution for the alloy conductivity measurements. The principle of this method is illustrated in Figure 1.2. The penetration depth of eddy currents (or thickness of the measured layer) depends on the operating frequency of the measurement device. Accurately characterised standards can be needed because the procedure typically provides a comparative, rather than absolute value measurement [37].

These simulations are valid for the air-core coil based conductivity measurements with "infinite" size of metal plates, consisting of one or several metal layers. The "infinite" size is typically not very significant constraint for real-life measurements, as the eddy current electro-magnetic fields are decreasing quickly in the media. Only a few millimetres larger metal plate than the size of the sensor is typically enough to have reasonably precise results [III (14)].

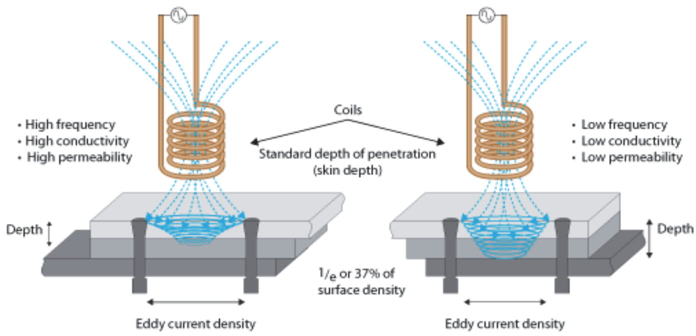


Figure 1.2. Eddy current conductivity measurement principle [31].

Electrical conductivity measurements are also employed for production and inspection of finished goods. Usually, manufacture of the coins-mints use conductivity meters at two frequencies, namely 120 and 480 kHz.

Mathematical modelling

Work of Dodd and Deeds (1968) [33] is the basis for a number of next works, simulation and software for eddy current modelling. As cited, in this work: “Solutions have been obtained for axially symmetric eddy current problems in two configurations of wide applicability. In both cases, the eddy currents are assumed to be produced by a circular coil of rectangular cross section, driven by a constant amplitude alternating current”.

This solution is provided for the configuration for a coil above a semi-infinite conducting slab with a plane surface, covered with a uniform layer of another material. This solution includes the special cases of a coil above a single infinite plane conductor or above a sheet of finite thickness, as well as the case of one metal clad on another. The solutions are in the form of integrals of first-order Bessel functions giving the vector potential, from which the other electromagnetic quantities of interest can be obtained. The coil impedance has been calculated for the case of a coil above a two-conductor plane.

One version of a numerical solution of this work has been realised [34] as software in the BASIC programming language. Only the real part (active loss and real impedance from this) of the probe-coil impedance is calculated by this programme. A more advanced simulator, TEDDY, having several options and a good graphical user interface has been developed by prof. Theodoulidis [35].

Thus, described air-core model combined with Dodd-Deeds mathematical computations provides the advantageous solution for electromagnetic conductivity measurements of coin alloy.

1.4. Acoustic sensorics implementation for coin recognition

Alternative way for examination of the coin alloy is applying of the acoustic sensor with corresponding signal processing. The characteristics of the acoustic signal like natural frequencies and corresponding amplitudes could be investigated for this reason. The various alloys of metal and the varying hardness properties produce a special vibration spectrum on impact, which could be used for discrimination of coins of various denominations. Taking into account that the acoustic signal of each euro coin is unique, due to sophisticated metal alloy, it is possible to match and validate coin with various denominations by its acoustic signal by signal spectrum analysis techniques [38]. The main idea of the acoustic coin validation is to detect and store the acoustic vibrations of coin after kick against the specified surface by microphone. The acoustic signal of each coin denomination has own unique time-frequency domain features. Therefore, after signal spectrum analysis and comparison of the extracted features, the coin is classified or rejected.

In 1991, was published the patent, where the FFT based spectrum analysis method for coin validation was presented, with the main idea of which was to calculate the standard deviation of the locations of the six peaks in the signal spectrum to classify the coins. Described method allows to determine the authentication of the coin and to specify the denomination [38].

Acoustic approaches examine the sound and vibration of the coin whilst either falling or rolling. The acoustic response will depend on the construction, trajectory of falling and geometry of the coin. Typically, this kind of sensorics is useful for detecting frauds made out of softer materials (e.g., lead or tin alloys) which, if combined in certain proportions, can replicate certain electrical and magnetic properties of legal tender coins [40].

The invention [41] is related to the coin validation using acoustic measurement of coin impact upon an impact member. The vibrations of the impact element have been stored and analysed. The various alloys of metal produce various vibration spectrum on the impact, which could be used for coin classification.

The acoustic signal based solution, described by [VII (15)], is illustrated in Figure 1.3, where a floating cylinder is located on one of the walls at the end of the ramp, and is perpendicular to the movement of the coin. The cylinder stands partially out from the wall, and has one degree of freedom in such a way that it retracts 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 to centre of the coin when influencing.

Typically, the spectrum of acquired signal is analysed. Sound harmonics have been found to be close to the theoretically predicted for a metal disc. Coin under test is accepted or rejected by results of comparison with reference spectra. Counterfeit coin could be distinguished from authentic one if the spectral analysis has good enough frequency resolution [42].

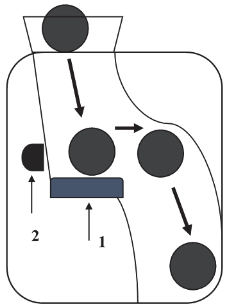


Figure 1.3. Device used for coin acoustic signal capturing, where 1 is metal plate and 2 is microphone [VII (15)].

FFT of the acoustic signal spectrum

The FFT is widely used for signal spectrum investigation, in particular, to characterize the magnitude, frequency and phase of a signal. The acoustic waveform can be represented in the frequency domain as a pair of amplitude and phase values at each component frequency [42, 43]. FFT allows analysing the spectrum of a whole signal or some part of it. The frequency resolution of FFT directly depends on relationship of FFT size and sampling rate of input signal. Thus, the bigger is the size of FFT, the higher is resolution. In the same time, big size of FFT means growth of computational level that should be avoided. So, only applying of optimal FFT parameters provide accurate and reasonable fast frequency spectrum analysis [VI (44)].

Modal analysis of the acoustic signal spectrum

Another way to evaluate the frequency spectrum and extract the properties of the acoustic signal is the implementation of modal analysis. Essentially, it is the analysis of vibration modes of the signal and is applied for testing of the vibrations of cars, airplanes, wind turbines and has many other applications. The investigation of the dynamic behaviour (vibration characteristics) of the signal by modal analysis based on time and/or frequency domain is widely used in industry [45]. The analysis by using frequency domain is preferred for coin detection, as this allows to identify the important modal parameters: natural frequencies, damping ratios and mode shapes [46] in relatively simple way. In this thesis, it is proposed to apply this method to research the vibration of falling coin.

Modal analysis measures and analysis the dynamic response during vibration, where the natural frequencies, damping ratio, magnitude modal constant and phase modal constant of every signal are calculated (Figure 1.4) [VI, 44].

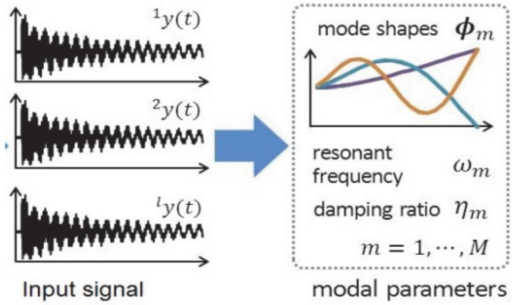


Figure 1.4. Schematic representation of modal analysis [47].

The natural frequency is the frequency at which any excitation produces an expanded response. The damping ratio is dimensionless measure, which describes decays after the impact.

Two ways exist for modal parameters calculation:

1. Based on knowledge of the structural matrixes;
2. Experimental modal analysis based on system response.

The system response can be measured in the time domain (acceleration) as well as in the frequency domain by FRF. The possibility of improving of identification techniques made FRF more popular. The algorithm of modal analysis with the description and equations of which are presented in tutorial [48].

The crucial issue of modal analysis is to have a correct selection of model order, which is related to the number of degree-of-freedom (modes). In the case if the model order is higher than the actual one presented in the data, the result of computational modes will be random (not from dynamic system properties) [49, 50]. To solve this issue the value of degree-of-freedom should be organised in ascending of the model order. All outputs are combined in one single diagram called the stabilisation diagram, where in the horizontal axis is the pole frequency and in vertical axis is the model order [51].

Typically, modal analysis is very computation expensive technique. So, in this thesis the optimisation of modal analysis by decreasing the number of degree-of-freedom is proposed and investigated.

1.5. Visual sensorics

The main issue of the object detection and recognition process is extracting and locating of the unique features or regions of interest accurately and reliably. Variety of the object recognition techniques are existing for finding, detecting and identifying the boundaries of objects from particular image. Extracting meaningful boundaries or regions from image with great accuracy ensures precise object recognition. The classification and evaluation of the extracted features by their importance and definition of the optimal number of the features have direct influence to the speed and robustness of the algorithm. Thus, the variety of object detection techniques could be evaluated and compared [52].

Regarding to the methods used for coin recognition, such approaches can be divided to two types: the rotation invariant feature extraction based and methods using the registration. Invariant features based methods for object recognition can use neural networks, Bayesian networks or other classifiers.

The registration can be a combined algorithm or use a single technique like FFT, DCT, edge detectors, corner detectors, feature descriptors methods, gradient, Canny edge detector, standard Hough line transform, convolution, correlation etc., extracting unique features from the images. Then the comparison of template and real time images is usually implemented. Correlation and convolution are basic methods to extract information from images, but these approaches are computationally expensive. The improvement and optimization of the correlation function provide to decrease computations. The corner detectors are rotation-invariant. It is considered, that the corner detector based features are more stable features over changes of viewpoint [53-57].

A rotation invariant ANN have been extensively used for various purposes, due to their ability to almost fully exploit the parallelism of some available highly flexible hardware devices. Various structures of rotation invariant neural network has been proposed, tested and compared [58-64].

In the paper [65] a neural network system for recognition of Japanese coins is presented. The following features are extracted: colour, radius, the centre of the coin and pattern. The successful coin recognition has been achieved in overall 99.4% level with rotated coins by single degrees. The drawback of this approach is, that it is computationally expensive and that it is not clear how the rejection of the coin should be expressed. In [66] it is described a fast and reliable coin recognition system based on gradient directions. Another paper proposed by Reisert et al. in 2011 describes the coin recognition technique based completely on the direction of the gradient vectors [67]. Here the results of the discretizing the gradient directions of two coins the FFT Transform have been used for comparison.

In 2011 the coin recognition with combined methods: Robert's edge detection, LoG edge detection method, Canny edge detection method and ML-CPNN has been proposed and tested in Matlab [25]. The gray level of image has been used. In addition, the image is resized, cropped and rotated for better recognition. The results of the implementation of these methods are as follows: the Robert's edge detection method gives 93% of accuracy and LoG method 95% of the result, the Canny edge detection method yields 97.25% result and the ML-CPNN approach yields 99.47% of recognition rate.

Canny edge detection algorithm is more costly in comparing to Sobel, Prewitt and Robert's operator, but has a better performance. Evaluation of the images showed that under noisy conditions Canny, LoG, Robert, Prewitt, Sobel exhibit better performance, respectively [68-72].

The Hough transform can be used to determine the radius of the coins in the coin detection approach for Android phones, as presented in [73]. Here the thresholding of grey scale image, binary mask, Hough transform and SIFT matching are implemented for coin recognition and counting with reasonably high accuracy and speed. The limitations of this technique is that the background colour should be significantly different from the colour of the coin under test.

In [74] Dagobert describes the coin recognition and sorting system based on the pattern recognition, where a short list of interesting objects is created for coin examination. In [75] it was developed a coin recognition and sorting system, where the main feature is the classification of the large number of modern coins from 30 various countries. The classification is achieved by correlating the image under test and the pre-selected template image. Preselection has been done by diameter and thickness of the coin, and three rotation invariant features, namely: edge angle distribution, edge distance distribution and various rotation invariant patterns are used. The experiments have been performed on 12,949 coins, where 99.24% positive recognition rate was achieved.

The corner detectors, like Moravec, Harris, Shi and Tomasi are specified to find intuitively the corners as junctions of contours in the image [76]. The Harris corner detector is a mathematical way to determine the large variations as analysis windows are moved in any direction. A score criteria is associated with each window and provide to figure out which ones are corners and which ones are not. Shi and Tomasi corner detector uses various score criteria and, as claimed the experimental result, having much better performance, compared with Harris Corner Detector method.

The advantages of complicated algorithms for object recognition, like SIFT, SURF, GLOH are clear, as being scale, rotation, illumination and viewpoint invariant [66, 77, 78]. The listed features with the extracted keypoints could be detected if reference image is rescaled, or illumination is changed, or image is noisy and even if the image is rotated. The experimental results of SIFT approach show very good result of object recognition. Typically for image with dimensions 500 x 500 pixels about 2000 features will be generated, being stored in the databases. Due to the huge number of keypoints to be extracted, the application of this algorithm needs much computing power and high performance technologies increasing the price of end-device. This method could be very useful in coin recognition and classification approach, but it is not suitable for counterfeit or unfit coin detection. The reason is - it matches similarities, which will occur in unfit coin matching, but does not discover the dissimilarities.

Thus, these methods are eliminated from good candidates for counterfeit coin detection. The location of detected keypoints is determined by measurements of their stability. The disadvantage of variably transforms is the high computational cost, moreover a reduction in the number of key points leads to poorer stability.

In the most visual based coin recognition and validation methods the similarity of two coin with the same denomination images is calculated by combining various techniques. In counterfeit and unfit coin detection the goal is opposite, namely, it is crucially important to detect mismatches of coin under test and reference one. Correlation method is good solution satisfying the requirements.

Correlation and cross-correlation in coin recognition

The basic technique for image matching is correlation, which is widely used in various applications to measure similarity. The purpose of this technique is to highlight peculiar properties of the image at each pixel and extract to singular features. It is computationally expensive method. Several solutions have been described for object recognition by template matching based on correlation. The extremely significant feature of correlation is the opportunity to find the locations in an image that are similar to a template. The sliding window with the specified region is applied to the template image looking for location with overlapping area, where the values of template coincides with values of specified region. The similarity between specified region and template is usually measured by the correlation filter output values. Correlation of the similar or near to similar regions are much greater than other results of correlation [79-84].

A correlation describes the degree of relationship between two variables, which can be computed by equation from tutorial [43]:

$$Correlation = \sum \left(\frac{x_i-\bar{x}}{\sigma_x}\right)\left(\frac{y_i-\bar{y}}{\sigma_y}\right), \tag{1.1}$$

where x_i and y_i are numbers in pixels, $\sigma_{x,y}$ is standard deviation.

For image based template matching of 2D matrix X with dimensions M x N and H with dimensions P x Q, the correlation function is usually applied, the equation of which is:

$$Correlation(k,l) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} X(m,n)H(m-k,n-1)\ , \tag{1.2}$$

where

$$-(P-1) \le k \le M-1,$$
$$-(Q-1) \le l \le N-1.$$

One more convenience of correlation is local averaging or smoothing feature, what is very important for image processing because extra average filtering is avoided. Additionally it does not depend to the dimensions of image.

In the same time if the brightness, exposure conditions, dimensions of two images are equal, the cross-correlation shows similarity on the one hand (if the output of correlation is high) and mismatch on the other (if the output is small).

Taking into account, the increasing volume of counterfeit and unfit coins in EU, the visual approach becomes extremely important due to several aspects:

- Precise determining of the diameter and thickness;
- Pattern recognition combined with pyramid method allow to decrease the computational cost;
- Investigation of the coin pattern, edge contour (should be smooth) and texture;
- Correlation function provide estimation of the full image;

1.6. Combined sensors

A number of combined methods are proposed to satisfy the coin validation criteria and tasks. Frequently electromagnetic method is used in combination with other (acoustic, imaging) sensors and corresponding signal processing [25].

In conjunction with other visual processing and multimode sensors, the acoustic sensors are applied in the commercial vending service machines. The combination of various technical solutions, based on acoustic sensor, multimode sensor and visual processing, makes vending machines fast, accurate, robust and sensitive to counterfeit coins [1-4].

Image processing combined with electromagnetic and acoustic sensors is an efficient method for coin recognition and validation. While electromagnetic (eddy current) sensors can allow relatively simple, precise and efficient solution, still some different coins (worldwide) can have similar electrical or magnetic properties, and so image processing-based solutions can have their place [11].

If validators are configured to accept coins having a wide range of variations, the risk of accepting non-genuine coins, which may have an overlap of parameters with a genuine coin, increases. These considerations indicate that therefore it is important that each of the relevant characteristics be specified in as much in details as possible and those tolerances be as tight as possible in the minting process. The enforcement of quality controls is also key to make sure that coins that do not match the specification and tolerances are discarded.

1.7. Commercial solutions

Market trends drive the need to improve the design and process of verification and validation. Today manufacturers provide a great opportunity to choose coin handling machine according to the application. The reason is that coin validators could be implemented in very different approaches from soda machines to coin counters/sorters in the bank. Thus the specification of validator, namely: requirements, properties, physical characteristics strongly depend on the application where it should be implemented.

Implemented in coin handling machines methods and technologies are usually confidential and only brief summary is available. The speed of handling and validation, capacity, the number of coin denomination that can be accepted, and the flexibility of program, play an important role and influences the end-price of the coin validator are important features presented by manufacturer. The classic version is: the better are the properties of coin validator, the higher is the price.

In Table 4, the features and price of devices from various manufacturers are presented.

TABLE 4. Coin validators

Nr.	Manufacturer, type	Device properties	Type of coin	Speed / coins per minute	Capacity (number of handled)	Price
1	Safescan 1200 [1]	counter / sorter add function	euro	220	500	199€ excl. VAT
2	Safescan 1550	counter / sorter	all currencies	2300	5000	599€ excl. VAT
3	Guobang, China, GB-860 [2]	counter / sorter	euro	500-800	1000	100 – 120€ *
4	Thomas Automatics [3]	validator	euro	216	300-500	-
5	Azkoyen Group, L66S [4]	validator	euro (32)	One by one		85€ *

*The price of 85€ for L66S Azkoyen Validator is relevant if order quantity is more than 10 pieces.

In the properties of the devices 1, 2 and 3 (Table 4) is described as only "counter and/or sorter", that means the function of detecting of the counterfeit coins is not implemented. Moreover, the price of the counters 1 and 2 is high for wide use of these devices.

Devices 4 and 5 are coin validators, the technical characteristics of which are given below.

Desktop coin counting and sorting machine PELICAN 309 S+ by Thomas Automatics, as shown on Figure 1.5, has higher speed, lower noise level and more options in comparison with the previous generation of coin counters produced by the same manufacturer.

Figure 1.5. Coin counting and sorting machine PELICAN 309 S+ [3].

The presented features of this device are as follows:

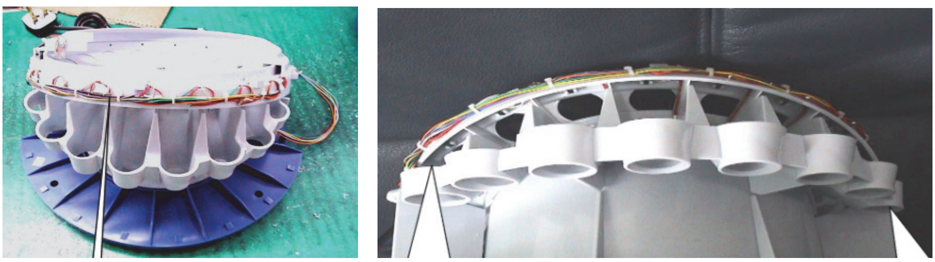
- Speed: Up to 1100 coins/minute;
- Non-sorting or sorting of up to 9 coin denominations;
- Counting of up to 20 different coin denominations;
- Rejection of foreign coins, counterfeit coins, tokens etc.;
- Programmable bag stop (by number or weight);

Due to international traveling of people, the euro currencies are mixed. So, counting of only 20 coin denominations from 130 coin types is the significant limitation of this device.

Another automatic coin counter and sorter device MUSTANG 450 proposed by Thomas Automatics, demonstrated in Figure 1.6, has LCD display, memory function and easy to use control panel.

Figure 1.6. Coin counter and sorter device MUSTANG 450 [3].

The inner structure of sorting machine, as shown in Figures 1.7a and 1.7b, demonstrates that combined methods are used for coin validation in this device.



a) b)

Figure 1.7. Inner structure of MUSTANG 450 [3].

The features of MUSTANG 450 are as follows:

- Counting speed: 216 pcs/min;
- Power source: 230 V/50 Hz;
- Power consumption: max 45 W;
- Work temperature: 0 °C – 40 °C;
- Humidity: 30% to 80%;
- Hopper Capacity: 300 – 500 pcs.

In this validator the physical and magnetic characteristics of coins are tested, next coins are sorted. The eight holes for each coin are used to separate various coin denomination. Infrared radial diodes are located near every hole to determine the coin with what denomination has been inserted. This approach has limited accuracy: the token with similar magnetic features will be accepted. Information about counterfeit coins is not available.

The Azkoyen Group has been started manufacturing in 1945 in Spain for agricultural sector [5]. The validators have different target groups and involve three combined coin measurement and recognition methods to maximize coin acceptance and counterfeit coin rejection systems: sound inspection, multimode sensors and visual processing. MODULAR X8 & P8 is one of the presented by Azkoyen Group validator. The features and working conditions presented by manufacturer are following:

- Coin Acceptance: 32 (token acceptance: 2);
- Coin diameters: 16.25 mm - 32.5 mm;
- Thickness: 1.2 mm - 3.3 mm;
- Working Temperature: +5 ºC to +55 ºC;
- Relative Humidity (without condensation): 95%.

The disadvantage of this device is validation of 32 coin denominations of 130 coin types.

To conclude this chapter, no one of the presented validation systems is able to validate all 130 types of euro coins with reasonable speed and accuracy.

1.8. Summary

In this chapter, beneficial methods based on electromagnetic, acoustic and visual features of the euro coin that could be used for validation, recognition and classification have been described.

Eddy current based air-coil model for the electrical conductivity measurements of the coin alloy using Dodd-Deeds mathematical model has been proposed. Dodd-Deeds eddy current EM model is a beneficial and a simple method for alloy validation of the euro coins by conductivity evaluation. Therefore, this method has been implemented and evaluated for electrical conductivity calculations in the current work.

FFT and modal analysis is proposed for acoustic or vibration based coin validation. Both methods have been evaluated, implemented and optimal parameters discovered in this work. The results carried out on genuine and counterfeit euro coins are presented and analysed.

The cross-correlation technique is preferred for coin recognition. With respect to the euro coin validation area, the intensity of images to be recognised could be pre-conditioned for more reliable results.

These three aspects (electromagnetic, acoustic and visual) provide evaluation of all distinctive features euro coins.

2. EDDY-CURRENT EURO COIN VALIDATION

In this chapter the description of the eddy current Dodd-Deeds and Theodoulidis model based an inverse simulation model is presented [III (14)]. During the experiments, wide range electrical conductivities of the Nordic Gold plate (80 x 80 x 3 mm), samples of all authentic euro coins and three types of the counterfeit 2€ coin examples are evaluated. The examples of the counterfeit euro coins under test are presented in this chapter.

Counterfeit euro coins under test

Three types of various counterfeit classes, provided by EFSI, were used for experiments. In Table 5 the images of the counterfeit 2€ samples are presented. The national sides of presented coins refer to countries: Belgium, Germany and Italy.

Table 5. Overview of counterfeit 2€ coins used in experiments.

Country	Common side of coin	National side of coin
Belgium		

Germany		
Italy		

In this chapter, the electrical conductivities of the counterfeit coin examples will be evaluated and compared to conductivities of the authentic coins.

2.1. Description of the test-setup for eddy current coin validation

Team of researchers from Tallinn University of Technology has developed the eddy current based coil (actually array of 5 similar coils) for electrical AC conductivity measurements by the air-core model [III (14)]. There are 5 coils on the board, initially designed for the dynamic measurement of the coil-coin impedance. For conductivity evaluation, coin under test could be set on the centre of plate, as shown in Figure 2.1 (black cross).

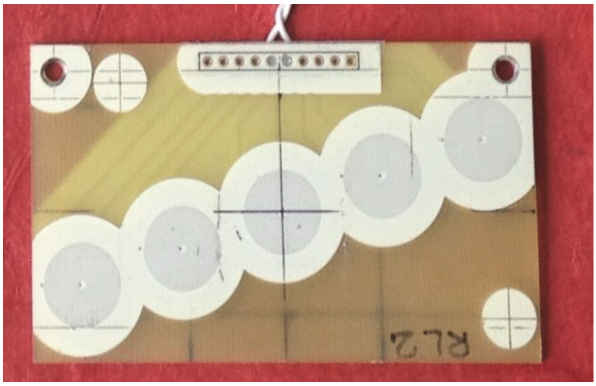


Figure 2.1. Developed coil for the electrical conductivity evaluation of coin alloy [III (14)].

The theoretical models consider zero-level real component of the impedance of the coil “in air”, the real world “in air” resistance of the coils (e.g. $r_0 = 7.4\ \Omega$ for coil at the centre of plate at the room temperature) is subtracted from the measured results before their using in the models [III (14)].

The functional block diagram of the proposed solution for measurements is presented in Figure 2.2 and consists of the developed coil, which is connected to NI high-accuracy 18-bit multifunction DAQ by NI connector block SCB-68.

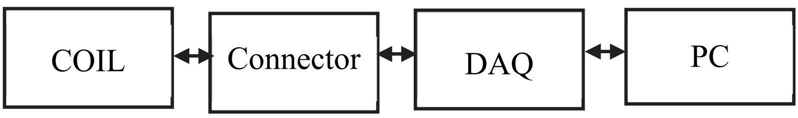


Figure 2.2. Block diagram of proposed eddy current based setup.

Figure 2.3 shows principle of the coil impedance measurement with proposed experimental setup, where the generator of the harmonic excitation signal (*G*) and two vector-voltmeters (U_G and U_L) are implemented by DAQ hardware and corresponding PC software. Resistor (*R*) and measurement coil (*L*) form the voltage divider, from which transfer function the complex impedance (*Z*) of (*L*) can be calculated.

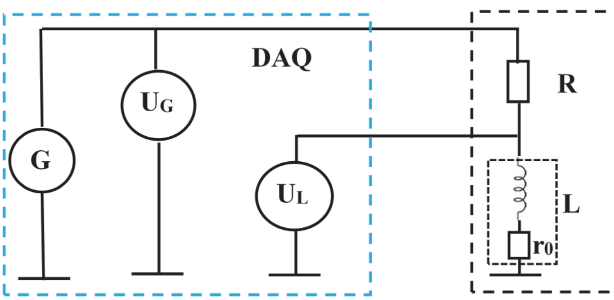


Figure 2.3. Functional diagram of the proposed setup.

Realised practical setup is connected to PC by USB, as shown in Figure 2.4, where resistance (current shunt) R = 213 Ω is added to the NI DAQ box.

Figure 2.4. Working setup for conductivity evaluation.

In this setup, the current through the coil and voltage across the coil were measured for impedance calculation. According to displayed system diagram, where U_G is the excitation voltage, the complex transfer coefficient K of the voltage divider is calculated by equation:

$$K = \frac{U_L}{U_G}, \tag{2.1}$$

U_L is the complex voltage drop on the coil:

$$K = \frac{Z_L}{R+Z_L}. \tag{2.2}$$

From equations (2.1) and (2.2) the complex impedance of the coil Z_L could be calculated:

$$Z_L = \frac{R}{(U_G/U_L)-1}. \tag{2.3}$$

According to the Dodd-Deeds theoretical model, the conductivity of the coin under test is evaluated from the difference of the coil complex impedance, measured “in air“ and with coin “above the (sensor-) coil”. An inverse simulation model is evaluated in C/C++ software for iterative finding of the best match for lift-off and conductivity of the metal alloy under test.

2.2. Eddy current experiments of coin validation

Practical implementation of the forward and reverse (conductivity calculation from coil impedance) by Dodd-Deeds model has been done by other members of research group. This approach is implemented in C/C++, with ECLIPSE CDT tools. The Dodd-Deeds model needs as input also the coil parameters (geometry, number of turns) and thickness of the measured coin. The relative magnetic permeability of the alloys has been not taken into account in the current work, to keep the model simple.

The conductivity of Nordic Gold is known and has a range 9.65 - 9.9 MS/m. The comparison of measured conductivity of Nordic Gold with pre-known values allows to estimate validation accuracy of metal using this method.

The selected test frequencies are 30, 60, 120, 240, 360 and 480 kHz. The frequency of 480 kHz is applied for measurements of the thinner central portion of 1€ and 2€ coins. The conductivities of the euro coins under test have been measured and computed two times at each frequency. In conductivity calculations the following thicknesses of the coins are used: 2.2 mm for 50c and 2.38 mm for 2€ (real and counterfeit).

At first, test was carried out on Nordic Gold plate to compare the theoretical conductivity value with conductivity measured and calculated in experimental way. The coil impedance in the air is measured first. Then the coin or metal plate is placed on the centre of the PCB based coil to measure again the coil impedance. Here it is important to put the metal to be explored in the right place because it influences the results. Then the electrical conductivity is computed from the coil impedance difference in the air and at the metal [35].

The experiments were carried out several times, stored and analysed. In Figure 2.5, the averaged conductivity of the Nordic Gold plate is presented.

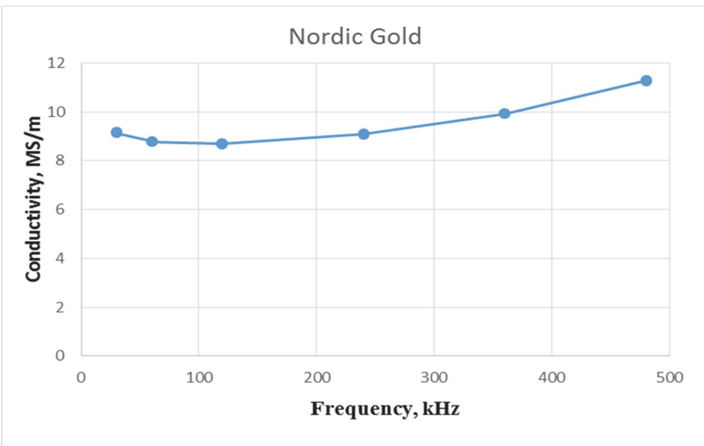


Figure 2.5. Evaluated conductivities of the Nordic Gold.

The evaluated range of conductivities, which is 8.6 MS/m - 11.2 MS/m, was compared to pre-known conductivity:

- In the highest frequencies the maximum deviation (tolerance) of experimental result with comparison to the Nordic Gold conductivity is 14%, what is within the allowable limit.
- The conductivities at central frequencies are the same.

Experiment with Nordic Gold plate shows the high accuracy of metal alloy conductivity evaluation.

10c, 20c and 50c coins are made of the same metal alloy (Nordic Gold). So, conductivities of those coins should be very similar. The impedances of these coins were measured 12 times, and then corresponding electrical conductivities were computed. This experiment was carried out for both side of the coin, and then the average conductivity value for every frequency was found. In Figure 2.6, there are shown evaluated conductivities of 50c, 20c and 10c coins compared to the Nordic Gold.

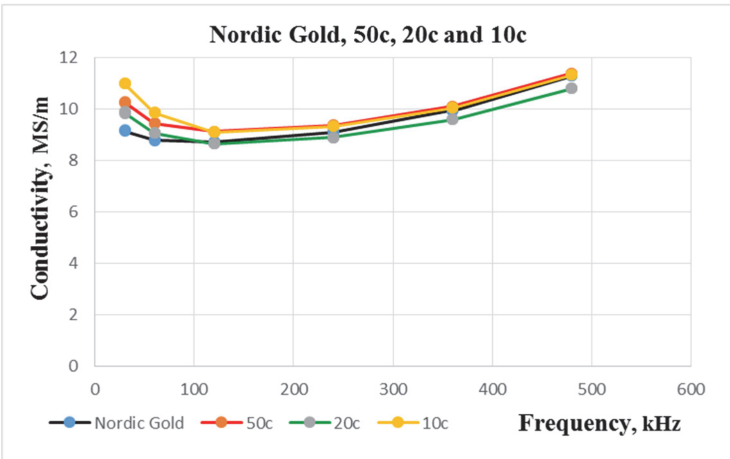


Figure 2.6. Evaluated conductivities of Nordic Gold, 50c, 20c and 10c coins.

As could be noted, the highest accuracy of measurements is achieved at frequencies 120, 240 and 360 kHz, where the maximum deviation is about 4% (50c at 120 kHz).

Figure 2.7 presents evaluated conductivities of 1€ and 2€ coin metal at multiple frequencies.

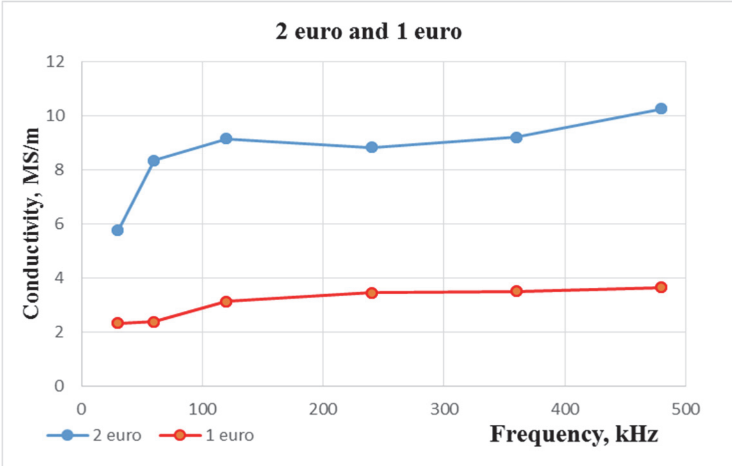


Figure 2.7. Conductivities of 2€ and 1€ coins metal.

Since the central part of 1€ and 2€ coin alloys consist of different metal, the results of evaluated conductivities are dissimilar.

Coins with dimension 5c, 2c and 1c coin are made for the same metal alloy, have same thickness but different diameters. In Figure 2.8, evaluated conductivities of the 5c, 2c and 1c coin examples are presented.

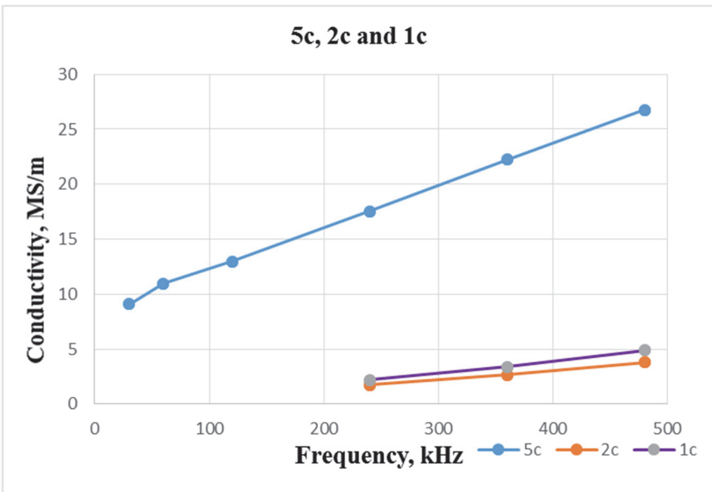


Figure 2.8. Evaluated conductivities of the 5c, 2c and 1c coins.

As could be noted, the conductivities of 2c and 1c coin examples were not estimated on the frequencies 30 to 120 kHz due to limitation of the setup and the model.

The experiments with counterfeit 2€ coin examples have been carried out in the similar way. Figure 2.9 presents conductivities of the counterfeit 2€ coin (Germany), the measured range of which is 2 MS/m - 1.8 MS/m.

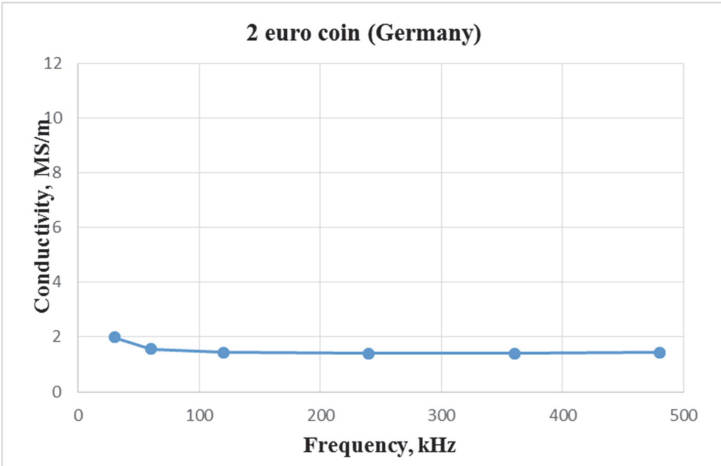


Figure 2.9. Evaluated conductivities of the counterfeit 2€ coin (Germany).

Figure 2.10 presents conductivities of the counterfeit coin (Italy), the range of which is 3.8 MS/m - 8.1 MS/m.

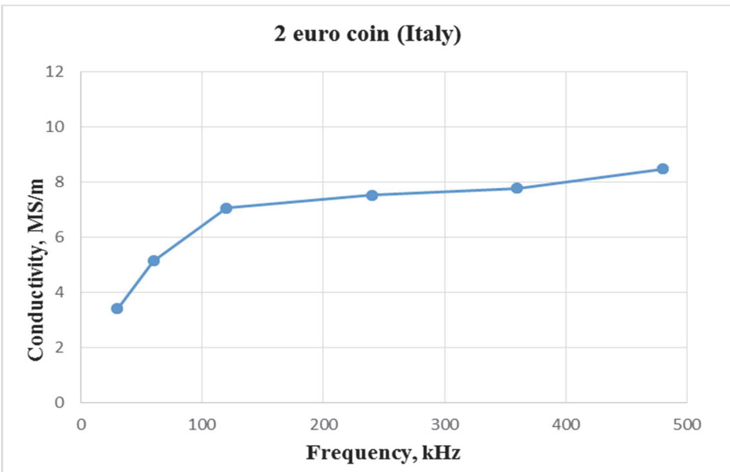


Figure 2.10. Evaluated conductivities of the counterfeit 2€ coin (Italy).

The conductivity of the counterfeit 2€ (Belgium) coin is out of the range and could not be calculated due to incompatibility of the parameters.

So, evaluated conductivities of the coins under test are presented in the Table 6.

Table 6. Evaluated conductivities of the authentic and counterfeit euro coins.

Coin or metal	**Conductivity (30-480 kHz), MS/m**
Nordic Gold	9.18 – 11.28
50c	9.3 – 11.37
20c	8.8 – 10.8
10c	9.1 – 11.3
1€	2.3 – 3.6
2€	5.7 – 10.2
5c	9.1 – 26.7
Counterfeit-G, 2€	2 – 1.8
Counterfeit-I, 2€	3.8 – 8.1
Counterfeit-B, 2€	out of range

The calculated conductivities of the Nordic Gold differ from the conductivities of 50c coin for about 1% what is in tolerance.

The conductivities of the metals of all counterfeit coins are different from each other and from the genuine 2€ coin.

Output of the experiments shows that the set of conductivity values (using multi-frequency approach) is unique. Thus, the conductivity of the authentic euro coin can be used as the reference value for coin metal validation and coin recognition.

Achieved AC conductivity values ensure accurate recognition as well as classification of euro coins. Thereby, results of the demonstrated solution provide the detection of the counterfeit and validate/classify authentic coins with high accuracy.

2.3. Summary

In this chapter, experimental tests based on proposed electromagnetic solution, using Dodd-Deeds eddy current method, combined with developed coil, have been carried out and analysed. Results of the experiments show that all authentic euro coins under test were validated correct and fast. All counterfeit coins were rejected, because the evaluated conductivities differ significantly from conductivities of the authentic coins, one was even out of range.

The magnetic permeability of coins affects the conductivity evaluation of the coins. Very precise results of the conductivity measurements are achieved by testing 50c, 20c and 10c coins, because they are not magnetic.

1€ and 2€ coins are slightly magnetic and affect measurements of conductivity slightly. Therefore, the results will have systematic deviation (shift) from correct value.

5c, 2c and 1c coins are strongly magnetic; the deviation of the measured conductivities is larger.

Due to fact that conductivity value is the same in constant conditions, evaluated conductivities of these coins (with the similar error) could be considered as reference values.

The difference of the conductivities of coins with different denomination is large enough to claim that this method ensures validation of the metal with high accuracy. Moreover, experimental measurements provide discrimination of euro coins fast and accurate due to unique alloy of the metal.

Obtained results of the experiments show that proposed eddy current solution is efficient for euro coin validation and recognition, as well as for counterfeit coin detection.

3. ACOUSTIC EURO COIN VALIDATION

In this chapter, the acoustic signal processing for validation of euro coins is investigated by spectral and modal analysis. In addition, the parameters of modal analysis methods are optimized. The experiments have been carried out on the authentic and counterfeit euro coins. The results are presented and compared [VI (44), VII (15)].

3.1. Setup for acoustic signal analysis

Setup for analysis of the coin acoustic signals is demonstrated in Figure 3.1 (left), which consists of the coin validation box with integrated microphone and oscilloscope.

Figure 3.1. Setup used for acoustic signal capturing (left), acoustic signal of euro coin on the oscilloscope screen (right).

Coin under test is inserted into the chute, where then it drops against a hard surface. The acoustic signal that is inserted into the box of the coin, is displayed on the oscilloscope (Figure 3.1 (right)). The acoustic signal is stored to the data file and analysed later. Sampling rate of the oscilloscope is 1 MSa/s, the length of the stored signal is 500 ms, in total 500 000 samples.

3.2. Experiments with acoustic signals of genuine coins

To reduce the original sample rate and minimise the influence of the noise and distortion, the acoustic signal is decimated by factor 10 using FIR filter, what decreases the computational cost in 10 times [VII (15)]. Therefore, the decimated acoustic signal under tests contains 50 000 numbers of points.

Next, the average value of the decimated signal is calculated and subtracted. Adaptive signal windowing (by Hamming window) improves the quality of the signal, increasing the accuracy of computing of spectrum frequencies.

Then the spectrogram function is applied to the decimated acoustic signal. Figures 3.2-3.9 show the oscillograms (left) and corresponding spectrograms (right) of the acoustic signal of all authentic euro coins.

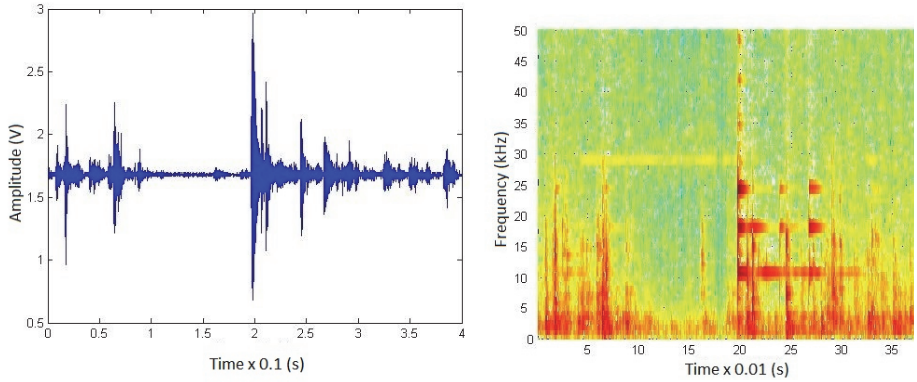


Figure. 3.2. Oscillogram of 2€ coin (left) and corresponding spectrogram (right).

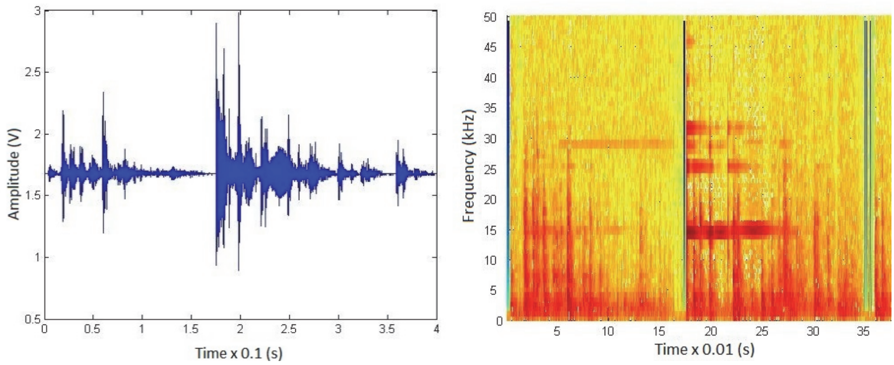


Figure. 3.3. Oscillogram of 1€ coin (left) and corresponding spectrogram (right).

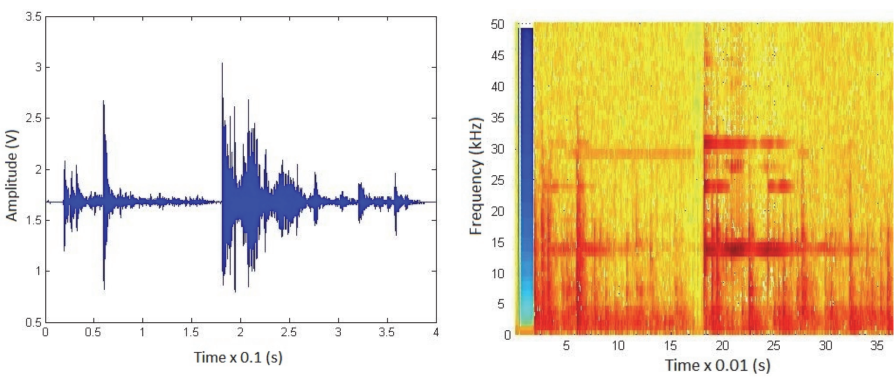


Figure. 3.4. Oscillogram of 50c coin (left) and corresponding spectrogram (right).

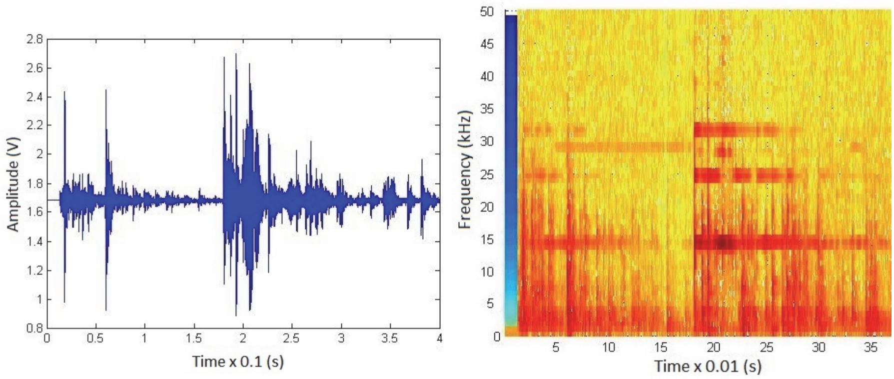


Figure. 3.5. Oscillogram of 20c coin (left) and corresponding spectrogram (right).

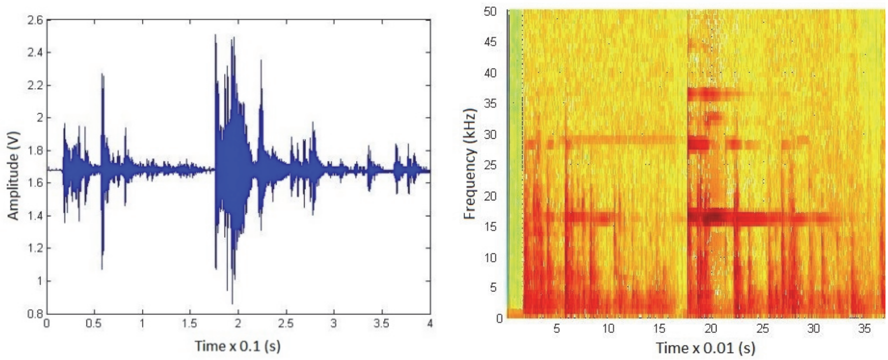


Figure. 3.6. Oscillogram of 10c coin (left) and corresponding spectrogram (right).

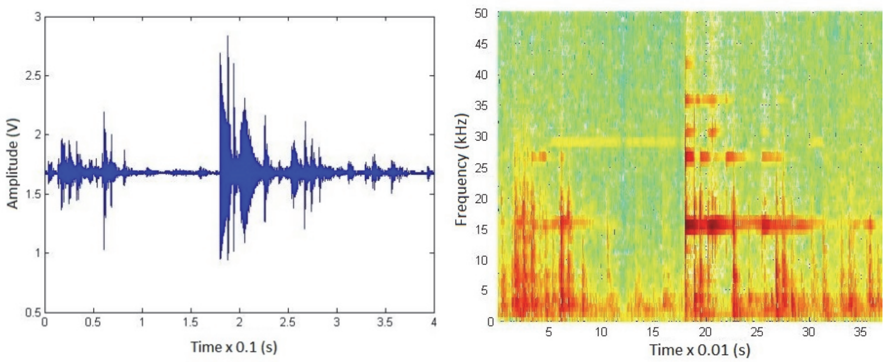


Figure. 3.7. Oscillogram of 5c coin (left) and corresponding spectrogram (right).

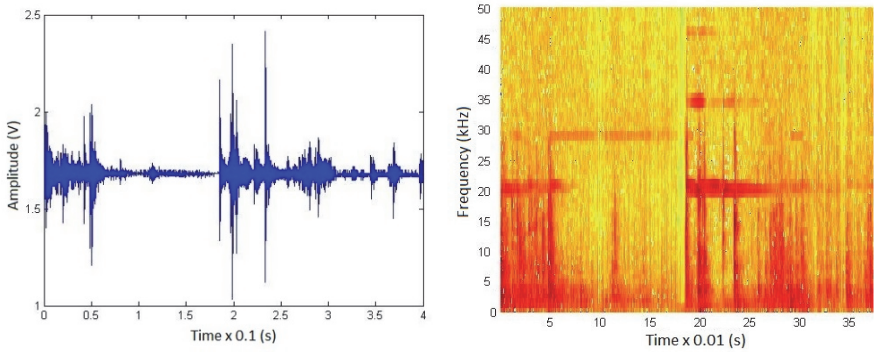


Figure. 3.8. Oscillogram of 2c coin (left) and corresponding spectrogram (right).

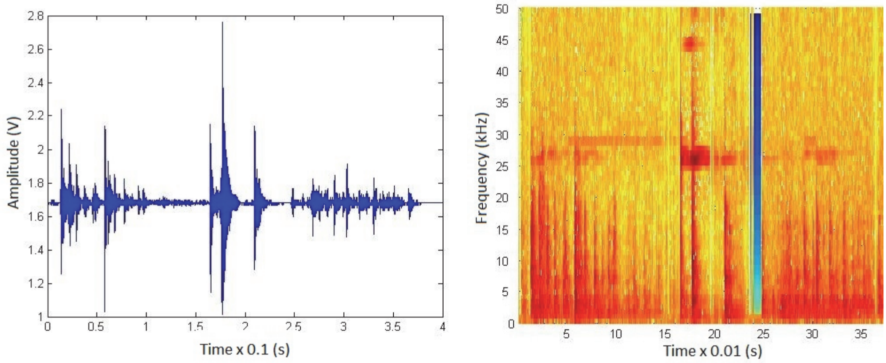


Figure. 3.9. Oscillogram of 1c coin (left) and corresponding spectrogram (right).

Here, the size of sliding window is 128 samples, number of sampling points to calculate the DFT is 128 and sampling frequency is 100 kHz. Experiments show that the optimal size of the overlapping, which allows to decrease calculations is 60 samples. As it can be seen from Figures above, the time interval from 0 ms to 150 ms the signal does not contain useful information and can be discarded.

Figure 3.10 depicts the most substantial frequencies and their corresponding magnitudes (in relative, non-normalized unit) of acoustic spectrum response of all euro coin nominations.

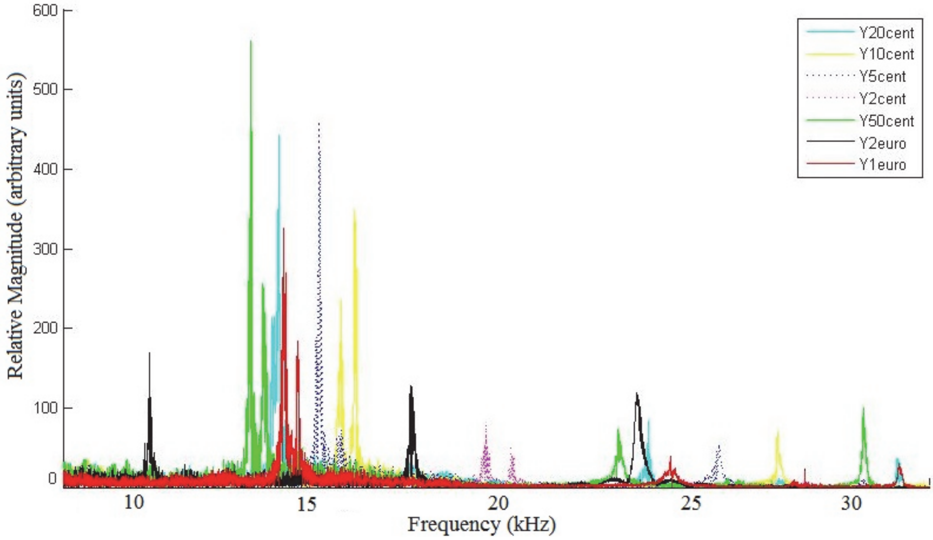


Figure 3.10. Frequencies and corresponding relative magnitudes of 2€, 1€, 50c, 20c, 10c, 5c and 2c coins [VII (15)].

It has been found, the most appropriate is to use the frequency and the magnitude values of first three maximum resonance peaks of the coin signature to classify and validate the coins [VII (15), VI (44)]. In the proposed solution values of the natural frequencies and the corresponding magnitudes are found by interpolation between the corresponding frequency bins of the relatively sparse and low sample-rate-based FFT, once per every interaction, allowing to have a simple and efficient solution, requiring very small processing power. The proposed solution is described in comparison with other frequency-response function based approaches with example plots for authentic coins. In addition, the required signal processing resources have been estimated [VII (15)].

Obtained results of the FFT based spectrum analysis are presented in Table 7, where only one frequency at maximum and corresponding relative magnitude is given. As it could be noted, a set of locations of maximum frequency peaks and their relative magnitudes of each type of the coin is unique, and can be used for coin validation.

The results of the acoustic signal analysis show, that each coin denomination has its own oscillation frequency and magnitude values, but some of them are located quite close to each other, that can cause overlap.

TABLE 7. Frequencies and magnitudes of acoustic spectrum response of euro coins [VII (15)].

Denomination of coin	**Frequency, kHz**	**Relative magnitude (arbitrary unit)**
2€	10.5	164
1€	14.4	281
50c	13.5	98
20c	14.2	397
10c	16.4	309
5c	15.3	420
2c	19.4	63
1c	25.4	105

The results of the frequency response analyses, presented in Table 7, show that the set of frequency and relative magnitude of the input signal is unique for each denomination of euro coins. Therefore, this approach could be implemented for validation of the metal of euro coins.

Modal analyses

Another method for evaluation of the acoustic signal vibrations is applying the modal analysis, what allows to measure and analyse the dynamic response during vibration. In the current work, the modal analysis-fitting of the experimental results into sum of damped oscillations, is done in the frequency domain. To determine the natural frequencies of the signal with reasonable confidence the stabilization chart has been implemented [45]. The greater is the number of computed modes, the more accurate is the result, but also computationally more intensive at the same time. The number of degree-of-freedom N depends on the complexity of structure of the system. For simple system, like coin metal validation, N is in the range of 40 – 65. To achieve accurate results the selected number of degree-of-freedom $N = 50$ has been tried first.

As was noted previously, the number of points of the decimated input acoustic signal is 50 000. In order to reduce the computational cost, several experiments with different input parameters have been carried out. It was found, that for optimisation of the modal analyses calculations, 1000 samples is enough for signal analyses without reducing in accuracy.

The stability diagram of the modal analysis with optimised input parameters, where 1000 samples is used, is applied to 2€ coin signal. The result is presented in Figure 3.11.

The informative part of the signal spectrum of modal analyses output is from 5 kHz to 35 kHz and is limited in the software.

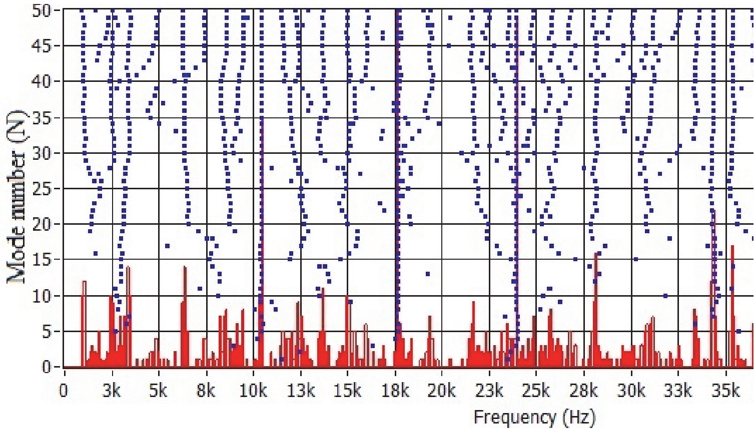


Figure 3.11. The stability diagram of 2€ coin, $N = 50$.

The stability histogram shows a statistics of the frequency distribution of the calculated outputs [50]. Figure 3.12 indicates that in the acoustic spectrum of the 2€ coin four natural frequencies (located at 10.4, 17.7, 23.9 and 24.4 kHz) appear more often than others. Here, the blue dots depict frequencies, which appear more often than pre-selected decision level of the occurrences L, namely $L = 20$.

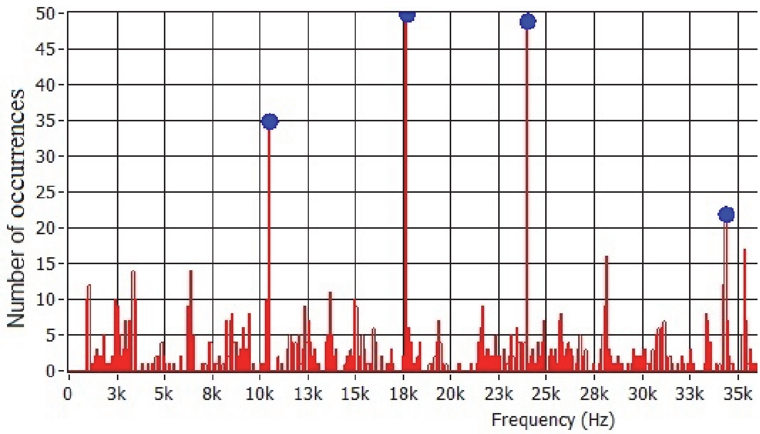


Figure 3.12. The stability histogram of 2€ coin, $N = 50$, $L = 20$.

Optimisation or simplifying of the analysis without losing the precision of the results is a complex task. During experiments to reduce the computational cost of the modal analysis, it was decided to decrease N as much as possible (until the accuracy remains reasonable).

Experimentally it was found, that the minimum number of degree-of-freedom N, without losing in accuracy of the results, is 20. Figure 3.13 presents the stability diagram, where $N = 20$.

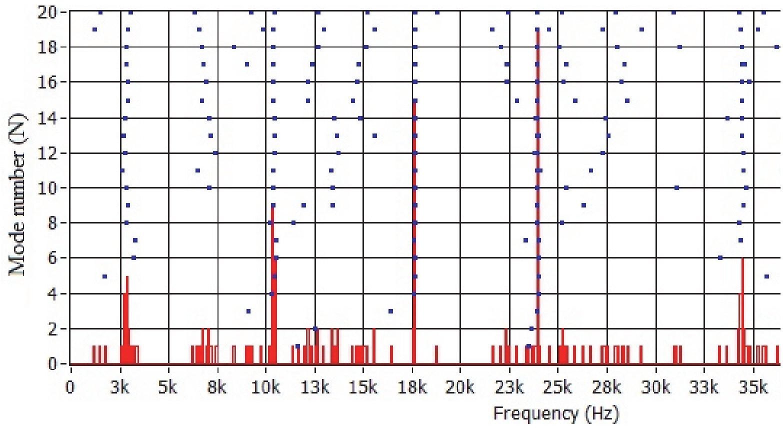


Figure 3.13.The stability diagram of 2€ coin, $N = 20$.

Figure 3.14 shows the stability histogram of 2€ coin for $N = 20$. Experimentally it was found, that efficient minimum decision level is $L = 7$. The results of the comparison of the stability histograms, where $N = 50$ (Figure 3.12) and $N = 20$ (Figure 3.14) are following: first three more often appeared natural frequencies of the signal spectra are located (determined) at the same places; the last one can be discarded due to closely location to the limit of investigated signal.

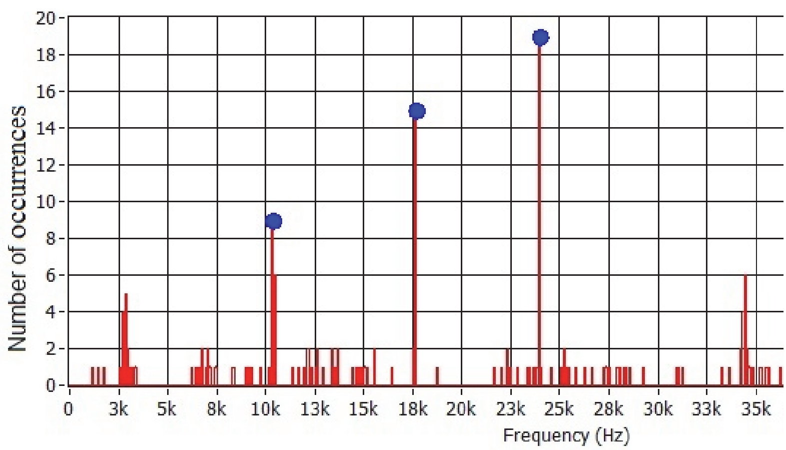


Figure 3.14.The stability histogram of 2€ coin, $N = 20$, $L = 7$.

The experiments with the modal analysis and simplified modal analysis were carried out with other euro coins, for both $N = 20$ and $N = 50$ cases.

Since the experiments and calculations show, that the degree-of-freedom of $N = 20$ is reasonable for all other coin nominations, the graphs for $N = 50$ are not shown in the following part.

The similar analysis has been performed for all other euro coins and the corresponding stability histograms, where degree-of-freedom N = 20 and decision level L = 7, are presented in Figures 3.15-3.21.

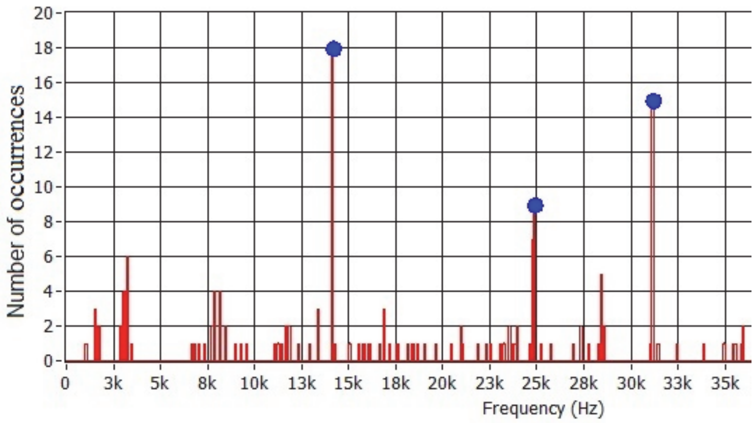


Figure 3.15. The stability histogram of 1€ euro, N = 50, L = 7.

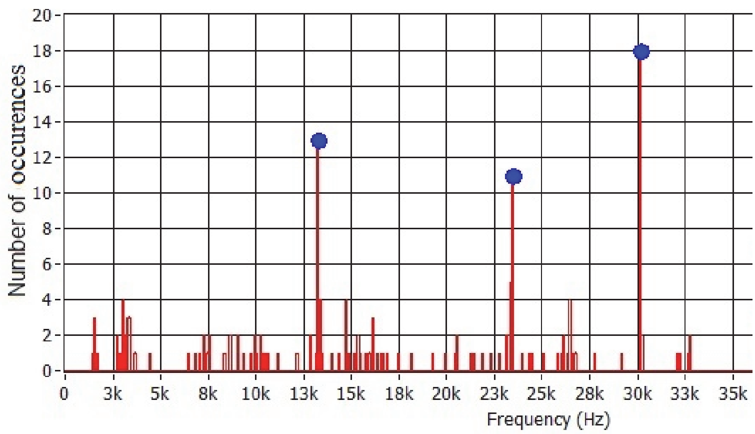


Figure 3.16. The stability histogram of 50c coin, N = 20, L = 7.

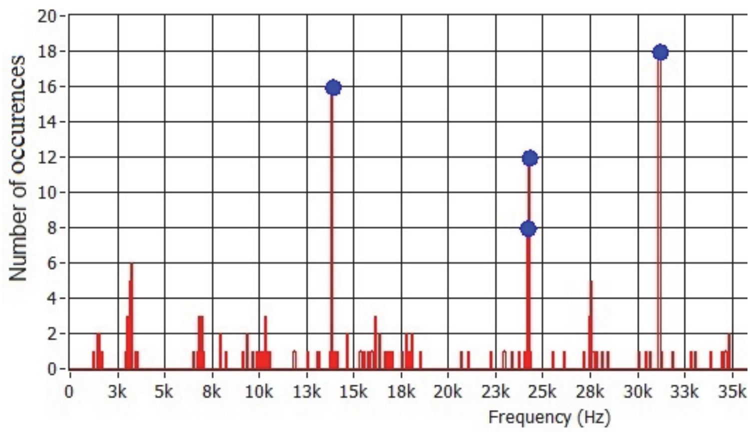


Figure 3.17. The stability histogram of 20c coin, $N = 20$, $L = 7$.

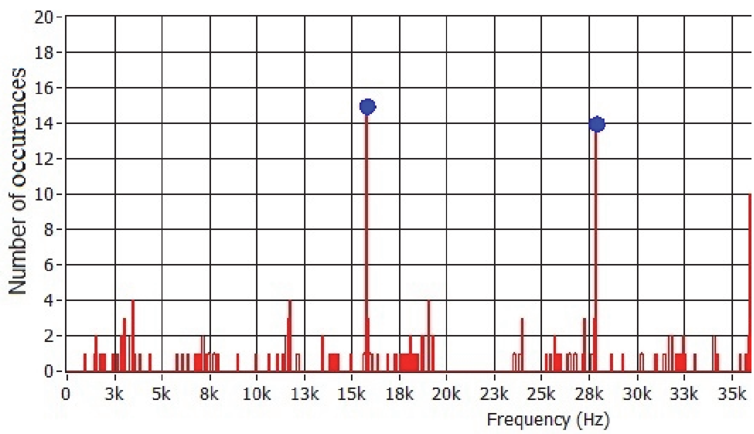


Figure 3.18. The stability histogram of 10c coin, $N = 20$, $L = 7$.

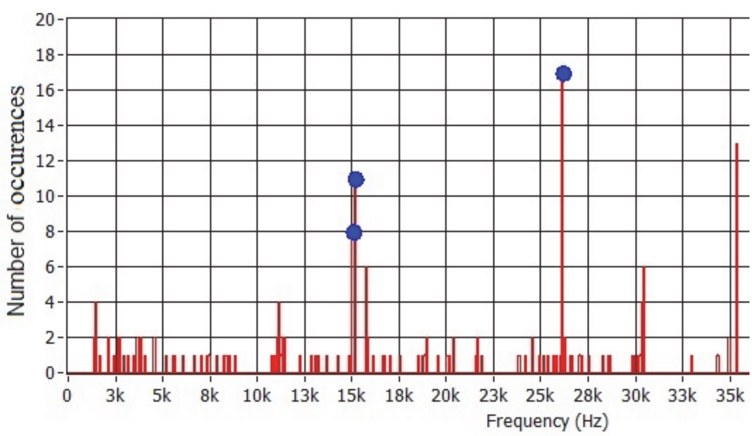


Figure 3.19. The stability histogram of 5c coin, $N = 20$, $L = 7$.

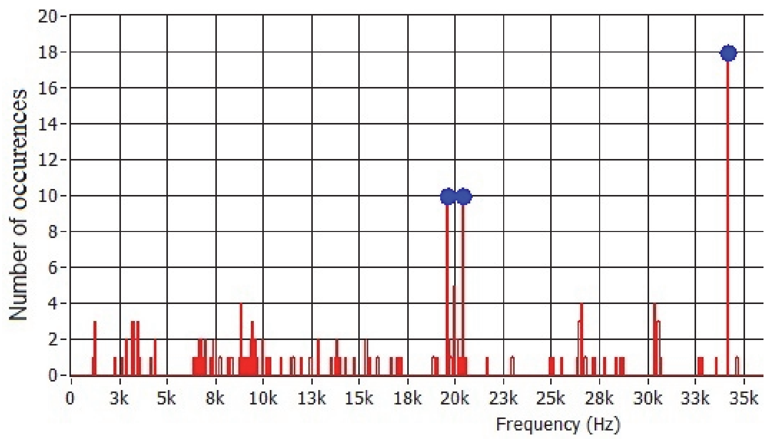


Figure 3.20. The stability histogram of 2c coin, $N = 20$, $L = 7$.

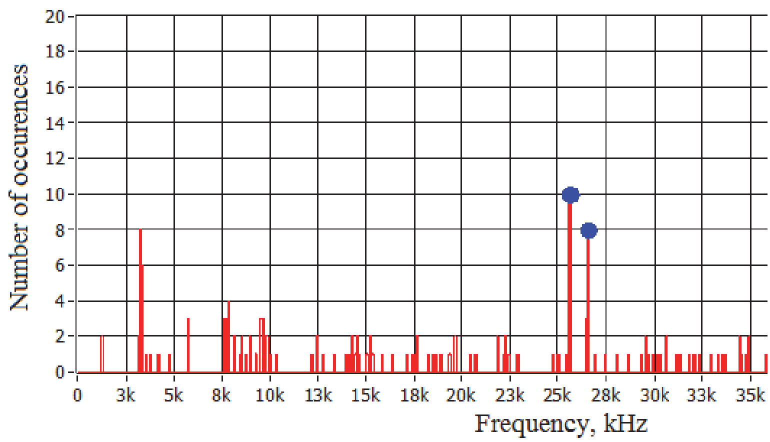


Figure 3.21. The stability histogram of 1c coin, $N = 20$, $L = 7$.

For coin validation a set of maximum frequencies, which exceed selected minimum number of the occurrences is used. Discovered set of the frequencies is distinguishing value for each euro coin. That fact makes it possible to validate and recognize euro coin by their acoustic signature.

In Table 8 the numerical representation of experimental results on all genuine euro coins are given, where the damping ratios are also presented.

In the case, if the values of the natural frequencies of the various coins are coinciding, the damping ratio could be used as an additional parameter for the alloy validation.

TABLE 8. The results of the modal analyses based on the authentic coins.

Coin type	Natural frequency, kHz	Damping ratio
2€	10.4	-0.591
	17.7	-0.161
	23.9	-0.189;
1€	14.4	-0.226
	24.9	-0.537
	31.2	-0.106;
50c	13.3	-0.319
	23.4	-0.648
	30.1	-0.072
20c	14.1	-0.371
	24.3	-0.179
	31.8	-0.084
10c	16.1	-0.231
	28.4	-0.492
5c	15.1	-0.503
	16.2	-0.815
	26.3	-0.416
2c	19.5	-0.281
	20.6	-0.152
	34.6	-0.351
1c	25.6	-0.101
	26.5	-1.01

The bin width of the stability histogram is selected to 100 Hz, therefore the resolution of the estimated natural frequency is ± 50 Hz, what is enough for precise validation of the coin metal.

The results of the modal analysis on the experimental data show that every coin has the unique frequency and damping ratio, what could be used for euro coin validation. The optimizations of the pre-settings of modal analysis parameters allow to reduce the computational cost up to 60% without losing the accuracy of results.

3.3. Experiments with counterfeit euro coins

Firstly, coins have been stroked against the hard metal surface and the acoustic sound has been tested by human ear. It was established, that all three coins have various acoustic tones, which differ from each other and from the tone of the genuine coin.

Acoustic signals of the counterfeit coins under test were stored using setup described above. In Figure 3.22, acoustic signals and corresponding spectrograms of the counterfeit coins are presented.

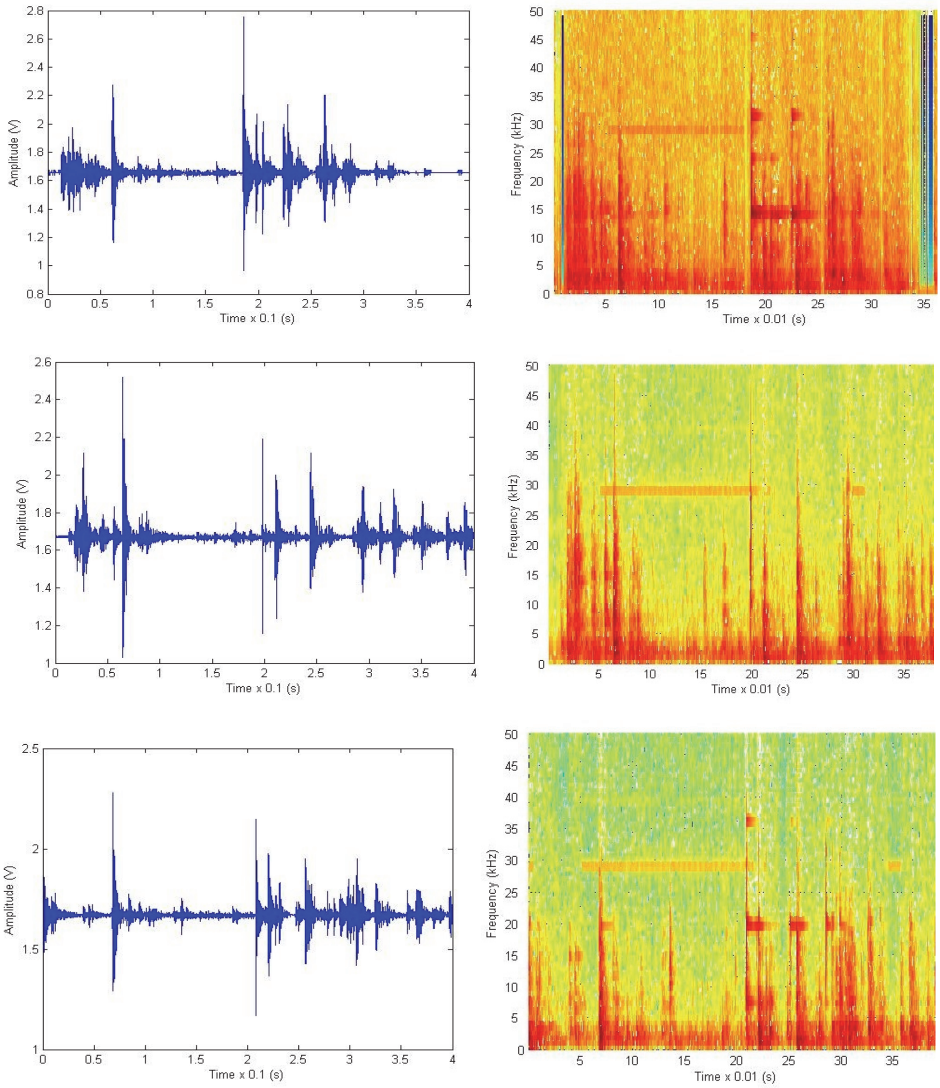


Figure 3.22. Acoustic signals (left) and corresponding spectrograms (right) of three types of the counterfeit 2€ coins (Belgium, Italy and Germany).

The acoustic signals of each counterfeit coin have been captured 10 times. Validation using FFT and modal analysis was performed in Matlab and LabView. The output of the FFT, applied to the acoustic signals of the counterfeit 2€ coin, is presented in Figure 3.23.

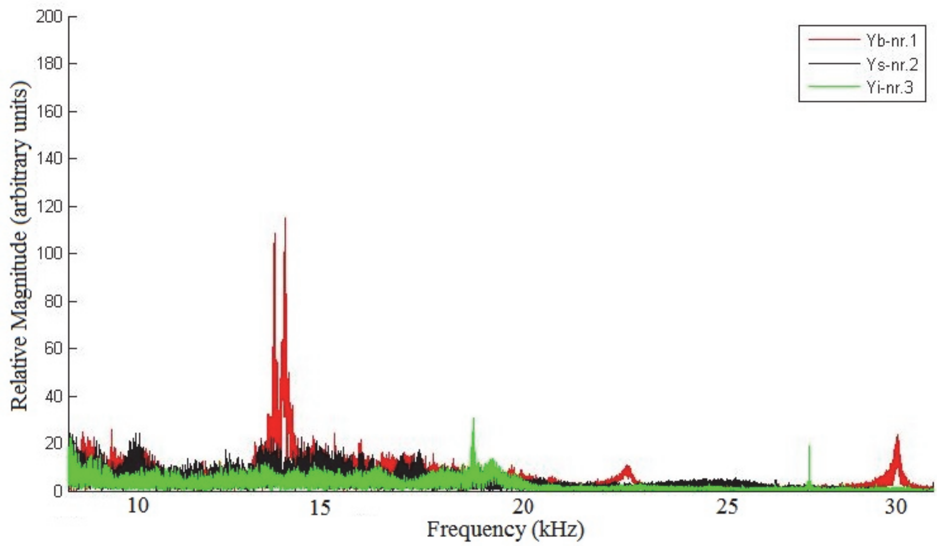


Figure 3.23. The frequencies of counterfeit coins [VII (15)].

The output of spectrum analysis and modal analysis of three types of counterfeit 2€ coins are totally different from each other and from authentic coin, as shown in Figure 3.24.

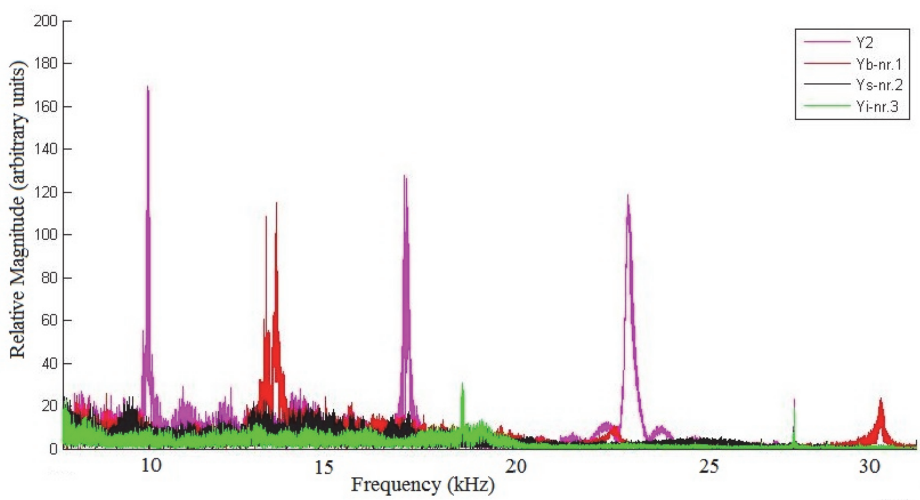


Figure 3.24. The representation of frequencies of the three type of counterfeit coins and authentic 2€ coin.

Taking into account that the set of three maximums is completely dissimilar from the set of frequencies of the authentic coin, it could be summarised, that the content of the alloy of counterfeit coin samples is not as expected.

Described above procedures are applied to the acoustic signals of all euro coins, allowing to determine the natural frequencies of euro coins under test. The implemented method of the signal spectrum analysis demonstrate that the set of the maximum frequency and amplitude of each coin is unique. Determined set of signal spectra values ensures validation and classification of the euro coins.

Next, the modal analysis was applied to the acoustic signal. The stability diagram and corresponding histogram of counterfeit Belgian coin are presented in Figures 3.25-3.26, where $N = 20$, $L = 7$.

Figure 3.27 demonstrate the stability diagram of the simplified modal analysis performed for counterfeit 2€ coin (Italy).

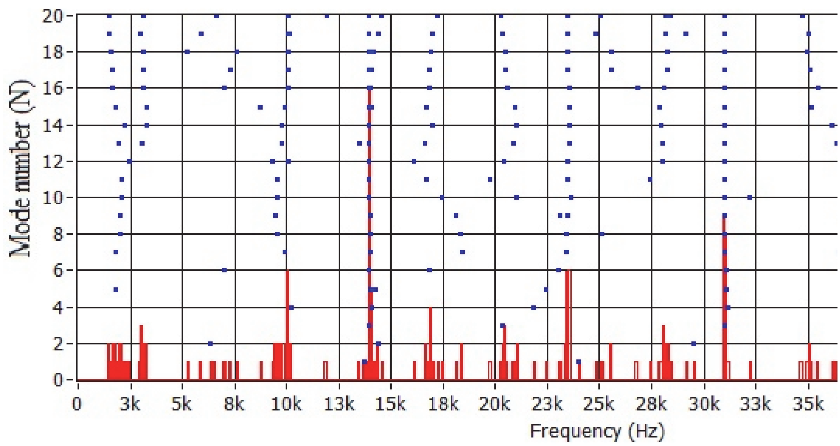


Figure 3.25. The stability diagram of counterfeit 2€ coin $N = 20$ (Belgium).

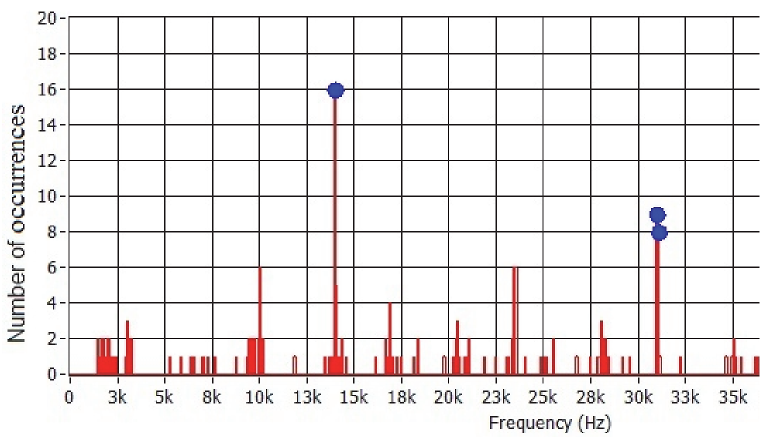


Figure 3.26. The stability histogram of counterfeit 2€ coin $N = 20$, $L = 7$ (Belgium).

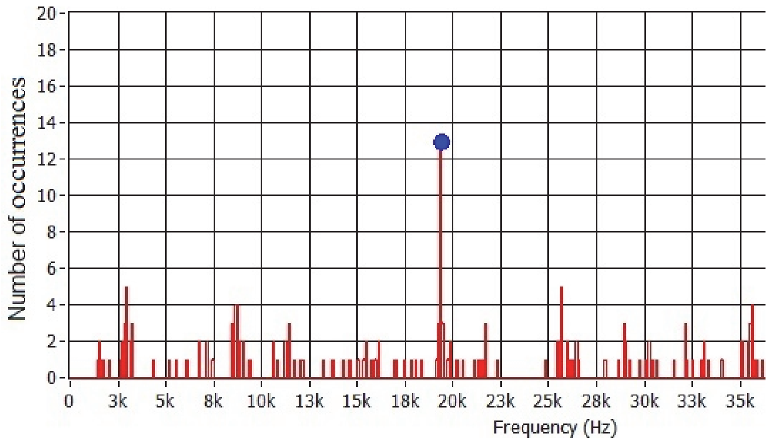


Figure 3.27. The stability histogram of counterfeit 2€ coin $N = 20$, $L = 7$ (Italy).

As could be marked from Figure above, only one stably appeared frequency is detected in the acoustic signal of counterfeit 2€ coin (Italy), but it does not match with frequencies of authentic 2€ coin.

In Figures 3.28-3.29 the stability histograms for both $N = 50$ and $N = 20$ cases, applied to counterfeit coin of Germany, are presented.

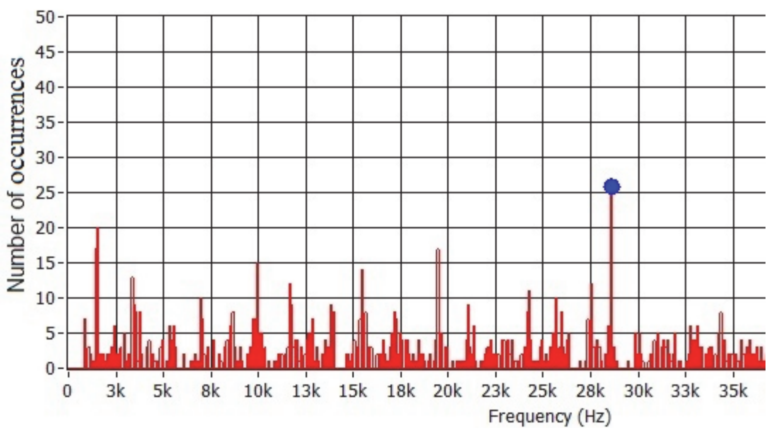


Figure 3.28. The stability diagram of counterfeit 2€ coin $N = 50$, $L = 20$ (Germany).

Here, the maximum level of stability of frequency (number of occurrences) is lowest (25) and does not match with the frequencies of the genuine coin. It means that the quality of this coin alloy is most different from others.

As could be noted from Figure 3.28, only one frequency can be extracted, the value of which does not match with the frequencies of the authentic 2€ coin.

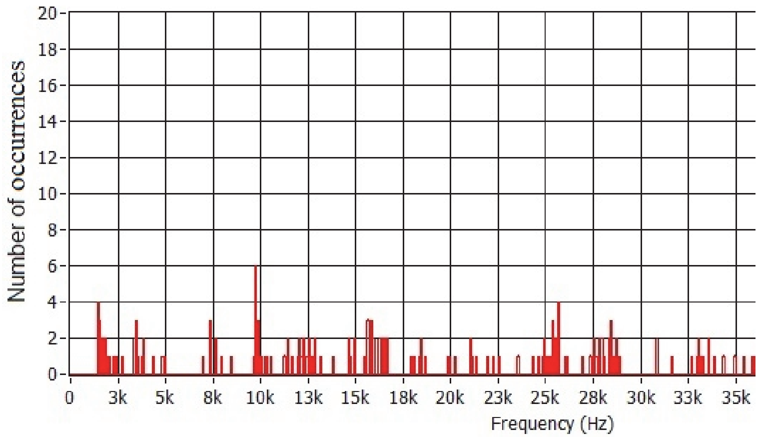


Figure 3.29. The stability histogram of counterfeit 2€ coin $N = 20$, $L = 7$ (Germany).

The result of the optimised modal analysis (Figure 3.29) shows, that there is no stable or more often appeared frequency in the spectrum of this signal (with regarding to selected parameters, where $L = 7$). Thus, as result of optimised modal analysis applying, this coin is rejected.

The numerical results of the modal analysis with counterfeit coins are presented in Table 9, where each coin has been tested 10 times, and the average value of outcomes are computed [VII (15)].

TABLE 9. The results of modal analysis, based on the counterfeit coins [VII (15)].

Country of counterfeit coin	Natural frequencies, kHz	Damping ratio
Belgium	31.1	-0.387
	13.8	-0.427
	23.5	-0.586
Italy	19.3	-0.64
	out of range	out of range
Germany	out of range	out of range

As could be marked, investigated by modal analysis counterfeit 2€ coin samples have totally different modal frequencies and damping ratios, which vary from each other and from authentic 2€ coin.

3.4. Summary

Results of the implemented acoustic signal processing methods for coin validation based on the spectrum analysis ensures authentic coin recognition with high accuracy.

In the presented solution, values of the natural frequencies and the corresponding amplitudes were determined by FFT. The disadvantage of this method is high computational cost, what makes it relatively hard to apply in cases, where only low computational capability is available. Applying the advanced FFT analysis for investigation of the spectrum of the acoustic signal of the coin is alternative solutions to the issue, which is described in [VI (44)].

Modal analysis needs pre-configuration of the parameters to achieve good results in reasonable time. The experiments with optimization of modal analysis show possibility to decrease the number number-of-freedom that allow reducing the computations more than 60% without losing of precision in results. Additionally, this method provides extra features of the signal spectra like damping ratio.

The disturbing feature of the acoustic signal investigation is that signal from the same coin varies slightly from test to test. It depends on the dropping trajectory; the way it was inserted (left, right, centre); the strength it was inserted in validator etc. Despite of variations of the input parameters, the results of acoustic analysis ensure that it is an accurate solution for coin validation and recognition.

Analysis of tests, which were carried out on the genuine and counterfeit coins, shows the cost-efficiency and high accuracy of described solution for validation and recognition of the genuine euro coins and discrimination of the counterfeit coins.

4. IMAGING SOLUTIONS FOR EURO COIN RECOGNITION

The algorithm presented in this chapter consists of the typical image processing stages: pre-processing, actual processing and extraction of the relevant features. The optimisation or conditioning of the properties of images provides the better result in feature detection and matching process. The segmentation of image, for example, is used for specifying and locating the objects in the image.

Applying of the pyramid method and bicubic interpolation to the original image allow to decrease computational complexity without loss of the accuracy [I (87)].

Development of the matching pattern provides fast and precise recognition of the coins. Investigation of pattern and symbols of the edge ensure recognition of the authentic coin as well as detection of the counterfeit coins [IV (85), V (88)]. Imaging algorithm based on the proposed solutions is developed and evaluated in Matlab. The results of the experiments, carried out on the authentic and counterfeit euro coins, are presented and analysed.

Low-cost and simple in realisation line-scan imaging solution is proposed and evaluated in this chapter and partially in paper [II (81)]. The results of experiments are presented and analysed.

4.1. Image pre-conditioning

Images under the test have been stored in 24 bit RGB for further processing. As result of several experiments on RBG images, it was found that using the 8 bit grey scale image not only decreases the volume of image in three times, but also gives possibility for implementation of efficient edge detection techniques.

In the pre-conditioning step, the pyramid method of the image could be applied to template image and image under test to reduce the size of processed data and time of the coin validation. The full (possible) resolution is not important in the first stage, since the position and rotation angle need to be specified first. The pyramid method is applied for the image decimation, which gives point values when convolved with the image. Typically, the higher-level image pyramid is represented by average of two neighbour values [IV (85)-I (87)].

The comparison of various interpolation methods have been performed: nearest-neighbours method; bilinear function, where the output value is calculated with a weighted average of pixel values of the nearest 2 x 2 neighbourhood); and standard bicubic function.

The standard bicubic function was preferred and applied for the down-sampling, where the output value is calculated with the weighted average of pixels of the nearest 4 x 4 neighbourhood values [I (87)]. This approach is considered as more accurate approximation, but the most calculation intensive of the mentioned here approaches. The reasonable levels of the pyramid to be used depend on the size of initial image. The results of the experiments carried out on the genuine 1€ coin are presented in Figure 4.1.

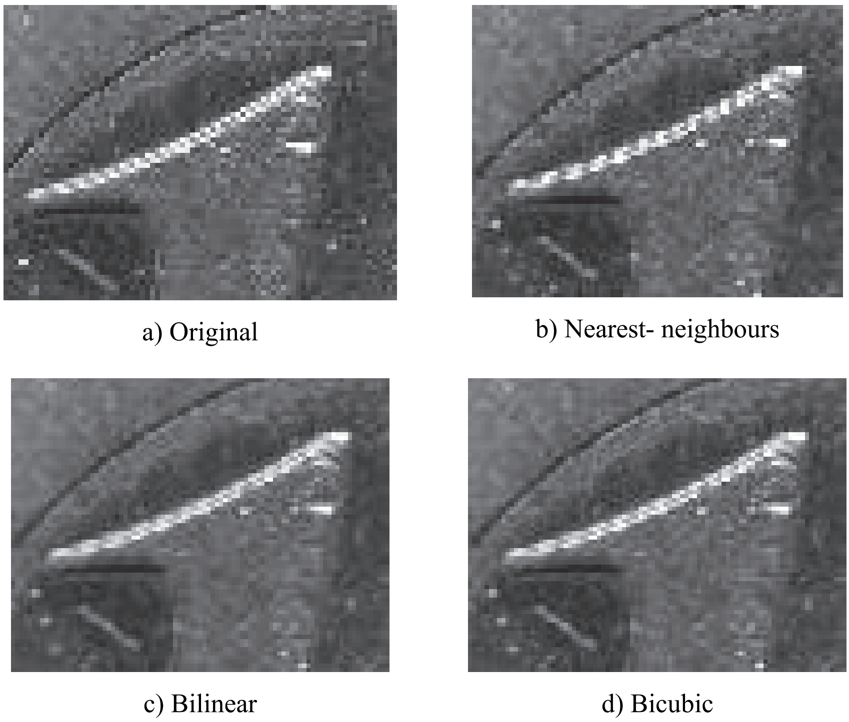


Figure 4.1. Methods of 1€ coin down-sampling: a) original image; b) nearest-neighbours interpolation; c) bilinear interpolation; d) bicubic interpolation [I (87)].

The output image of nearest-neighbours interpolation (Figure 4.1b) shows that the edges of pattern are become wider, what affects negatively to the accuracy of the contour detection.

The output image of bilinear interpolation (Figure 4.1c) is misty and edges of pattern are blurred, what makes it difficult precisly to extract contour precisely.

The output image of the bicubic interpolation (Figure 4.1d) is most clear of the three presented cases and edges of the pattern are well-defined.

Several tests based on these three functions were carried out. The goal was to define the edge (contour of the pattern) using inner and outer diameter calculations more precisely. The results show that the edges of the coin pattern were defined better after interpolation by bicubic function.

Inner and outer contours of the coin have been calculated during the experiment, as shown in Figure 4.2.

Figure 4.2. Inner diameter of 1€ and 2€ coins [I (87)].

Both diameters were compared with diameter of the genuine coin. The results show that the inner diameter (green line) is more accurate than the outer one.

The diameters of the coins are calculated from the images and are stored into the databases in pixels.

4.2. Adaptively subsampled cross-correlation approach

Variable-rate subsampling (by pixel blocks) of the images has been proposed and tested to reduce the number of computations and to optimize the cross-correlation technique. The idea is that most of the image blocks are sampled with zero or one sample-values, while a few blocks (some to some tens) of the image has been sampled at the full resolution [V, 88].

In Figure 4.3 a number of the possible variations for selection of the specific blocks with various number and dimensions of blocks of 2€ coin, are presented. The criteria, used for selection of the "specific segments" is the minimum value of the maximum cross-correlation of a block of samples (eg 20 x 20 or 30 x 30 pixels) against any other (shifted or rotated) block of the same coin image. Therefore, blocks with relatively high value of "secondary" correlation peaks at shifting and rotating are not considered as "good" or "unique" ones [V, 88].

1.

2.

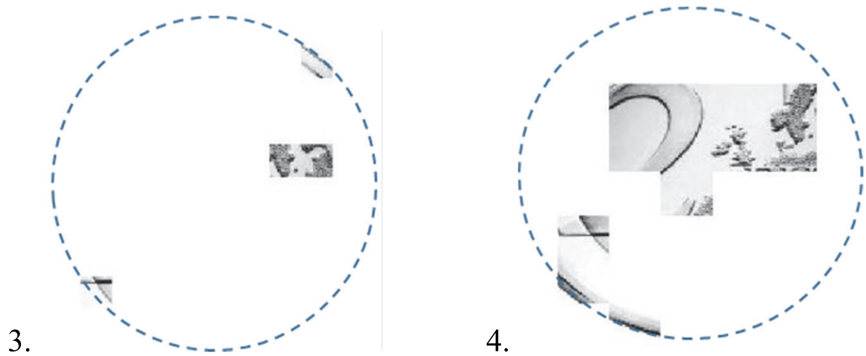


Figure 4.3. Adaptively subsampled images of 2€ coin [V, 88].

All of demonstrated on Figure 4.3 segments satisfy the requirements of uniqueness. Since computational efficiency of the cross-correlation depends on the size of data, the investigation of the optimal number and the dimensions of blocks is presented.

4.3. Matching pattern

Ideally, the object to be recognized (coin) has constant dimensions, distance from sensor to the object and illumination. Therefore, for euro coin recognition template matching technique is preferred. As template, the full image could be used as well as a region/part of it (number of selected regions). Thus, the optimal selection of special regions or blocks is becoming highly important, to minimize the computational cost and maintain the accuracy.

It was decided to divide the coin image into equal parts, so partition of 4, 8 and 16 blocks was applied. The tests were repeated many times with various dimensions of segments. It was noted that for image with dimensions 240 x 240 pixels, the most efficient segment size is 50 x 50 pixels.

The evaluation criteria of segments for "special blocks" is the high value of the average of cross-correlation function per block, which is obtained by the correlation of all segments within the template image [IV (85), I (87)].

Firstly proposed in [IV (85)] the average of cross-correlation function across the block is used for segment uniqueness evaluation. In Figure 4.4 two cases are shown, where average of cross-correlation function of different blocks are given graphically. Cross-correlation functions with the single maximum and low average level are preferred.

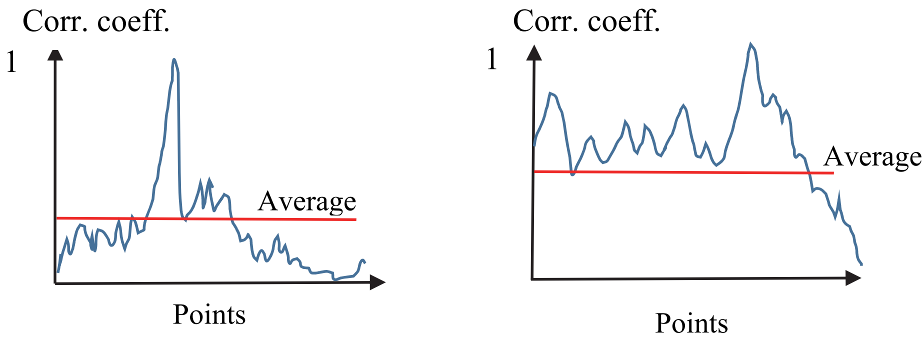
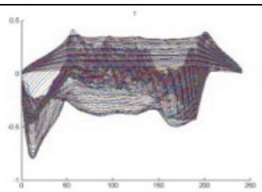
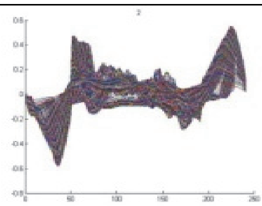
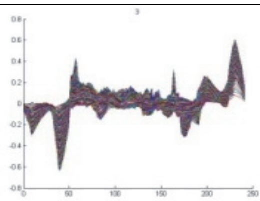
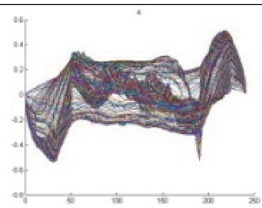
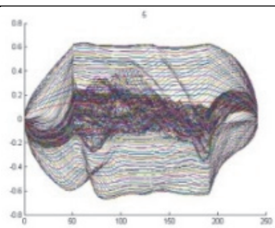
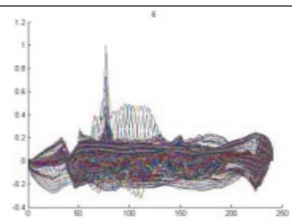


Figure 4.4. Average level of cross-correlation function of various blocks.

In this work, the minimum average level of cross-correlation within the image is proposed as matching criteria for selection specific blocks, which should be bigger than threshold parameter. Experimentally it was found that optimal number of segments to be used is 16. In Figure 4.5, 16 segments of 1€ coin image and corresponding 16 results of cross-correlation values are presented.

1 		2 	
3 		4 	
5 		6 	

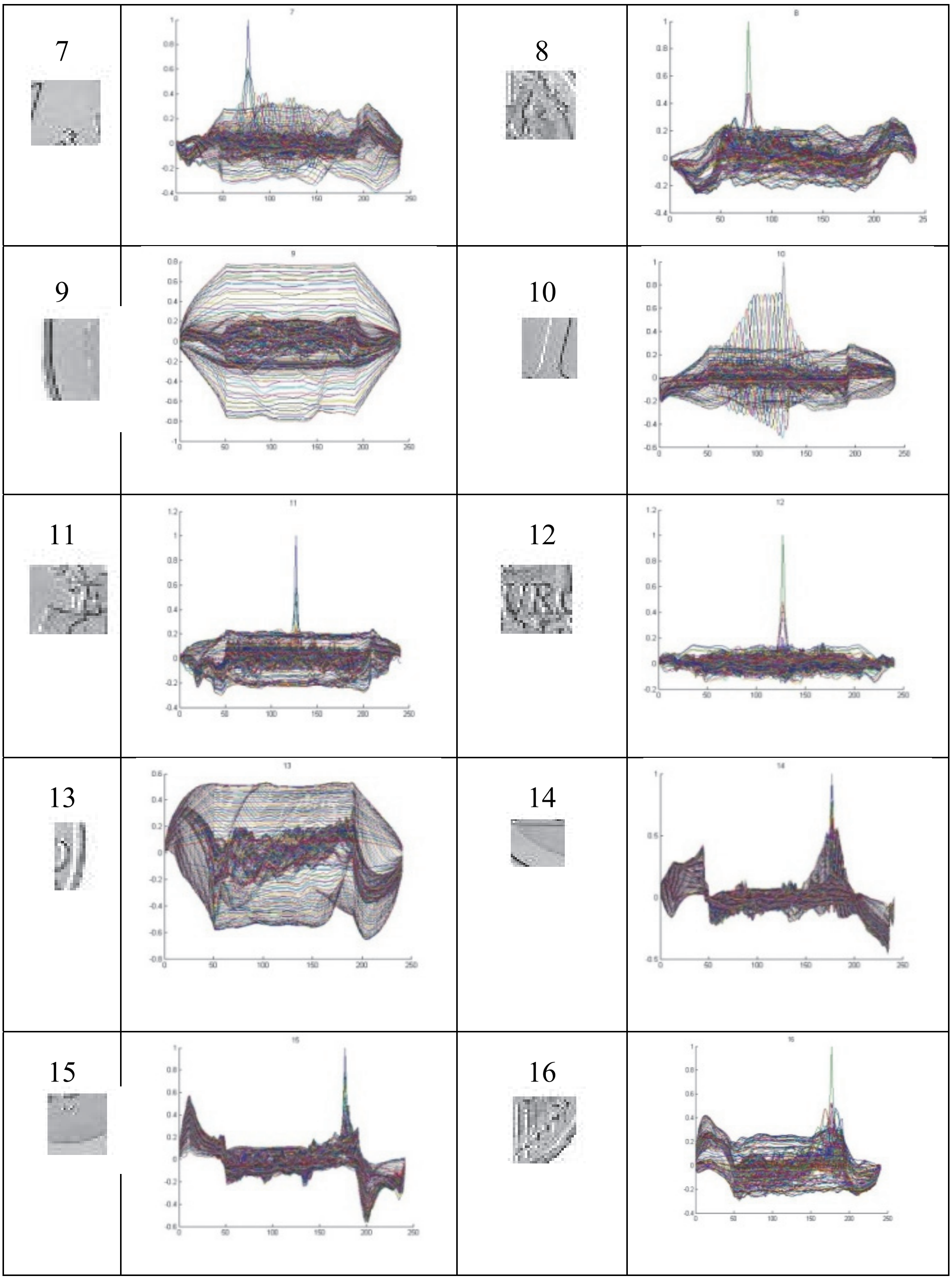


Figure 4.5. Segments of 1€ coin and corresponding cross-correlation function outputs [I (87)].

Visually, the most unique blocks are 6, 7, 8, 11 and 12. To determine mathematically the minimum average level of cross-correlation three ways for calculation *A*, *B* and *C* have been implemented and tested.

Method *A*: minimum average level of all values within the block is calculated by equation:

$$average = \frac{\sum_{k=1}^{n} x_k}{n} \quad (4.1),$$

where x_k is any value (Figure 4.6a).

Method *B*: Minimum average level of all positive values within the block is calculated by equation (4.1), where x_k is value greater than 0 (Figure 4.6b).

Method *C*: Minimum average level of absolute values within the block is calculated by equation (4.1), where x_k is absolute value (Figure 4.6c).

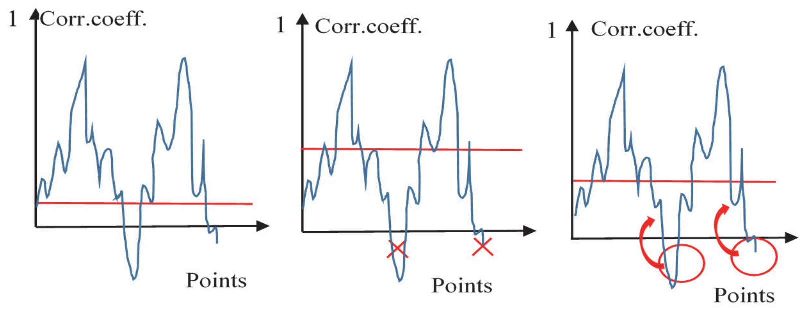


Figure 4.6. Minimum average level of cross-correlation calculated by methods *A, B* and *C* accordingly.

Calculated results of described handlings are presented in Table 10 accordingly.

TABLE 10. Minimum average level of image segments calculated by methods A, B and C [I (87)].

	Block nr.1	**Block nr.2**	**Block nr.3**	**Block nr.4**	**Block nr.5**	**Block nr.6**	**Block nr.7**	**Block nr.8**
A	-0.003	0.009	0.008	0.006	0.007	-0.001	-0.005	0.006
B	0.541	0.519	0.538	0.524	0.506	0.492	0.471	0.509
C	0.168	0.152	0.110	0.197	0.185	0.076	0.067	0.097

	Block nr.9	**Block nr.10**	**Block nr.11**	**Block nr.12**	**Block nr.13**	**Block nr.14**	**Block nr.15**	**Block nr.16**
A	0.007	-0.001	0.003	0.001	-0.003	-0.008	-0.001	0.001
B	0.554	0.494	0.517	0.507	0.524	0.444	0.480	0.462
C	0.149	0.078	0.078	0.033	0.212	0.108	0.140	0.118

The most efficient blocks calculated by method *A* were as follows: 14, 7 and 6. The most efficient blocks calculated by method *B* were: 14, 15 and 7. The most efficient blocks calculated by method *C* were: 6, 7 and 12. Thus the most precise results, with comparison to the blocks determined visually, were obtained by method *C*.

Optimization goal here could be to minimize the number of segments. Experimentally it was found that reasonable number of blocks for coin recognition is three. After three unique segments has been discovered, they are used as pattern or mask to determine coin position on the image and for coin recognition and classification. In Figure 4.7 the created mask for 1€ coin recognition is shown.

6 7 12

Figure 4.7. Created mask for 1€ coin recognition.

During experiments, described method was applied to create “matching pattern” or template for 1 €. The point of this solution is – to define the position of coin relatively to the reference image: about the position and an angle [I (87)].

The practical experiments of coin recognition based on template matching with cross-correlation technique using created pattern were carried out [I (87)]. In Figure 4.8, the output of template matching by unique pattern based on cross-correlation is presented.

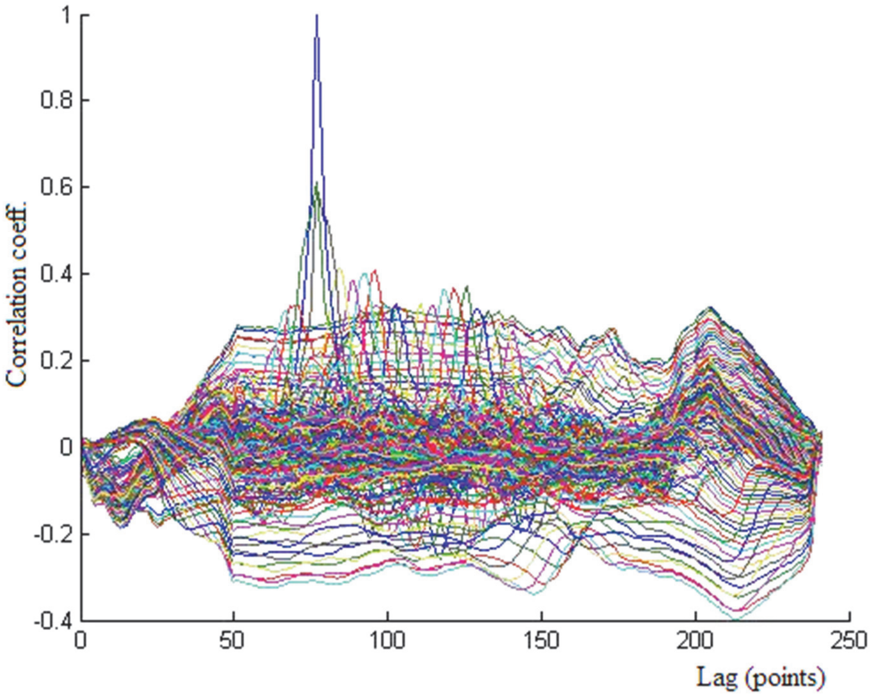


Figure 4.8. Cross-correlation of unique pattern of template image and image under test [I (87)].

As it could be seen from figure, the cross-correlation peak is enough high to conclude that the coin was recognized successfully.

The size of pattern used for recognition is about 104 x 104 pixels, what is 57% less than initial size. It means that the implementation of proposed cross-correlation based solution computational cost is reduced on 57%.

4.4. Investigation of the coin edge

The thickness and special features of coin edge or third part (like letters, interrupted milled, fine scallops, smooth surface) are investigated by image of edge. Thickness is calculated from the image with edge by inner contour detection technique.

For example, 2€ coins contain symbols on the edge side, what typically refers to the country of manufacturer (Figure 4.9). Letters and symbols discovered from the edge of coin insures not only the high accuracy of coin validation but also matching of counterfeit and unfit coins, the edge quality of which is poor usually [I (87)].

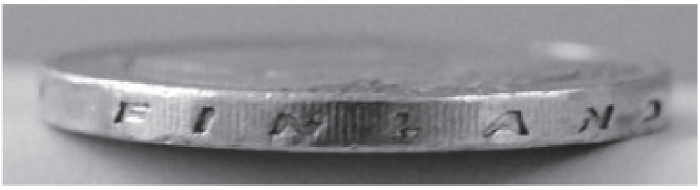


Figure 4.9. Image of authentic 2€ coin edge [I (87)].

The canny edge detector is applied to grey scale image for contour extraction. In Figure 4.10 extracted during the experiment from 2€ coin symbol *I* is shown.

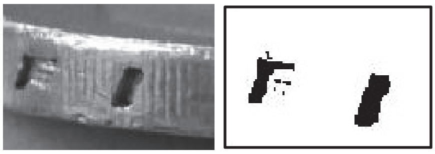


Figure 4.10. Extracted from 2€ coin symbol *I* [I (87].

Previously proposed in this chapter processing was applied to counterfeit coins. In Figure 4.11, the output of cross-correlation function with template image and counterfeit image is shown.

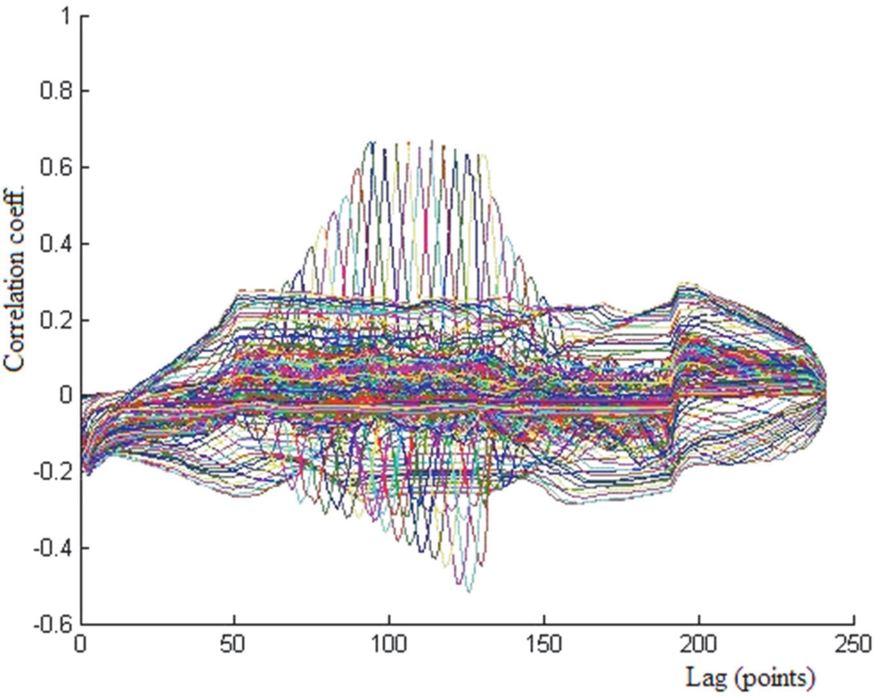
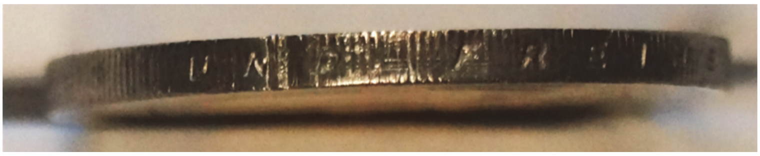


Figure 4.11. Output of the cross-correlation function of template image and counterfeit image.

The results of the investigation of edges of counterfeit coin examples are presented in Figures 4.12-4.14, where the original image of edge and processed one are given.

a) 

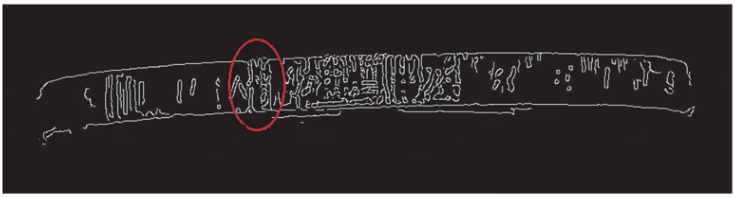
b) 

Figure 4.12a) Image of the coin edge, b) processed image of the edge of counterfeit coin (Belgium).

a) 

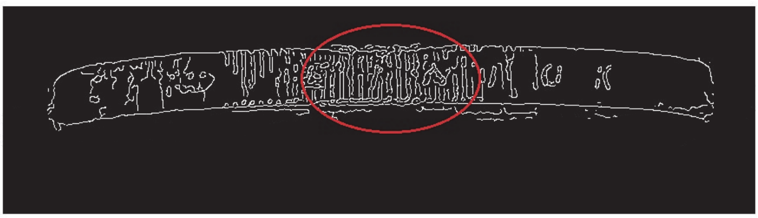
b) 

Figure 4.13a) Image of coin edge, b) processed image of the edge of counterfeit coin (Germany).

a) 

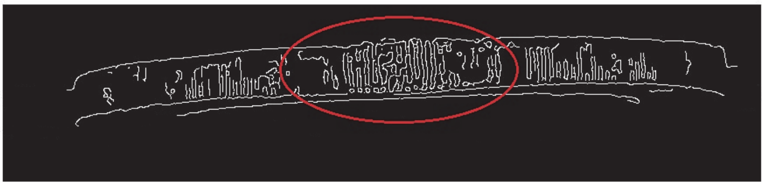
b) 

Figure 4.14a) Image of coin edge, b) processed image of the edge of counterfeit coin (Italy).

As could be noted from figures above, the red rings show the region of edge with defect or high roughness. This is the reason for rejection of such types of coins.

The experimental results show:

1. Coin edge has dent as shown in Figure 4.12b); as result this coin example was rejected;
2. From Figures 4.13b) and 4.14b) could be seen that the contours of both edges are rough. Coins were rejected;
3. Interrupted milled lines are not clear (Figures 4.12-4.14);
4. The diameter of counterfeit coin 3 is bigger than template, that coin was rejected.

Investigation of coin edge is extremely important by the reason that some classes of counterfeit coins have pretty good quality of common and national sides of coin and the only low quality part is edge of the coin. In this case, visual inspection of edge allows to reveal counterfeit coin.

4.5. Algorithm for visual coin recognition and classification

Taking into account all described aspects, cross-correlation based algorithm with unique pattern for visual based recognition and classification of euro coins and matching unfit and/or counterfeit coins have been developed. Typically, image based recognition in divided to pre-processing and real time processing parts as demonstrated in Figure 4.15. Pre-processing part contains template image conditioning, extraction and saving of special segments for each euro coin to be matched, where template image is initial image of authentic euro coin.

In step 1, the manipulations with template image are verified. 24-bit RGB image is converted to 8-bit grey scale, then thresholding and Canny filter are applied.

In step 2, the diameter of coin from template image is determined as was described in previous section.

Next (step 3), the pyramid method is applied to decrease the size of data and reduce computational cost. During experiments original image is reduced in 2 times.

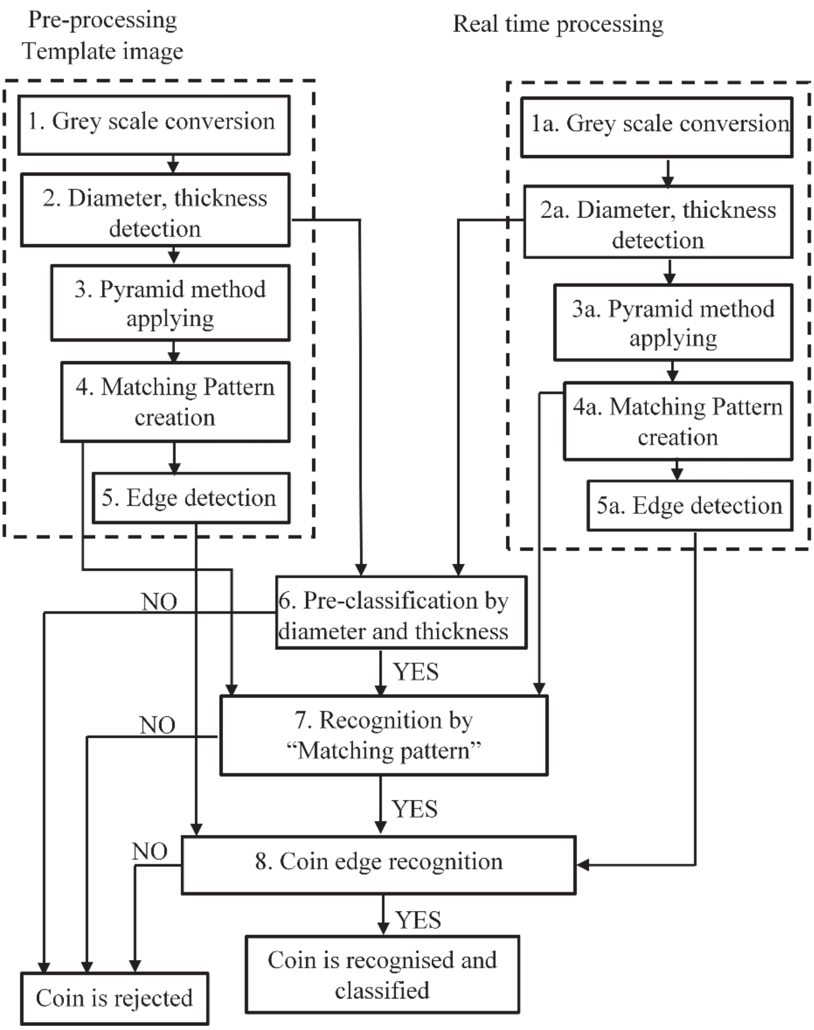


Figure 4.15. Algorithm for coin recognition.

The output of this part is two times smaller data file what saves resources of system significantly.

Step 4 is the implementation of proposed in previous section segmentation and matching pattern creation. In the end of this step, the matching pattern is created and stored.

In step 5, the edge features are discovered and stored to databases.

In real time processing part steps from 1a to 5a are the same like in pre-prospecting part but with image under test.

In step 6, pre-classification of coin is performed by diameter and thickness of the coin. Here, diameters of the coin image under test and template image compared

In step 7, the coin under test is matched, as well as the position and location are defined using created “matching pattern“. Then the cross-correlation of template image and image under test is applied for unfit or damage coin matching.

Next (step 8), the edge of coin is investigated and compared with template image edge: roughness of the contour, letters, reefing, scallops must be correct.

Euro coin is recognized and denomination is classified in case:

- The diameter and thickness of coin was specified as correct (step 6);
- The output of matching pattern and the cross-correlation function (step 7) with full image was in tolerance;
- Edge of coin is correct (step);
- If either one of the steps 6-8 is negative, the coin is rejected as counterfeit or unfit or unknown.

Proposed algorithm was evaluated in Matlab and tested. The results of experimental work with counterfeit euro coins are presented in Table 11.

Table 11. Results of counterfeit coin detection.

Country	**Diameter, mm**	**Thickness, mm**	**Measured with image processing algorithm, pixels**
Belgium	26.10	2.20	173
Italy	25.75	2.20	155
Germany	25.80	2.20	158

The simplicity of implementation, analysing and definition of extracted information combined with the efficient computation possibility provide the extreme usefulness of correlation. This function could be applied only to grey scale digital image, what makes image smaller than the RGB image. The processing of grey scale images decreases the computational cost as well as saves storage and transmission resources.

4.6. Simple imaging solution by line scan camera

In Figure 4.16, it is presented the setup for line scan camera based imaging solution consists of Parallax TSL1401 camera, terminal device (PC), the TI Piccolo DSC as interface between the camera and the coin stand with rotating euro coins. The maximum transmission speed of TI board is 5 MB/s [II (81)].

The main features of the camera are:

- 128-pixel linear image sensor;
- Focusable imaging lens;
- Resolution 128 pixels (grey scale);
- Dimensions (with lens) are 34.3 x 34.3 x 31 mm.

The camera has analogue output, so the internal 12-bit fast ADC of the Piccolo DSC can be easily installed for connection to the camera. This solution allows to increase the image acquisition speed up to several megapixels per second, with corresponding coin handling speed improvement. The stand with rotating coins simulates the coin moving process through validation device, where the velocity can be varied in a wide range.

The capturing speed of single line is 0.16 ms and transmission time is 3.28 ms, when clock frequency 800 kHz and length of line 128 pixels. Therefore, the total transmission time of single line is about 3.49 ms that means scan speed is 287 lines per second. Thus, if the dimension of image is 128 x 128 pixels, the frame rate is 2.27 frames per second.

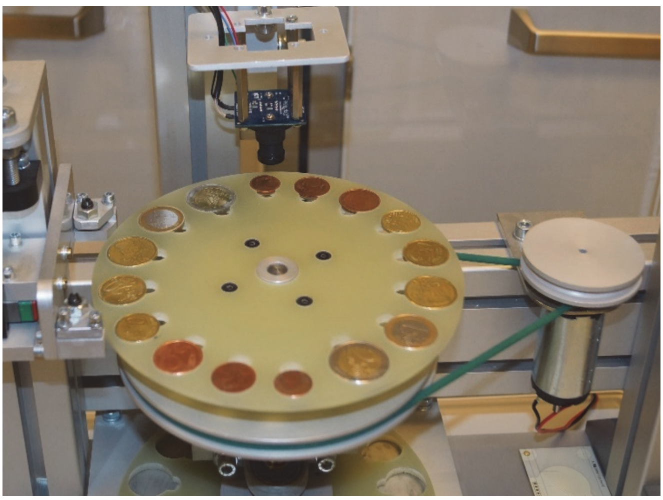


Figure 4.16. Setup of image based experiments with line scan camera [II (81)].

In this solution, simplified algorithm for coin recognition based on measurements of the diameter of the coin and cross-correlation is proposed. The cross-correlation along some segments of the coin (e.g. over the diameter of the coin or the neighbourhood of it) with image under test is performed.

The 1D array with dimensions 128 x 138 pixels has been stored and transmitted to PC as data file. Depending on moving speed of the stand with coins, the information of collected data could vary. At the standard moving speed, the collected data covers the coin totally (Figure 4.17, left). In higher moving speed, the data is obtained with intervals or sampled (Figure 4.17, right).

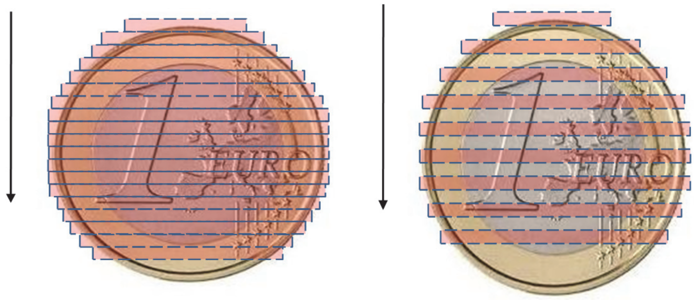


Figure 4.17. Data acquisition: with a standard speed of the coin (left); with a higher speed of the coin (right) [II (81)].

In Figure 4.17, in up to down direction, the dimension of the coin is depending on the moving speed. In other direction (left to right on the same Figure 4.17), the dimension is constant and can be used to determine the actual size of the coin.

Sampled data implementation, increase of the speed of the coin recognition process. In this case, the image creation from sampled data by spline interpolation function could be preferred.

In Figure 4.18, it is shown the genuine euro coin image captured from line scan camera and created experimentally in Matlab.

Figure 4.18. Frame created from line scan camera [I (81)].

Next, the Canny detector is applied to the grey scaled image to discover the edges of the coin, the result of which is presented in Figure 4.19a. Thereby, the boundaries are localized by filtering limits. For diameter calculation, the minimum and maximum points of limits were used.

Figure 4.19. Frame after canny edge detector [II (81)].

Next, the cross-correlation function of pre-classified template image and image under test is applied for recognition. The result of cross-correlation function is presented in Figure 4.20.

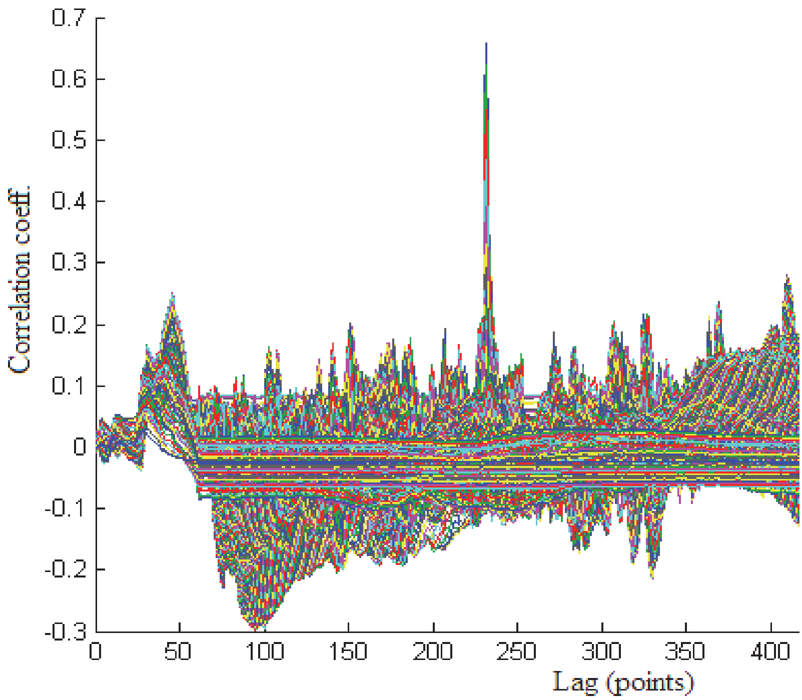


Figure 4.20. Result of cross-correlation [II (81)].

Clear maximum of the cross-correlation function shows that the coin was recognized successfully.

4.7. Summary

Described in this chapter, adaptively subsampled cross-correlation based imaging solution was evaluated and tested in Matlab. Experimental results demonstrate efficiency of this method for euro coin validation and classification as well as for counterfeit coin detection.

The output of tests ensures the following:

- Pyramid method implementation reduces the computational cost more than twice;
- Suggested pattern-matching by cross-correlation function is efficient for coin position matching and coin recognition/classification;
- Improved cross-correlation function, where only segments with more relevant correlation value are selected, allow to decrease the computational cost at least 60%;
- Investigation of coin edge allows to explore contour and roughness, what indicates the counterfeit and/or unfit coins; and to determine the thickness of the coin (physical feature for coin validation).

5. CONCLUSIONS

In this thesis, coin validation solutions based on electromagnetic, acoustic and visual features of euro coins have been proposed, developed, evaluated and analysed.

The tasks of present work have been performed:

- The eddy current based solution for coin validation by conductivity measurements of metal alloy has been evaluated and tested.
- Experimentally evaluated electrical conductivities of euro coins are presented.
- Acoustic solutions for euro coin validation and classification by signal spectra have been evaluated, studied and analysed.
- Image based algorithm for authentic euro coin recognition, classification and detection of counterfeit coins has been developed and evaluated in Matlab.

The main contributions of this thesis are:

1. Multi-frequency eddy current method combined with Dodd-Deeds model allows to determine the unique set of conductivity values for each coin.

The multi-frequency eddy current method combined with Dodd-Deeds model has been evaluated and tested. The described solution ensures evaluation of the set of conductivities (for each specified frequency), that allows to create the unique characteristic of the metal for each coin individually. Taking into account experimentally obtained results, the measured conductivities of coin metal alloy could be used as reference values for euro coin validation and recognition. The implementation of this solution provide precise validation and classification of euro coins by metal, as well as detection of the counterfeit coins. Thereby, the research task number one is performed.

The price of developed coil is 5-7€. Consequently, the demonstrated eddy current solution is a precise, high-speed, low-cost, robust, compact and simple in realization.

2. Proposed eddy current method allows not only to detect but also to classify the counterfeit euro coins.

Examination of various classes of counterfeit coins makes it possible to create the model of the set of conductivities for specified classes of counterfeits, because different classes of coins with same denomination have dissimilar values of conductivities. Thereby, this solution could provide not only detection of counterfeit coins but also classification. This conclusion follows from the experimental results achieved during research task number one.

3. **Frequency response and optimised modal analysis methods provide unique set of acoustic parameters for each coin.**

The investigation of frequency response of the acoustic signal of the coin metal for implementation in the coin validation area is suggested. Described acoustic signal based approaches using FFT and modal analysis demonstrate good result of euro coin validation.

A novel approach for acoustic signal investigation of the coin is based on the modal analysis. The modal analysis, as a tool for investigation of the acoustic signal of the coins, is proposed by author for the first time. Considering the results of modal analysis optimisation, the decreasing of freedom-of-degree level provides alloy validation fast and without reduction in accuracy.

Therefore, the second research task is performed, the parameters of modal analyses are optimised.

The results of the experiments demonstrate the efficiency of the described solutions and provide validation of the coin metal. The price of the proposed solution is about 6-8€ (technical setup with microphone).

4. **Acoustic signal based coin validation approach could be used as independent solution for coin validation and recognition.**

Experiments, carried out on the spectra of the acoustic signal of coin examples, reveal that the set of the natural frequencies of every coin nomination is unique. Therefore, experimentally evaluated natural frequencies could be used as reference values for validation, recognition and classification of the metal of the coin. This fact confirms that proposed solution could be used for coin validation separately from other validation methods, what satisfy the research task number three.

5. **Adaptively subsampled cross-correlation based imaging solution is efficient method for euro coin validation as well as for counterfeit coin detection.**

To fulfil the requirements of research task four the image based solution for euro coin recognition and classification has been developed and evaluated.

Optimisation of the cross-correlation function by sub-sampling, pyramid method and developed "matching pattern" has been implemented and tested in respect to imaging solution. In pre-conditioning stage, the pyramid method reduces the size of the data to be processed. Segmentation and optimal selection of unique regions minimises the number of required cross-correlation calculations in "matching pattern" technique. Proposed approach reduce computational complexity more than 60% (in comparison to full image cross-correlation).

Extraction of the symbols from the edge of the coin and evaluation of the thickness provides recognition of the authentic coins and detection of the counterfeit coins.

Described algorithm with combined adaptive sub-sampled cross-correlation and designed matching pattern is suitable not only for recognition and classification of genuine coins but also for detection of the counterfeit and unfit euro coins. The price of the setup is about 25€.

6. **Blockwise "matching pattern" is fast and computationally efficient method for coin recognition.**

Development and implementation of the cross-correlation based "matching pattern" for visual coin recognition and classification allows to save computational resources; to define the position and location of the coin under test fast and accurately. Designed "matching pattern" approach shows high efficiency for image based coin validation that satisfy the research task number 4.b.

For future work, the main task could be the sensor fusion-combining various sensor approaches into one solution, in order to use the advantages and benefits of all the approaches.

REFERENCES

1. Safecsan, [Online]. https://www.safescan.com/en/, March 2013.
2. Guobang Industrial & Trade CO. LTD, [Online]. http://www.chinaguobang.com/about/index.asp?i=1, March 2013.
3. Thomas Automatics, [Online]. http://thomasa.co.uk/products/, March 2013.
4. Azkoyen Group, [Online]. http://www.azkoyen.com/maquinas-expendedoras, March 2013.
5. The European Anti-Fraud Office, [Online]. http://ec.europa.eu/anti_fraud/, March 2013.
6. The European Central Bank, [Online]. https://www.ecb.europa.eu/press/pr/activities/bc/html/index.en.html, March 2013.
7. Safemetal (FP7-SME-2010-262568), [Online]. http://www.safemetal.eu/, September 2011.
8. European Anti-Fraud Office, *Regulation No 1210/2010*, [Online]. http://ec.europa.eu/anti_fraud/documents/regulations_en.pdf, 2010.
9. The Estonian Forensic Science Institute, *Counterfeit Euro Coins*, [Online]. http://www.ekei.ee/sites/www.ekei.ee/files/elfinder/dokumendid/voltsingute_naited_01_03_2015.pdf, March 2015.
10. K. Segrave, "Vending Machines: An American Social History," McFarland, 12 July, 2002, pp.5.
11. Crane Payment Innovations, [Online]. http://www.cranepi.com/en/, October 2013.
12. R. Griese, "Mechanical coin-acceptor unit,“ U.S. Patent 8 100 247, January 24, 2012.
13. P. Rossiter, *Electrical Resistivity of Metals and Alloys*. Cambridge, University Press, 1991.
14. R. Gordon, O. Martens, R. Land, M. Min, M. Rist, A. Gavrijaseva and A. Kolyshkin, "Eddy-current validation of euro coins,“ in *Lecture Notes on Impedance Spectroscopy: Measurement, Modeling and Applications 3*, 2012, pp. 47-63.
15. A. Gavrijaseva, O. Martens and R. Land, "Acoustic Spectrum Analysis of Genuine and Counterfeit Euro Coins,“ in *Elektron. Ir Elektrotechnika*, accepted Feb-2015.
16. K. Fredriksson and E. Ukkonen, "Faster template matching without FFT,“ in *Image Processing*, Vol. 1, 2001, pp. 678-681.
17. N.Y. Khan, B. McCane and G. Wyvill, "SIFT and SURF performance evaluation against various image deformations on benchmark dataset,“ in *Digital Image Computing Techniques and Applications* (DICTA), 2011, pp. 501-506.
18. European Anti-Fraud Office, "Report from the Commission to the European Parliament and the Council,“ [Online]. http://ec.europa.eu/

anti_fraud/documents/euro-protection/report_authentication_euro_coins_and _handling_euro_coins_unfit_for_circulation_551.pdf, January 2014.
19. O. Martens, R. Land, A. Gavrijaseva and A. Molder, "Adaptive-Rate Inductive Impedance Based Coin Validation," in *Intelligent Signal Processing* (WISP), IEEE 7th International Symposium, 2011, Floriana, Malta, pp. 122-125.
20. H. Molbak, "Coin counter/sorter and coupon/voucher dispensing machine and method," U.S. Patent 6 494 776, December 17, 2002.
21. J. McGinty, "Coin validation apparatus," U.S. Patent 6 223 877, May 1, 2001.
22. L. Crain, "Automated coin grading system," U.S. Patent 5 224 176, June 29, 1993.
23. T. Nara and T. Ueki, "Coin discriminating apparatus," U.S. Patent 5 263 566, November 23, 1993.
24. K. Reis, "Coin sorting and counting machines," U.S. Patent 3 771 538, November 13, 1973.
25. A. Carlosena, A. J. López-Martin, F. Arizti, A. Martínez-de-Guerenu, J. L. Pina-Insausti and J. L. García-Sayés, "Sensing in coin discriminators," Proc. IEEE Symp., San Diego, CA, USA, 2007, pp. 1-6.
26. G. Howells, "Coin discriminators," U.S. Patent 7 584 833, September 8, 2009.
27. G. Howells, "Coin discriminator where frequencies of eddy currents are measured," U.S. Patent 7 537 099, May 26, 2009.
28. T. Takehiko and T. Ueki, "Coin discriminating apparatus," U.S. Patent 5 263 566, November 23, 1993.
29. G. Rietveld, Ch. V. Koijmans, L. C. A. Henderson, M. J. Hall, S. A. C. Harmon, P.Warnecke and B.Schumacher, "DC conductivity measurements in the van der Pauw geometry," in *Conference Digest*, vol. 52, 2002, pp. 449–453.
30. A. C. Lynch, A. E. Drake and C. H. Dix, "Measurement of eddy-current conductivity," in *IEE Proceedings A (Physical Science, Measurement and Instrumentation, Management and Education, Reviews),* 1983, pp. 254–260.
31. L. Henderson, "Techniques and materials for the measurement of DC and AC conductivity of non-ferrous metals and alloys," Final Rep., 2004, pp. 149.
32. Olympus NDT, *Eddy Current Array (ECA) Theory, Practice and Application.* [Online]. http://www.azom.com/article.aspx?ArticleID=8016, December 2014.
33. C. V. Dodd and W. E. Deeds, "Analytical solutions to eddy-current probe-coil problems," in *Journal of Applied Physics*, vol. 39, 1968, pp. 2829-2838.
34. C. V. Dodd and W. E. Deeds, "Calculation of magnetic fields from time-varying currents in the presence of conductors," in *OAK Ridge National Laboratory*, Rep., July 1975.
35. N. Bowler, Y. Huang, "Electrical conductivity measurement of metal plates using broadband eddy-current and four-point methods," in *Measurement Science and Technology*, 2005, pp. 2193–2200.
36. T. Theodoulidis and M. Kotouzas, "Eddy current Testing Simulation on a Personal Computer," in *Roma 2000 NDT World Conference,* Roma (Italy), 2000.

37. Vrije Universiteit Brussel, *Eddy current testing*. [Online]. http://www.absolutende.com/en/eddycurrenttesting/principle, February 2015.
38. L. Ziomek, *Fundamentals of acoustic field theory and space-time signal processing*, CRC press, 1994.
39. C. L. Chitty, R. W. Whatmore, "Coin validation apparatus," U.S. Patent 5 062 518, November 5, 1991.
40. R. G. Bointon, R. D. Allan and N. M. Funnell, "Coin validation," U.S. Patent 5 797 475, August 25, 1998.
41. D. M. Furneaux, "Coin store measurement," E.P. Patent 1 413 991, April 28, 2004.
42. C. H Hansen and C.H. Sehrndt, *Fundamentals of acoustics. Occupational Exposure to Noise: Evaluation, Prevention and Control.* World Health Organization, Geneva, [Online]. http://www.who.int/ occupational_health/publications/noise1.pdf, 2013.
43. S. W. Smith, The Scientist and Engineer's Guide to Digital Signal Processing. [Online]. http://www.dspguide.com/, October 2013.
44. O. Martens, A. Gavrijaseva, R. Land and M. Min, "Simple acoustical signature based coin validation," in *Intelligent Signal Processing (WISP), IEEE 9th International Symposium,* Siena, Italy, 2015.
45. H. Ward, P. Sas, "Modal analysis theory and testing," in *Katholieke Universteit Leuven*, Departement Werktuigkunde, 2006.
46. Vrije Universiteit Brussel, *Sound and Vibration*. [Online]. http://mech.vub.ac.be/teaching/info/Experimentele_modale_analyse/introduct ion_modal_analysis.pdf, Experimental Modal Analysis, January 2015.
47. M. Döhler, A. Palle and M. Laurent, "Operational modal analysis using a fast stochastic subspace identification method," in *Topics in Modal Analysis I*, Volume 5, Springer New York, 2012, pp. 19-24.
48. Robotics Laboratory, Hiroshima University, [Online]. http://www.robotics.hiroshima-u.ac.jp/vision_sensing/modal_parameter_ estimation.php, December 2014.
49. D. W. Herrin, *Vibro-Acoustic Design in Mechanical Systems*. [Online]. http://www.ewp.rpi.edu/hartford/~ernesto/F2013/SRDD/Readings/ ModalAnalysis-ANSYS_Tutorial-UKentucky.pdf, October 2014.
50. P. Guillaume, *Modal analysis*. [Online]. http://mech.vub.ac.be/avrg/ publications/ModalAnalysis.pdf, October 2014.
51. B. J. Schwarz and M. H. Richardson, "Experimental modal analysis," in *CSI Reliability week*, 35(1), 1999.
52. D. Mehta and A. Sagar, "A survey on various techniques of coin detection and recognition," in *International Journal of Computer Applications* 69(5), New York, 2013, pp. 28-32.
53. S. Z. M. Kampel, "Coin data acquisition for image recognition," in *Proceedings of the 36th CAA Conference,* Vol. 2, 2008, pp. 6.
54. M. Wollny, "Method and device for testing coins," C.A. 2 516 111, February 8, 2011.

55. J. Grove, “Coin Identification System and Method Using Image Processing,“ U.S. Patent 20 130 202 184, August 8, 2013.
56. P. J. Burt, C. Yen and X. Xu, “Local Correlation Measures for Motion Analysis: a Comparitive Study,“ in *IEEE Conf. Pattern Recognition Image Processing*, 1982, pp. 269–274.
57. E. Hibari, “Coin discriminating apparatus,“ E.P. Patent 1 049 054, March 21, 2001.
58. Ch. Wang and M. H. Leibu, “Pattern recognition using artificial neural network for coin validation,“ U.S. Patent 5 485 908, January 23, 1996.
59. A. Zaknich, *Neural networks for intelligent signal processing*. World Scientific, 2003.
60. A. R. Omondi and J. Ch. Rajapakse, *FPGA implementations of neural networks.* Vol. 365. New York, NY, USA: Springer, 2006.
61. H. Kaur and N. Sharma, “Modified Coin Identification Using Neural Network,“ in *International Journal of Emerging Technology and Advanced Engineering*, Volume 4, 2014.
62. C. M. Velu, P.Vivekanadan, K. R. Kashwan, “Indian Coin Recognition and Sum Counting System of Image Data Mining Using Artificial Neural Networks,“ in *International Journal of Advanced Science and Technology*, 2011, pp. 67-80.
63. S. Modi and D. Bawa, “Automated Coin Recognition System using ANN,“ in *arXiv preprint arXiv: 1312.6615*, 2013.
64. T. N. Nimbhorkar and M. M. Bartere, “Coin recognition by using artificial neural network,“ in *International Journal of Computer, Information Technology & Bioinformatics*, 2013, pp. 88-91.
65. M. Fukumi, S. Omatu, F. Takeda and T. Kosaka, “Rotation-invariant neural pattern recognition system with application to coin recognition,“ in *IEEE Transactions on Neural Networks 3*, 1992, pp. 272–279.
66. M. Reisert, O. Ronneberger and H. Burkhardt, “A fast and reliable coin recognition system,“ in *Pattern Recognition,* 2007, pp. 415-424.
67. D. G. Lowe, “Distinctive image features from scale-invariant keypoints,“ in *International journal of computer vision*, 2004, pp. 91-110.
68. M. D. Heath, S. Sarkar, T. Sanocki and K. W. Bowyer, “A robust visual method for assessing the relative performance of edge-detection algorithms,“ in *Pattern Analysis and Machine Intelligence*, IEEE Transactions on, 19(12), 1338-1359.
69. M. D. Heath, S. Sarkar, T. Sanocki and K. W. Bowyer, “Comparison of edge detectors: a methodology and initial study,“ in *Computer Vision and Pattern Recognition,* IEEE Computer Society Conference, 1996, pp. 143-148.
70. M. C. Shin, D. B. Goldgof and K. W. Bowyer, “Comparison of edge detector performance through use in an object recognition task,“ in *Computer Vision and Image Understanding*, 2001, pp. 160-178.
71. T. Peli and D. Malah, “A study of edge detection algorithms,“ in *Computer graphics and image processing,* 1982, pp. 1-21.

72. M. Reisert, O. Ronneberger and H. Burkhardt, “An efficient gradient based registration technique for coin recognition,“ in *Proc. of the Muscle CIS Coin Competition Workshop*, Berlin, Germany, 2006, pp. 19-31.
73. M. Pendse and Y. Wang, “Automated Coin Detection on Android Phone,“ 2012.
74. M. Nolle, H. Penz, M. Rubik, K. Mayer, I. Hollander and R. Granec, “Dagobert–A New Coin Recognition and Sorting System,” in *Proceedings of the 7th International Conference on Digital Image Computing-Techniques and Applications* (DICTA’03), Syndney, Australia, 2003.
75. K. Mikolajczyk and C. Schmid, “Scale and affine invariant interest point detectors,“ in *International Journal of Computer Vision,* 2004, pp. 63–86.
76. M. Sharifi, M. Fathy, and M. Tayefeh Mahmoudi,(2002, April) “A classified and comparative study of edge detection algorithms,“ in *Information Technology: Coding and Computing,* International Conference on IEEE*,* 2002, pp. 117-120.
77. W. Chen, “An improved SIFT algorithm for image feature-matching,“ in *Multimedia Technology* (ICMT), 2011 International Conference on. IEEE, 2011.
78. R. Maini amd A. Himanshu, “Study and comparison of various image edge detection techniques,“ in *International journal of image processing* (IJIP) 3.1, 2009, pp. 1-11.
79. H. Williams, J. F. Brenner and R. W. Neurath, “Cross-correlation digital registration techniques for multispectral cell images,“ in *Computers in biology and medicine,* 1978, pp. 71-80.
80. K. Ahuja and P. Tuli, “Object Recognition by Template Matching Using Correlations and Phase Angle Method,“ in *International Journal of Advanced Research in Computer and Communication Engineering*, 2(3), 2013.
81. A. Gavrijaseva, O. Martens, R. Land and M. Reidla, “Coin Recognition Using Line Scan Camera,“ in *Baltic Electronics Conference,* Tallinn, IEEE, 2014, pp. 161 - 164.
82. Y. J. Zhang, “A survey on evaluation methods for image segmentation,“ in *Pattern recognition*, 29(8), 1996, pp. 1335-1346.
83. A. Mahmood and S. Khan, “Correlation-coefficient-based fast template matching through partial elimination,“ in *Image Processing*, IEEE Transactions on 21(4), 2012, pp. 2099-2108.
84. K. Briechle and U. D. Hanebeck, “Template matching using fast normalized cross correlation,“ in *Aerospace/Defense Sensing, Simulation, and Controls* International Society for Optics and Photonics., 2001, pp. 95-102.
85. A. Gavrijaseva, A. Molder, O. Martens, C. Kyrkou and T. Theocharides, “Cross-Correlation-based Image Matching of Coins,“ in *Baltic Electronics Conference, 13th Biennial Baltic*, 2012, pp. 319-322.
86. E. H. Adelson, C. H. Anderson, J. R. Bergen, P. J. Burt and J. M. Ogden, “Pyramid methods in image processing,“ in *RCA Engineer*, 1984, pp. 33–41.
87. A. Gavrijaseva and O. Martens, “Image Based Counterfeit Coin Validation,“ in *Electronics Conference (BEC),* Tallinn, IEEE, 2014, pp. 153-156.

88. O. Martens, T. Saar, A. Gavrijaseva and A. Molder, “Variable-resolution image processing for validation of coins“, *Intelligent Signal Processing (WISP), IEEE 7th International Symposium*, 2011, Floriana, Malta, pp. 176-179.

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ABSTRACT

The project SAFEMETAL, which funded under the European Commission (EC) Seventh Framework Programme (FP7-SME) in 2010 – 2012, was focused on the development of advanced signal processing and data-fusion techniques able to discriminate between counterfeit and authentic euro coins [7]. Current thesis is motivated by the project described above and focused on:

1. Development, evaluation and testing of the electrical conductivity measurements (by eddy current method) based solution for euro coin validation and recognition;
2. Investigation, implementation and testing of the acoustic signal spectra based on FFT and modal analysis for euro coin validation;
3. Design, implementation and testing of the algorithm for visual based coin recognition and classification by cross-correlation and subsampling.

Conductivity measurement, using designed coil and calculation by Dodd-Deeds model, provide accurate low-cost, small dimension, promising solution for coin alloy validation.

Novel approach based on acoustic signal spectra investigation enables not only validate and classify all euro coins, but also detect counterfeit ones.

Imaging solution based on developed “matching pattern” by using cross-correlation function provide authentic coins recognition and classification as well as counterfeit and unfit coin detection. Proposed methods have been evaluated and tested in this work. The output of experimental results are presented and analysed.

The results of the experiments, based on electromagnetic, acoustic and visual features of coins, could be used as reference values for euro coin validation, recognition and classification.

KOKKUVÕTE

Euromündid on tänapäeval kõige paremini kaitstud raha maailmas. OLAF andmetel oli 2014. aastal ringlusest kõrvaldatud võltsitud euromüntide kogus umbes 175 900 ja Euroopa riikide kahju vähemalt 500 miljonit eurot.

Euroopa Tehnika- ja Teaduskeskuses on klassifitseeritud enam kui 80 valeraha klassi.

Euroopa Liidu FP7-SME projekt Safemetal (2010–2012) oli suunatud autentsete ja võltsitud müntide tuvastamiseks innovaatiliste signaali- ja pilditöötluse meetodite väljatöötamisele.

Käesolev doktoritöö on motiveeritud nimetatud projekti nõuetest ja käsitleb teemasid:

1. Pöörisvoolu põhise meetodi hindamine ja testimine mündi metalli elektrijuhtivuse mõõtmiseks. Mündi tuvastamine ja klassifitseerimine elektrijuhtivuse järgi;
2. Müntide tuvastus FFT ja modaal-analüüsi meetoditel põhineva akustilise signaali uurimise ja hindamise abil;
3. Müntide eristamiseks ja klassifitseerimiseks sobivate ristkorrelatsioonil ja alavõendamisel põhinevate pilditöötlus-algoritmide väljatöötamine ja hindamine.

Pöörisvooluga metalli erijuhtivuse mõõtmine Dodd-Deeds mudeli põhjal on efektiivne, odav ja kompaktne lahendus mündi valideerimiseks.

Akustilise signaali spektri analüüsil põhinevad uudsed lahendused võimaldavad tuvastada ja klassifitseerida nii ehtsaid kui võltsmünte.

Ristkorrelatsioonil põhinevad mustri-sobitusega pilditöötluse lahendused sobivad nii ehtsate, võlts- kui moondunud müntide tuvastamiseks.

Kõiki mainitud meetodeid on hinnatud ja analüüsitud teoreetiliselt ja eksperimentaalselt nii autentsete kui ka võltsitud müntide näidistega.

Läbiviidud eksperimentide tulemusena leitud müntide elektromagnetilised, akustilised ja visuaalsed tunnused on kasutatavad tugiväärtusena mündi tuvastamiseks, eristamiseks ja klassifitseerimiseks.

APPENDICES

PAPER I

"IMAGE BASED COUNTERFEIT COIN VALIDATION"

A. GAVRIJASEVA AND O. MARTENS

IEEE 14th Biennial Baltic Electronics Conference,
2014, pp. 153 - 156.

Image Based Counterfeit Coin Validation

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***Abstract*—This paper presents the imaging solution for counterfeit and unfit coin detection based on extraction of unique segments on the reference image to be used for cross-correlation matching for validation, calculation of the diameter and thickness of coin and extraction of symbols from the "third" side of a coin or edge. The selection method of the unique segments to be used for cross-correlation is described and analysed. In the validation by cross correlation technique at least two images of one coin are used: face side and edge side are used, providing the high accuracy of proposed solution.**

This algorithm was implemented and tested in Matlab. The results of experimental tests on real euro coin images are presented and analysed.

Keywords— image-based; unique segments; edge of coin; cross correlation, image processing, counterfeit coins;

I. Introduction

The European Anti-Fraud Office (OLAF) confirms that the euro coins are one of the most counterfeited currencies in the world nowadays [1]. According to European Central Bank (ECB, being responsible for detection, analysis and withdrawal of counterfeit euro coins) statistics the number of coins with denomination 50 cent, 1 euro and 2 euro in circulation (all over the European Union) in 2014 is about 17 millions [2].

In Table 1 the number of counterfeit euro coins detected in circulation all over EU is presented. In 2012 the total number of counterfeit euro coins withdrawn from circulation was about 184 000 units [2].

TABLE 1. Counterfeit euro coin detected in circulation all over EU

Year	50 cent	1 euro	2 euro	TOTAL	Value
2012	32 700	29 500	121 000	183 200	288 000
2011	28 400	32 800	96 300	157 500	239 600
2010	25 100	31 000	129 700	185 800	302 950
2009	18 100	26 500	127 500	172 100	290 550

According to the statistics of Estonian Forensic Science Institute (EFSI), the total number of counterfeit euro coins removed from circulation in Estonia in period 2011-2013 was 417 units, as presented in Table 2 [3].

The regulation (EU) No 1210/2010 introduces that all coins unfit for circulation and counterfeit coins have to be withdrawn, replaced and reimburse by EU countries. The EFSI is the only place in Estonia to verify the unusual coin. Thus the detection issue of counterfeit and unfit coins is relevant today and highly important [4].

TABLE 2. The number of counterfeit euro coins removed from circulation in Estonia

	50 cent	1 euro	2 euro	TOTAL
2011	1	26	77	104
2012	4	39	118	161
2013	0	21	131	152
TOTAL	5	86	326	417

Despite the fact that euro coin is one of the best protected currencies in the world, there are found more and more counterfeit coins every year. The quality of fake coins becomes better and more similar to real that makes it very difficult to distinguish. Detected illegal coins are analyzed and classified according to counterfeit classes [1].

The purpose of this paper is to present image based validation solution of counterfeit and unfit coins using cross correlation of unique segments of coin and also the "third side" of coin or edge.

The image–based validation can be used together with other (electromagnetic, acoustical and optical) sensors and corresponding signal processing [5].

Based on the analysis of EFSI [4], the most common features of detected illegal euro coins are:

- The outer circle of coin surface is uneven (irregular);
- The pattern of coin is not clear or relief;
- Symbols on the third side of coin are not clear or absent.
- Physical parameters of coin: size, weight, thickness, metal.

So, the first three aspects of the coins can be validated with corresponding image processing. The ultimate goal of the solution could be precise and fast automatic optical inspection (AOI) of the coins.

The edge of coin can be plain, reefed, lettered. The design of different types edges are known and presented on ECB web page.

Several papers were devoted to image based recognition and validation of the coins. Proposed in [6] solution for coin recognition describes the contour based algorithm, where the Bayesian fusion is used at the end of recognition process.

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Also, the contour and gradient based solutions can be considered with the edge based segmentation and generalized Hough transform [7].

This paper is focused on the defining of the inner and outer contours of the coin with the following cross-correlation image matching [8] based detection of counterfeit coins by intelligent finding of the most unique blocks of coin. The adaptive under-sampling can be used for fast findings in the first steps [9].

II. Description of Proposed Algorithm

At least two images of one coin are used in proposed solution: obverse and/or reverse and edge (as "third side") images. To mention here, while the obverse sides of the euro-coins are unique for every country, the reverse sides are identical for all countries [2]. So, the identification and validation of obverse sides has to consider the variants of the reference images and parts of them.

The architecture of coin detection algorithm is divided onto two parts: preprocessing and real time processing.

A. Preprocessing

In preprocessing stage the down-sampling of template image is applied to decrease the size of processed data and time of coin validation. For down-sampling the so-called *bicubic* function, where the output pixel value is calculated as the weighted average of pixels of the nearest 4x4 neighbourhood values, was preferred in comparison with nearest function (where nearest-neighbours interpolation are used) and bilinear function (where the output value is calculated by a weighted average of pixel values of the nearest 2x2 neighbourhood) [10]. This approach has been considered as more accurate approximation, but the most calculation intensive, compared with others, mentioned here. Fig.1 illustrates the results of implemented down-sampling methods and the original image, tested on 1 euro coin. Still, if going to final practical solutions, usage of more simple down-sampling kernels can be considered and investigated (also from the validation accuracy viewpoint).

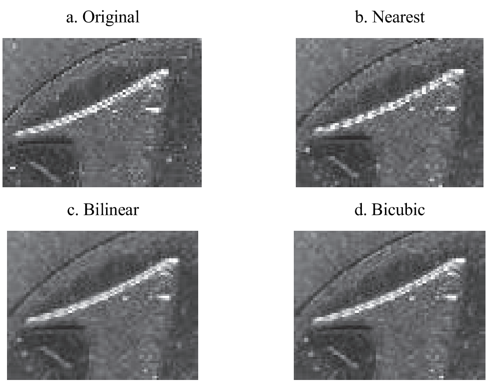


Fig. 1. Methods of 1 euro coin down-sampling: a. original image; b. nearest-neighbors interpolation; c. bilinear interpolation; d. bicubic interpolation.

Next, the template image is converted into binary image, based on threshold, which further reduces the size of data also.

The diameters of different denominations of coins are calculated from real images to get results in pixels and stored in the database. Inner and outer contours were calculated, as an example, during one experiment [11]. The results of diameter measurements compared with real diameter of coin, show that the inner diameter (green line) is more accurate than the outer one (Fig.2).

Fig. 2. Illustrated inner diameter of 1 euro and 2 euro coins.

The goal of image segmentation, used in presented algorithm, is to define blocks with most unique pattern with reasonably small size. The main criterion of unusual block definition is the minimum average level of cross-correlation within the template image.

The number of these blocks is selectable and depends on the system configuration setup. Three unique blocks were used in the experiments, to provide high accuracy of coin validation.

Finally, the thickness of coin was calculated (and stored) by found inner contour, using image of the coin edge.

B. Real Time Image Processing of Real Coins

The processing of images of real coins could be required to be a real-time process or at least the computationally faster solutions are beneficial.

To obtain the same scale data the down-sampling and converting into binary mode was implemented in the same way as in pre-processing stage.

Next, the diameter and thickness of coins by their images are calculated by the inner contour. The classification of coin denomination is established according to the results of this calculation.

Unique blocks of template image, defined in pre-processing stage, were used for coin validation and to define the position of coin regarding to template coin. As the correlation-based matching of coins is not rotation invariant- the determination of the position and rotation angle of the coin on the image frame by the correlation maximum for all possible positions and angles is computationally huge work- so the using of small unique block dramatically reduces the workload. So, the peak of the cross-correlation function value shows the relation between unique blocks of template image and all blocks of reference image and discovers precisely the place and position of unique block as well as position of coin, with significantly decreased number of calculations.

The detection of counterfeit coin by the "third" side of the coin, based on extraction of letters is suggested. Usually the title of manufacturing country (that can be identified by extraction of symbols) is located there. The image of coin edge is converted to grey scale, than canny feature detector is applied and further converted to binary scale. Template matching of binary image by cross-correlation has been implemented.

Finally, when the denomination of coin is recognized and the position of reference coin with respect to template coin is determined, the cross-correlation of template and reference image is calculated for counterfeit and unfit coin detection.

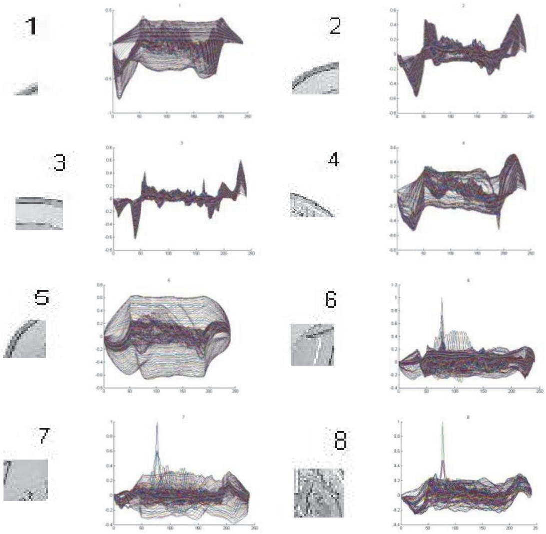
Calibration is not necessary because setup conditions guarantee the constant distance to object, light and speed of coin moving. In this stage the classification of coin denomination based on diameters of reference and template images of coins is executed.

III. Results of Experiments

In experiment the coins with denominations: 1 euro, 2 euro and 50 cent were used. As was described above two images of one coin were used in this solution. The initial size of font template image was 685x685 pixels. During practical test it was found, that the most efficient down-sampling factor was 0.35.

After image capturing, it was converted into a binary image, based on threshold. Then the diameter of template image was calculated, e.g. the size of 1 euro was in the experiment 168 pixels.

The experiments of finding of unique blocks have been repeated many times with different dimensions of segments. In practical way was determined, that for image with dimensions 240x240 pixels, the size of most efficient segment is 50x50 pixels. Fig. 3 demonstrates 16 segments of template coin (1 euro) and correspondingly 16 results of cross-correlation values. Results of cross-correlation function are obtained by correlation of all segments within the template image.



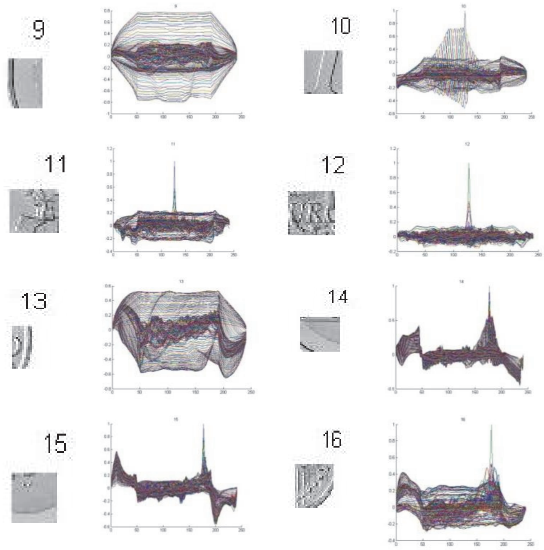


Fig. 3. Segments of 1 euro coin and according CC.

Cross-correlation functions with the single maximum and low average level are preferred. By visual estimation the most unique blocks are 6, 7, 8, 11 and 12.

To determine mathematically the minimum average level of cross-correlation three methods were implemented, the results were compared and analysed:

a) Minimum average level of absolute values within the block was calculated by equation:

$$average = \frac{\sum_{k=1}^{n} x_k}{n} \quad (1),$$

where x_k is absolute values.

b) Minimum average level of all positive values within the block was calculated by equation (1), where x_k is value greater than 0.

c) Minimum average level of all values within the block was calculated by equation (1), where x_k is any value.

The results of proposed methods are presented in Table 1, where *a*, *b* and *c* are proposed methods accordingly.

The most efficient blocks calculated by method *a* were: 8, 11 and 12. The most efficient blocks calculated by method *b* were: 14, 15 and 7. The most efficient blocks calculated by method *c* were: 14, 7 and 6.

In conclusion, we can summarize that most precise results was obtained by method *a*. According to results of described method the unique blocks was defined efficiently.

Next, the coin validation was carried out using unique segments of template image. The first point of this solution is – to define the position of coin relatively to the reference image- about the position and the angle.

TABLE 1. Minimum average level of image segments calculated by methods *a*, *b* and *c*

	1	2	3	4	5	6	7	8
a	0.168	0.152	0.110	0.197	0.185	0.076	0.067	0.097
b	0.541	0.519	0.538	0.524	0.506	0.492	0.471	0.509
c	-0.003	0.009	0.008	0.006	0.007	-0.001	-0.005	0.006

	9	10	11	12	13	14	15	16
a	0.149	0.078	0.078	0.033	0.212	0.108	0.140	0.118
b	0.554	0.494	0.517	0.507	0.524	0.444	0.480	0.462
c	0.007	-0.001	0.003	0.001	-0.003	-0.008	-0.001	0.001

In the next stage, the method ensures the validation of the coin. In Fig.4 the cross-correlation result of the first unique segment is presented. As seen, the cross-correlation peak is enough high to conclude that the coin was validated successfully.

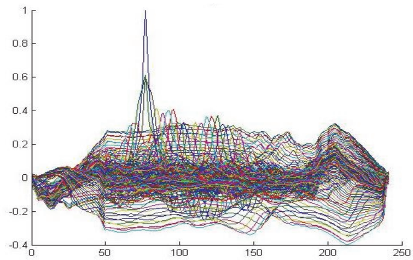


Fig. 4. Cross-correlation between unique block of template image and reference image.

The thickness of all coins could be calculated from the edge image by using inner contour detection technique.

Coins of 2 euro nomination contain symbols on the edge side (Fig.5). By this reason, the edge symbol extraction is the last step of the coin validation algorithm. Reading of the letters and symbols from the edge of the coin insures not only the high accuracy of coin validation but also to define counterfeit and unfit coin.

Fig. 5. Image of 2 euro coin edge.

After feature extraction technique by canny edge detector implementation, the template matching by cross-correlation is used for extraction of the symbol. In Fig. 6 is presented symbol *I* that was extracted from 2 euro coin during the experiment.

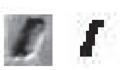


Fig.6. Extraction of symbol *I* from 2 euro coin.

When the diameter of coin was successfully determined, the denomination of the coin was classified as 2 euro coin, then the validation by third side starts. If all steps of suggested algorithm are successfully applied, the conclusion is – what nomination of the coin was under test and was is counterfeit or correct coin.

CONCLUSION

The coin validation (the counterfeit coin detection) solution has been proposed and investigated, by using of diameter founding and cross-correlation with pre-calculated unique segments of the reference images. Also, the extraction of the symbols from the edge of the coin was implemented, to increase the quality of the counterfeit coin detection. The solutions have been suggested and successfully tested.

As, by the reporting of ECB new types of counterfeit coins are found and withdrawn from circulation every year, the advantage of the proposed method is flexibility, as new known unique blocks for illegal coin detection can be included into algorithm easily.

Additionally to the proposed image –based validation also other tests could be added: weight and composition of the alloys used in coins (e.g. by electromagnetic sensors).

ACKNOWLEDGMENT

Current work has been supported by Doctoral School in ICT and by Estonian Research Council projects IUT19-11 and the European Regional Development Fund supporting the Centre of Research Excellence CEBE.

REFERENCES

[1] The European Anti-Fraud Office, http://ec.europa.eu/anti_fraud/

[2] The European Central Bank, https://www.ecb.europa.eu/press/pr/activities/bc/html/index.en.html

[3] The Estonian Forensic Science Institute, http://www.ekei.ee/orb.aw/class=file/action=preview/id=56065/V%F5ltsingute+n%E4ited+01+07+12.pdf

[4] B. Xiaoping and K. Rui. “A New Integer Programming Model about Counterfeit Coin Problem Based on Information Processing Method and Its General Solution“, In Information and Automation, Springer Berlin Heidelberg, 2011, pp. 508-513.

[5] A. Carlosena, A. J. Lopez-Martin, F. Arizti, A. Martinez-de-Guerenu, J. L. Pina-Insausti, and J. M. Garcia-Sayes, “Sensing in Coin Discriminators “, Sensors Applications Symposium, 2007. SAS '07. IEEE, pp.1-6.

[6] M. Zaharieva, M. Kampel, and S. Zambanini, “Image based recognition of coins – An overview of the COINS project”, in Proc. Of the 31st AAPR/OAGM Workshop, Krumbach, 2007, pp.57–64.

[7] M. Reisert, O. Ronneberger, and H. Burkhardt, “An efficient gradient based registration technique for coin recognition“, in Proc. of the Muscle CIS Coin Competition Workshop, Berlin, pp. 19-31, Sept. 2006.

[8] A. Gavrijaseva, A. Molder, O.Martens, C. Kyrkou, and T. Theocharides, “Cross-correlation-based image matching of coins”, IEEE Electronics Conference (BEC), 2012 13th Biennial Baltic, pp 319 – 322, Oct. 2012.

[9] O. Martens, T. Saar, A. Gavrijaseva and A. Molder, “Variable-resolution image processing for validation of coins“, 2011 IEEE 7th International Symposium, pp. 1-4, Sept. 2011.

[10] W. Pratt, Digital Image Processing, John Wiley, New York, 1978.

[11] D. Xu and K. Takis, “Detection and localization of edge contours“, International Society for Optics and Photonics, 2003, pp. 79-89.

PAPER II

"COIN RECOGNITION USING LINE SCAN CAMERA"

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IEEE 14th Biennial Baltic Electronics Conference,
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Coin Recognition Using Line Scan Camera

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***Abstract*—In this paper simple in realization efficient imaging solution based on line-scan (1-D) camera and PC (with low-cost hardware) for euro coin recognition and validation has been proposed and investigated.**

Various approaches for image-based coin validation have been discussed. In proposed solution a 128-pixel linear image sensor of line scan camera with intelligent coin detection algorithm allows achieving real time, accurate results with reasonable speed. This method has been implemented and tested using Matlab on real euro coins. The presented results show, that it is reasonable to use line scan camera in coin validation technology.

Keywords—image-based; unique segments; edge of coin; cross correlation;

I. Introduction

Nowadays millions of people use coins in daily life for different purposes: parking, self-services, gaming machines, etc. Thus the development of coin detection and validation technology has reached a great progress, but nevertheless there is still interest and need in a continuous research of cheapest, simplest and more efficient solutions.

There are developed various coin validators for fast and accurate coin validation, sorting and counting to provide stable working of all areas of industry and applications with coin validation units.

In modern coin validators different recognition and validation techniques are used [1], based on testing of physical characteristics of coins [2], such as size, weight, thickness and electro-magnetic characteristics [3]. The huge progress of the IT-technology in the field of the image acquisition and processing, it becomes possible to use smart, reasonably fast and complicated methods and algorithms for high accuracy image-based coin recognition, based on FFT [4], SIFT [5], correlation and other image-processing methods, but this leads to increasing of end-system price because of the required computational complexity.

One opportunity for imaging system development is implementation of line scan cameras [6], especially where the objects are passing through the sensors, what could be often the case for coin validation solutions. The medicine and product quality inspection are also some of the applications of line-scan-camera based solutions [7].

A. Line Scan Camera vs Area Camera

The main difference between line scan and area or frame scan cameras is the image capturing mode. The benefits of area camera are well-known: bigger size of frame and resolution means higher speed and accuracy. But actually – more larger the dimensions of the frame are - the longer time it takes to capture, transmit and store image to PC. To guarantee real time processing and decrease processing time of image the professional camera and high performance processor has to be applied. That causes the increase of the price of solution on the one hand. On the other hand, in real time processing every next frame with moving coins contains a lot of redundant information from previous one, what is practically useless and have to be filtered out.

Thus, the line-scan camera implementation ensures the continuous image acquisition without overlapping with minimum level of redundancy. The minimization of redundant data decreases significantly the size of real time processing array, therefore less storage space and processor performance are required.

The maximum spatial resolution of the modern line scan camera can be up to 12000 pixels [8]. For example, the dimensions of frame of PixeLINK industrial camera vary from 752x480 to 3000x2208 pixels, depending on camera model and the price is accordingly from 565.25 to 1,230 euros [9].

Thereby, the combination of high accuracy and cost efficiency can be ensured by installation line scan cameras into coin recognition solutions.

B. Previous Work

The research approaches in coin detection and recognition area through digital image processing include demonstration of intelligent methods and algorithms that can be implemented efficiently in real-time. In the paper [10] authors present rotation invariant circular histogram based image processing, where are indicated 30 most characteristic pixel blocks with dimensions 20x20 for coin detection and recognition.

Proposed in [11] algorithms of template matching based on cross-correlation and Canny feature detection provide achieving of high precision results at reduced number of computations.

Presented in paper [12] adaptively subsampled cross-correlation approach, SIFT feature point detection and intelligent segmentation methods show reasonable speed and

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good results of image based coin detection and recognition. The main disadvantage of this method is a great number of computations.

Paper [13] gives an overview and comparison of different technologies for modern and ancient coin recognition. The presented experiments show that best results are achieved with the following techniques: decision tree, edge angle and distance distribution, neural network pattern averaging etc.

The comparison and analyses of four methods for edge detection with high accuracy by 1-D optical sensor are presented in paper [14]. As result of described experiments, the efficient methods could use the grey level moment and approximation with Erf (so called error) function based (AEF) methods.

One of latest works [15] describes Hough transform based automated coin detection for Android phone, using the embedded phone camera. The main issue of this approach is that camera and coins must be parallel in respect to each other, otherwise inaccuracy in coin radius detection will occur.

For the described above technologies, based on external and texture characteristics of coins, frame cameras are frequently used. Although it is important to note, that the resolution of area cameras and camera price are correlated: the higher resolution – the higher price. Thereby, there are still actual issue of developing high speed, real time coin image processing algorithms and methods with acceptable cost.

The goal of this work is to present a novel setup based on line scan camera combined with fast, intelligent algorithm of coin recognition by combining segmentation and cross correlation for euro coin recognition. Described solution has been implemented on Parallax TSL1401 Line scan camera, the "Piccolo" TMS320F28069 Digital Signal Controller (DSC)-based USB-stick, acting as simple low-cost interface between camera and PC.

II. Practical Test Setup

The setup of proposed solution consists of Parallax TSL1401 Line scan camera, terminal device (PC), the Piccolo DCS as interface between the camera and the coin stand with rotating euro coins (Fig.1).

The camera has simple analog output, so the internal 12-bit fast ADC of the Piccolo DSC can be easily installed for connection to the camera. This solution allows to increase the image acquisition speed up to several megapixels per second, with corresponding speed improvement. The maximum speed of transmission of TI board is 5 MB/s.

The stand with rotating coins, the velocity of which can be controlled by testing person, simulates the coin moving process through validation device.

With clock frequency 800 kHz and 128 pixel length of line, one line capture speed is about 0.16 ms and transmission time is about 3.28 ms. The total transmission time of one line array is about 3.49 ms that means scan speed is 287 lines per second. Thus frame rate of presented camera is about 2.27 frames per second when size of one image is 128x128 pixels.

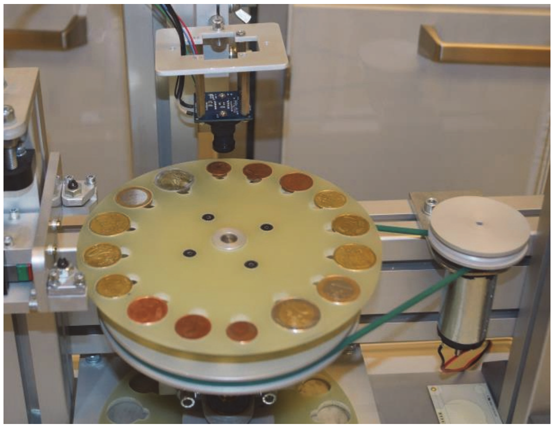

Fig. 1. Setup with line scan camera Parallax TSL1401 and coin stand with rotating euro coins.

The main characteristics of camera under experiments are:

- 128-pixel linear image sensor;
- Focusable imaging lens;
- Resolution 128 pixels (grey scale); 255 pixels (interpolated binary);
- Dimensions (with lens) are: 1.35x1.35x1.22 in (34.3x34.3x31mm).

Additionally, in order to obtain higher transition time in current experiment the binary format of data is used instead of the ASCII-based one.

III. Algorithm for Coin Recognition

Suggested algorithm for coin recognition is simple and based on the determination of the diameter of the coin. The cross-correlation along some parts of the coin (eg over the diameter of the coin or the neighborhood of it) with reference templates is performed.

This solution has been implemented and tested on Matlab. The main steps include the following manipulations:

- Data capturing (grey scale) form line scan camera;
- Creation of the image frame in the software;
- Edge detection by Canny algorithm or optional thresholding;
- Estimation of the diameter of coin;
- Diameter based euro coin classification;
- Additional cross-correlation based recognition of classified coin.

The one-dimensional array from camera to TI board was sent for frame data collection. The dimensions of frame were 128x138 pixels. Then data was transmitted to PC by frames, converted and stored as *.txt ASCII file or alternatively, in raw binary format.

Depending on moving speed of coin under the camera, the information of collected data could vary. At a standard moving speed the collected data covers the coin totally (Fig. 2, left). In case of high moving speed, the data is obtained with intervals or sampled (Fig. 2, right).

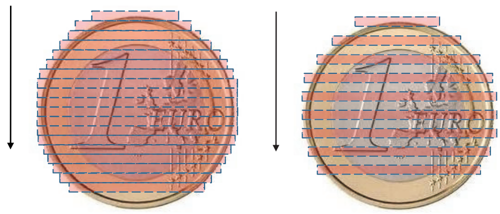

Fig. 2. Data acquisition under camera: with a standard speed of the coin (left); with a high speed of the coin (right).

While in one dimension (up to down on the Fig. 2) the virtual size (diameter) of the coin is depending on the speed of the moving of the coin, then in other dimension (left to right on the same Fig. 2) is constant and can be used to determine the actual size of the coin, the speed of the movement and the scale of the “up-to-down” scale to be used in correlation and other calculations.

Using of sampled data provide to increase of the speed of coins passed through detector. One of the ways to create image from sampled data is to use the spline interpolation function.

The real euro coin image captured from line scan camera with the standard moving speed is created experimentally in Matlab and shown on Fig. 3.

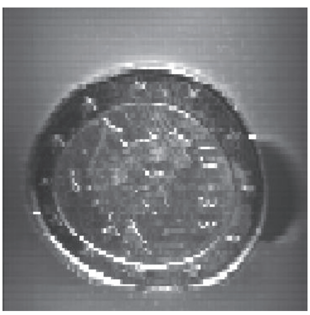

Fig. 3. Frame created from line scan camera data.

Next, the Canny Edge detector is applied to the grey scale image, which ensures strong edge discovering of coin.

Fig. 4(a) shows the euro coin image after Canny Edge detector implementation. In this stage the thresholding instead of Canny detector of the gray scale image is also acceptable and demonstrate good result which is presented on Fig. 4(b). Thereby, we localize boundaries of coin by filtering limits. For diameter calculation was used minimum and maximum points of coin width.

Fig. 4 (a) Frame after canny edge detector, (b) frame after threshold.

Finally, the cross-correlation function of classified template image and reference image of euro coin is applied for recognition. In Fig. 5 is submitted the result of cross-correlation function applying.

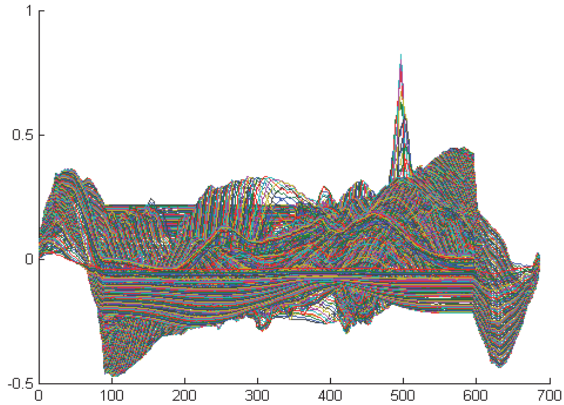

Fig. 5. Cross-correlation function of classified template image and reference image of euro coin.

IV. Results

In this paper novel, cost efficient, computationally expensive, easy in implementation with reasonable accuracy based on line scan camera setup for euro coin recognition was presented. The image processing algorithm was implemented and tested on Matlab, and performed on real euro coin images with denomination: 2 euro, 1 euro, 50 cent and 20 cent. In a practical way calculated diameters of real coins are presented in Table 1 in pixels, coin dimensions in mm are provided by Bank of Estonia.

All denominations of euro coins have unique technical specifications including dimensions, defining the diameter of euro coin in pixel is sufficient for classification of coin denomination. The calibration is not necessary because the reference image was captured at the same conditions as template image (distance and illumination).

As follows, 1 mm corresponds to near 4.83 pixels. The accuracy of practical measurements calculated by mean absolute error and is about ± 0.68 % of the full scale (so in absolute terms – below 1 pixel or about 0.2 mm.

TABLE 1. Results of experiment

	2 euro	1 euro	50 cent	20 cent
Diameter in mm	25.75	23.25	24.25	22.25
Measured diameter in pixels	~ 121	~ 114	~ 117	~ 106

Further improvement in the resolution and accuracy of the diameter measurement can be achieved by various interpolation techniques, for example, to use not only the maximum length (diameter) line length, but more neighborhood information.

Described algorithm for coin detection and validation takes into account the peculiar properties of line scan camera that makes solution simple and cost efficient.

The maximum capturing speed of proposed algorithm based on line scan camera is about 136 frames per minute. It means about 120 euro coins can be recognized per minute. The price of described one-dimensional camera is about 50 euros as a board (probably the imaging sensor itself much cheaper), what makes current solution cost efficient.

But suggested setup is not all-purpose solution and has some limitations, such as:

- Accuracy linearly depends on camera resolution and it is smaller than resolution of area cameras;
- Capturing speed is limited by camera parameters;
- Image based approach does not allow identify physical characteristics (magnetic properties, weight).

Obtained results demonstrate that implementation of line scan camera is reasonable in coin recognition application, where significant decrease of redundancy in image processing, simplicity of installation and price of the coin validation system are important.

CONCLUSIONS AND FUTURE WORK

This paper presents a solution for euro coin recognition based on 128 pixel linear camera and combined with accurate and resource efficient algorithm. The experimental results show the reasonable accuracy of coin recognition at the considerably reduced price of the end-system.

Thus this solution could be interesting for the industry, especially for the cost sensitive applications. The real time processing and efficient cost makes it possible to implement it in specific areas of industry, where use of area cameras is limited by some reason.

To improve algorithm, the image can be processed by one acquired 1D-line at a time, just by the DSC in real-time, so simplifying the data processing.

Further development of setup can be achieved by improving algorithm of coin detection and transferring module with calculations from PC to the Texas Instruments DSC. In this case the image processing algorithm will be transferred to the DSC, having reasonable processing power (about 200 MMACs of 16x16-bit calculations) and program (Flash, 256kB) and data (SRAM, 100kB) memory.

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REFERENCES

[1] W. Pratt, Digital Image Processing, John Wiley, New York, 1978.

[2] D. Mehta and A. Sagar, “A survey on various techniques of coin detection and recognition”, in International Journal of Computer Applications 69(5), New York, 2013, pp 28-32.

[3] R. Gordon, O. Märtens, R. Land, M. Min, M. Rist and A. Gavrijaševa, “Eddy current validation of euro-coins”, Lecture Notes on Impedance Spectroscopy: Measurement, Modelling and Applications, 3, 47, London, 2012, pp 47–63.

[4] K. Fredriksson and E. Ukkonen, “Faster template matching without FFT“, IEEE Image Processing, vol. 1, 2001, pp. 678-681.

[5] N. Y. Khan, B. McCane and G. Wyvill, “SIFT and SURF performance evaluation against various image deformations on benchmark dataset”, IEEE Digital Image Computing Techniques and Applications, Dec. 2011 pp 501–506,

[6] M. Huang, “PC-based line-scan imaging systems”, Adlink Technology Inc, Sep. 2005.

[7] D. H. Joeng, Y. R. Kim, K. M. Lee, K. W. Jin and C. G. Song, “The design and implementation of linescan camera based real-time image scanning system“, 2008.

[8] Introduction to Line Scan Cameras, Schäfter + Kirchhoff GmbH. http://www.sukhamburg.com/products/line-scan-cameras/introduction.html

[9] Edmund Optics Inc., PixeLINK technical documentation. http://www.edmundoptics.eu/imaging/cameras/usb-cameras/pixelink-usb-2-0-cmos-cameras/2569?showall#products

[10] A. Molder, O. Martens, and T. Saar, “Adaptively undersampled, circular histogram based image processing for rotation invariant coin detection”, IEEE Electronics Conference (BEC), 2012 13th Biennial Baltic, Oct. 2012, pp 137–140.

[11] A. Gavrijaseva, A. Molder, O.Martens, C. Kyrkou, and T. Theocharides, “Cross-correlation-based image matching of coins”, IEEE Electronics Conference (BEC), 2012 13th Biennial Baltic, Oct. 2012, pp 319–322.

[12] O. Martens, T. Saar, A. Gavrijaseva and A. Molder, “Variable-resolution image processing for validation of coins“, 2011 IEEE 7th International Symposium, Sept. 2011, pp. 1-4.

[13] S. Modi and S. Bawa, “Image processing based systems and techniques for the recognition of ancient and modern coins”, in Computer Analysis of Images and Patterns, Springer Berlin Heidelberg (IJCA), Dec. 2013, pp. 547-554.

[14] M. Hagara, P. Kulla, “Precise edge detection in 1-D images for contactless measurement of object“, in Proc. of the 9th International Conference, Measurement 2013, Smolenice, May 2013.

[15] M. Pendse and Y. Wang,Y, “Automated Coin Detection on Android Phone“, Stanford University.

PAPER III

"EDDY-CURRENT VALIDATION OF EURO COINS"

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2012, pp. 47 - 63.

Eddy current validation of Euro-coins

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ABSTRACT: The measurement of electrical conductivity using eddy current (electro magnetic induction) sensors is the most promising solution for validation of metal coins in coin handling devices, as the electrical conductivity is a very distinctive property of specific alloys. Low cost, simple and robust nature, and also possibility for high-speed precise measurements are the advantages of electromagnetic sensors. Multi-frequency scanning the coins under test at various field penetration depths is preferred due to the sophisticated "construction" of various alloys in nowadays coins. Air-core measurement coils have an additional advantage—a possibility to measure absolute values of conductivity without repetitive calibration of sensors and the measurement systems. Development of solutions for eddy-current validation of metal coins has been investigated together with comparing the experimental results with the values derived from theoretical models. Frequency range of 10 kHz to 10 MHz have been considered (particularly up to 500 kHz for precision measurements) and conductivity values to be measured from 4 to 40% of IACS (International Annealed Copper Standard) conductivity (about 60 MS/m). The results demonstrate that the precise, high-speed, low-cost and robust coin validation system can be developed on the basis of air-core coil arrays.

Keywords: coin validation, eddy current, inductive sensors, conductivity, coin validation, electromagnetic sensors

1 INTRODUCTION

Electrical conductivity is one of the most distinctive properties of various metal alloys (Rossiter 1991). So the electrical conductivity of metal coins consisting nowadays of sophisticated alloys and structures, are widely used for coin discrimination and validations, as proposed in (Howells 2009, Harris, Churchman, Sharman, et al., 2007). Frequently this method is used in combination with other (acoustical, imaging) sensors and corresponding signal processing (Carlosena, Lopez-Martin, Arizti, Martínez-de Guerenu, Pina-Insausti, and García-Sayés 2007). A clear model for analysis of the impedance of the measurement coil placed above the metal plate has been developed by Dodd and Deeds. Their analytical (Dodd and Deeds 1968) and numerical results (Dodd and Deed 1975) are published more than 35 years ago already. In the last work (Dodd and Deed 1975), only active (real) part of the coil impedance (losses in the measurement coil) has been considered in the calculations. In the work (Bowler and Huang 2005) by Bowler and Huang, both eddy current and contact-based (ohmic) measurement theory for metal plates has been investigated, theoretically and experimentally in parallel. More advanced numerical model for eddy-current simulations has been developed and published by Theodoulidis and his colleagues (Theodoulidis and Kotouzas 2000) in 2000.

These simulations are valid for the air-core coil based conductivity measurements with "infinite" size of metal plates, consisting of one or several metal layers. The "infinite" size is typically not very significant constraint for real-life measurements, as the eddy current electro-magnetic fields are decreasing quickly in the media. Only a few millimetres larger metal plate than the sensor's size is typically enough to have reasonably precise results.

By using the complex value (real and imaginary parts) measurements of the coil impedance and the inverse model against the previously described simulation modeling, both conductivity value and liftoff between a measurement coil and a measured metal piece could be found. Such solution has been also described in the patent (Snyder 1995).

2 MEASUREMENT AND THEIR INVESTIGATION

For investigation and concept validation, two measurement coils has been prepared:

1. a flat wound coil N14 (inner diameter $d = 3$ mm, outer diameter $D = 20$ mm, $N = 200$ turns, $r_0 = 22.856\ \Omega$), see figure 1.
2. a PCB based coil array RR1 of 5 coils (for each $N = 40$, outer diameter $D = 14$ mm, $r_0 = 7.441\ \Omega$), see figure 2.

Impedance of the both types of coils, the N14 and the third (middle) coil RR1-3 of the array RR1 has been measured in the air against 4 metal plates having different conductivities (Fig. 3):

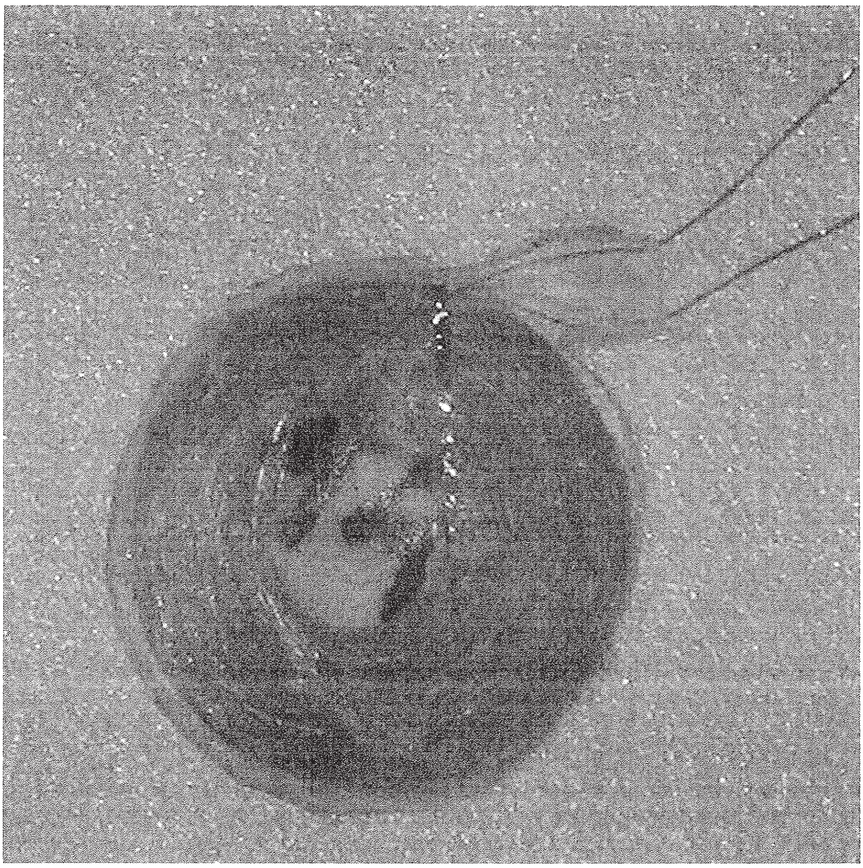

Figure 1. Coil "N14" ($d = 3$ mm, $D = 17$ mm, $N = 200$).

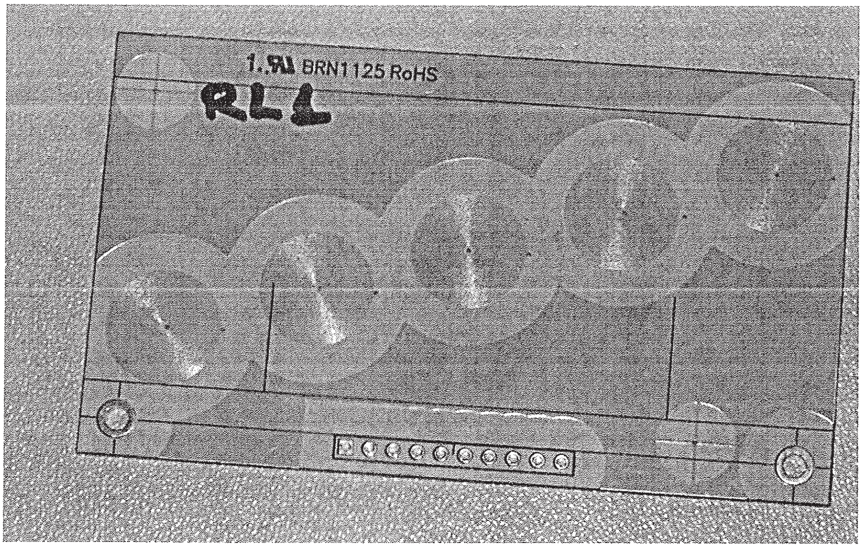

Figure 2. Planar (PCB) sensor array "RR1" of 5 coils ($N = 40$, $D = 14$ mm), used in the experiments.

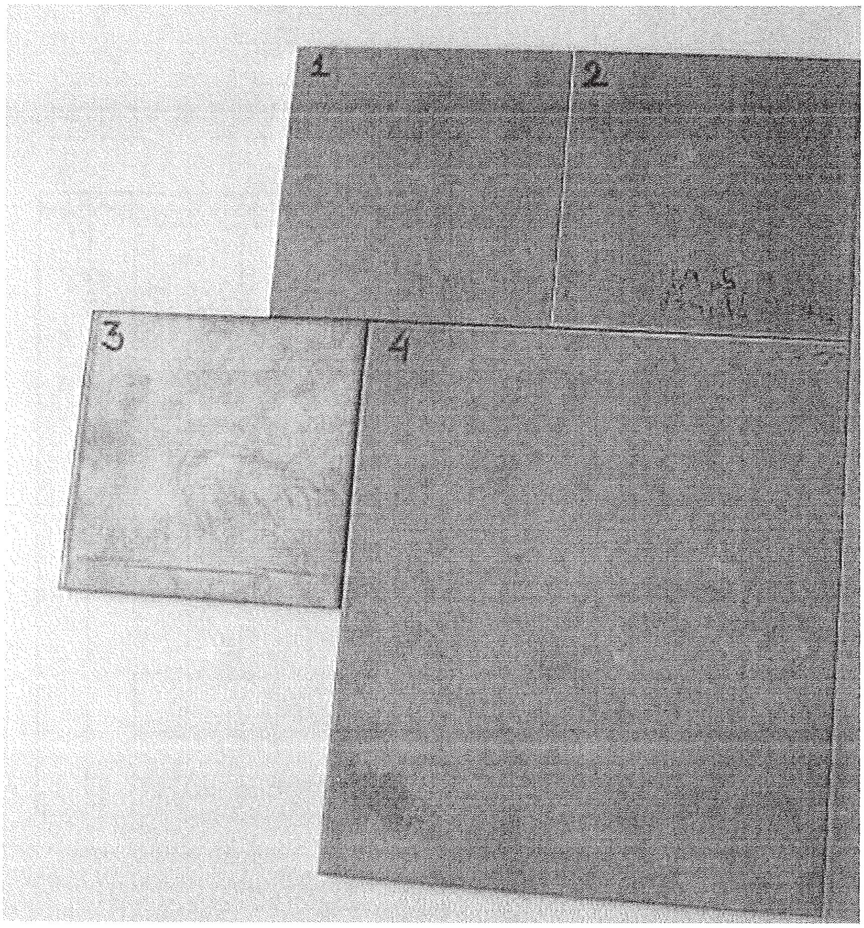

Figure 3. Metal plates with various conductivities.

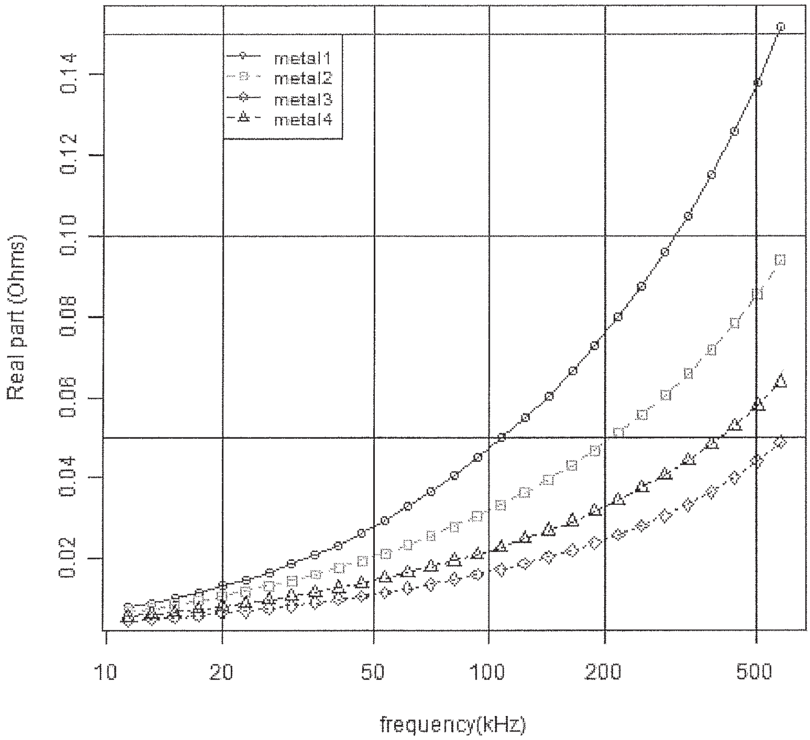

Figure 4. Real part of the N14 coil impedance.

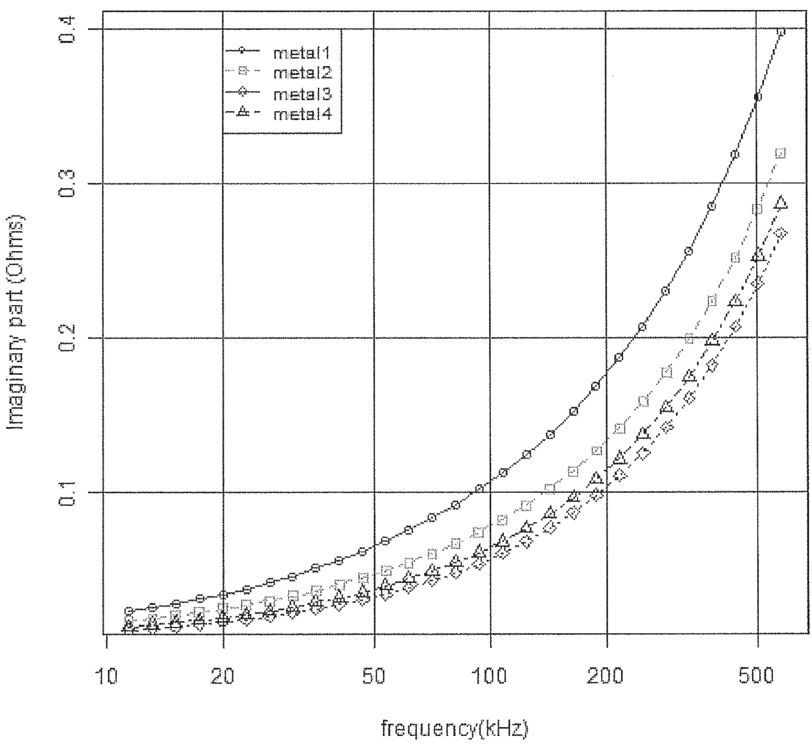

Figure 5. Imaginary part of the N14 coil impedance.

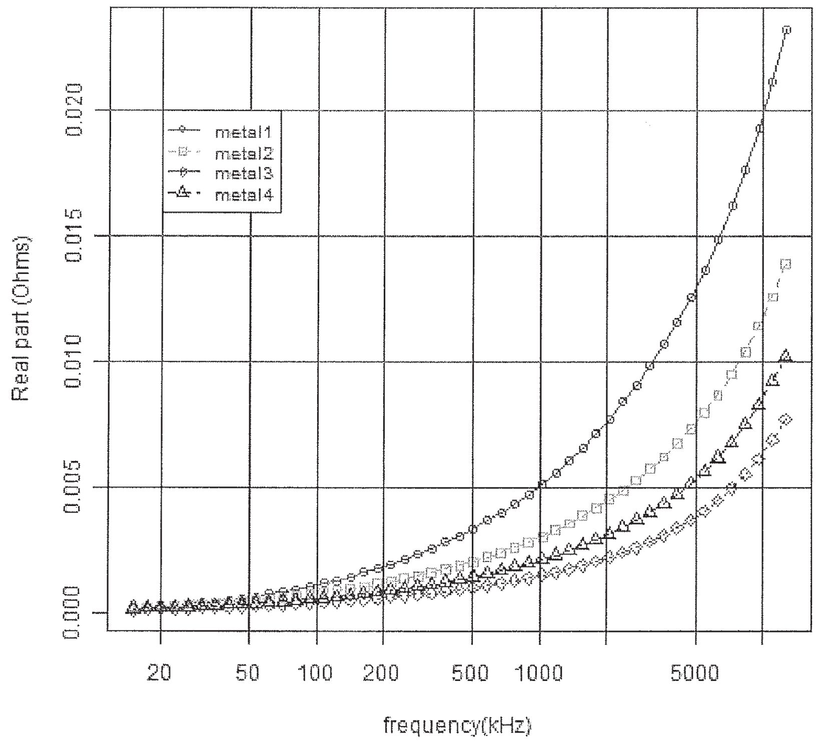

Figure 6. Real part of the RR1-3 coil impedance.

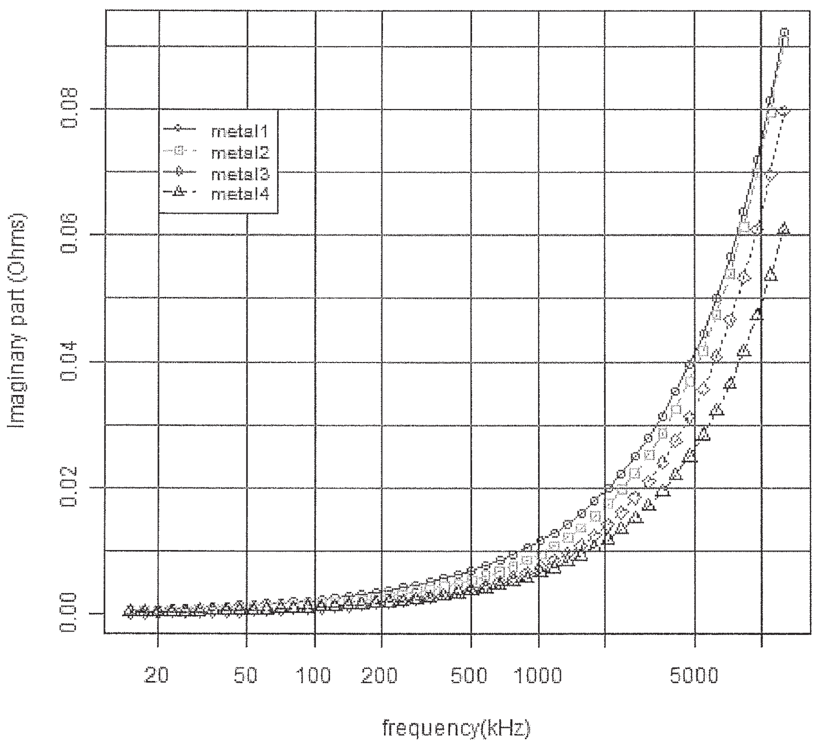

Figure 7. Imaginary part of the RR1-3 coil impedence.

"metal1" (CuNi, 3.11 MS/m), "metal2" (Nordic Gold, 9,6 MS/m), "metal3" (45 MS/m) and "metal4" ("Brass63", 26.6 MS/m).

As previously described theoretical models consider zero-level real component of the impedance of the coil "in air" (with metal plate or coin near the coil), the ohmic resistance of the coils ($r_0 = 22.585\ \Omega$ for N14 and $r_0 = 7.441\ \Omega$ Ohm for RR1-3) is subtracted from the measured results before their using in the models and showing in the Figures below.

In the experiments approximate lift-off of 0.2 mm has been hold. The following impedance analysers have been used in the experiments: 1) 6500 Series Precision Impedance Analyzer, 20 Hz–120 MHz, from Wayne Kerr Electronics, and 2) HF2IS Impedance Spectroscope, 50 MHz, 210 MSa/s, from Zurich Instruments.

The measured impedances of the measurement coils (in Ω) are given as follows—for N14, the real part in Figure 4 and imaginary part in Figure 5, for RR1-3, the real part in Figure 6 and imaginary part in Figure 7.

3 REVERSE ESTIMATION OF CONDUCTIVITY FROM THE MODEL

To estimate the possibilities for precise measurement of the conductivity by using previously described models of Dodd and Deeds (Dood and Deeds 1968, Dodd and Deed 1975) and Theodoulidis (Theodoulidis and Kotouzas 2000), a reverse simulation model have been developed as a C/C++ software for iterative finding of the best match for lift-off and conductivity of the metal under test. The results of the estimated (from the previously measured real and imaginary parts of the coil impedance) conductivities for metal plates 1 to 4 are given in figures below in the frequency range up to 500 kHz for N14 and up to (?, 10) for RR1-3.

This combined theoretical-experimental investigation shows the possibilities to use eddy current approach with a coil-in-air sensor for reasonably precise (in some % accuracy)

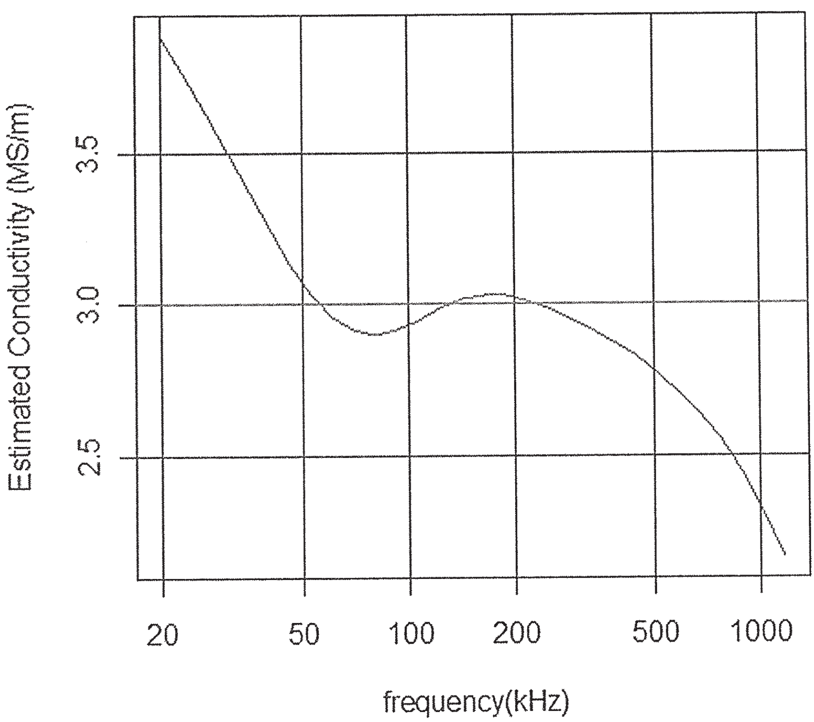

Figure 8. Back estimated conductivity for N14 coil and "metal1".

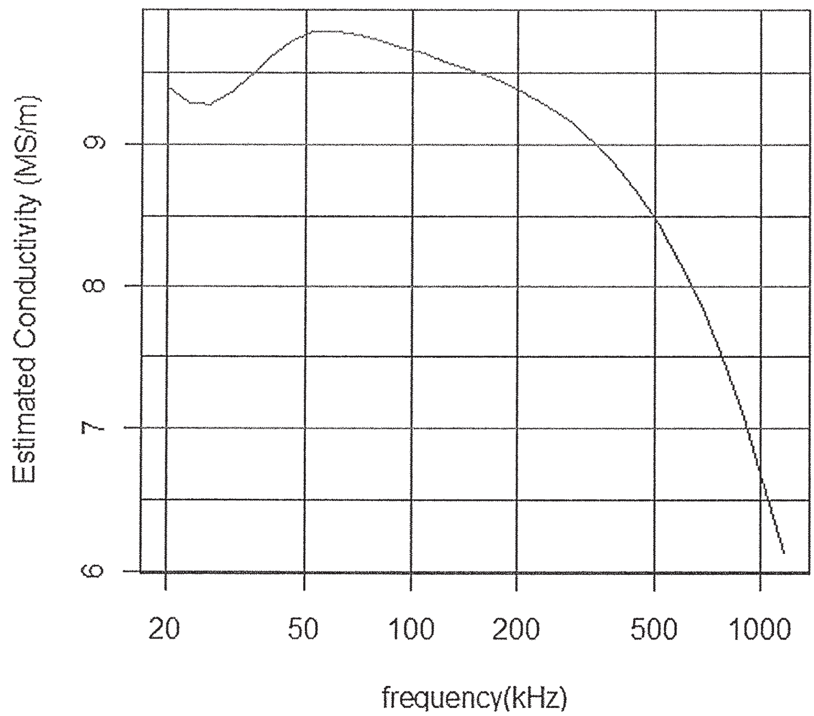

Figure 9. Back estimated conductivity for N14 coil and "metal2".

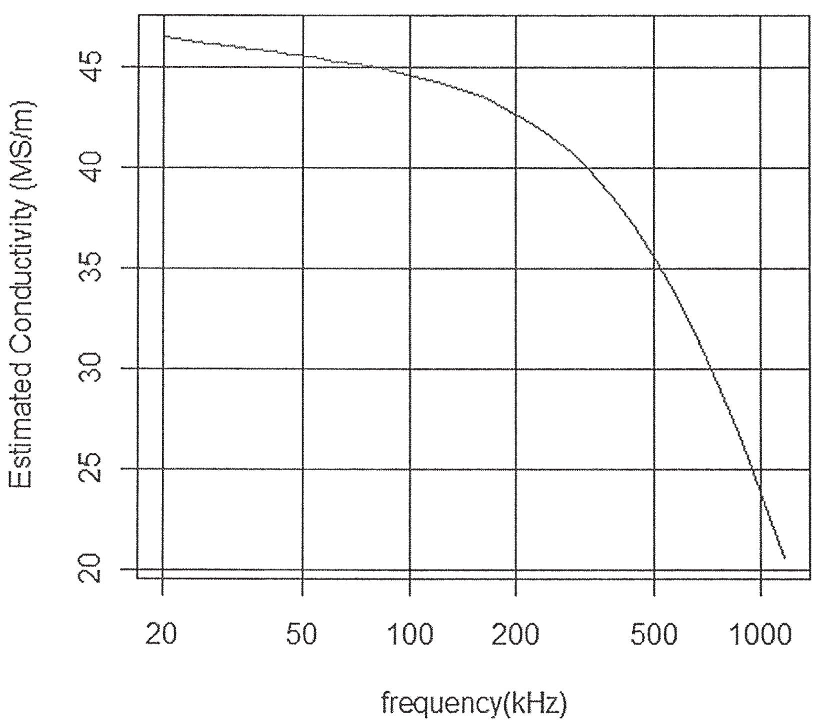

Figure 10. Back estimated conductivity for N14 coil and "metal3".

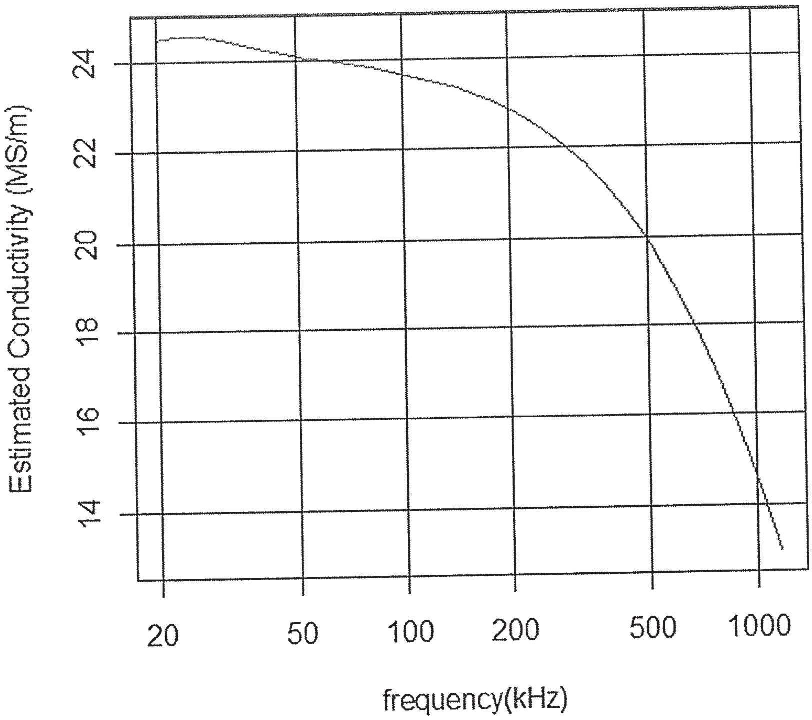

Figure 11. Back estimated conductivity for N14 coil and “metal4”.

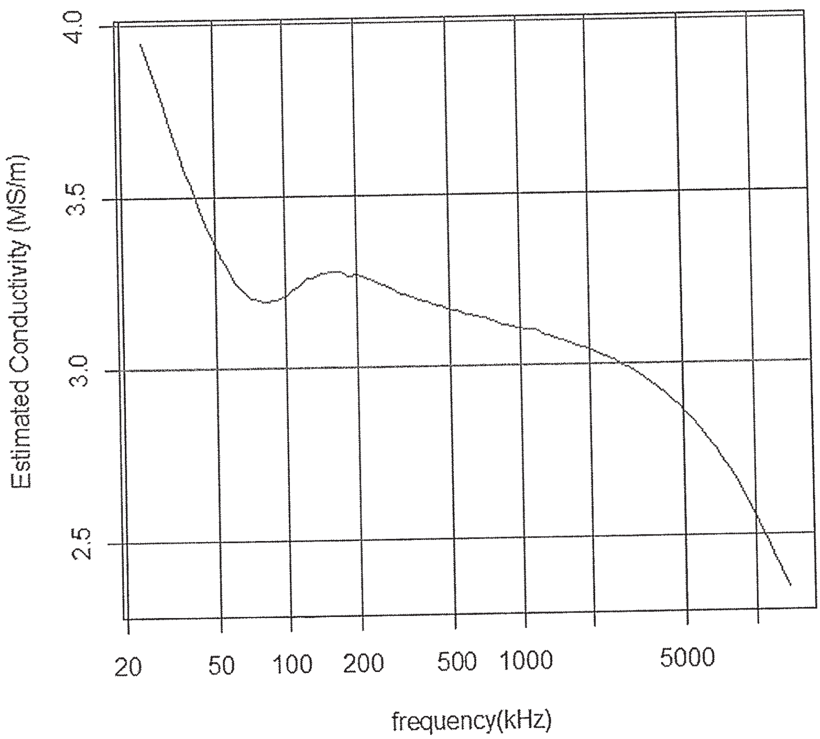

Figure 12. Back estimated conductivity for RR1-3 coil and “metal1”.

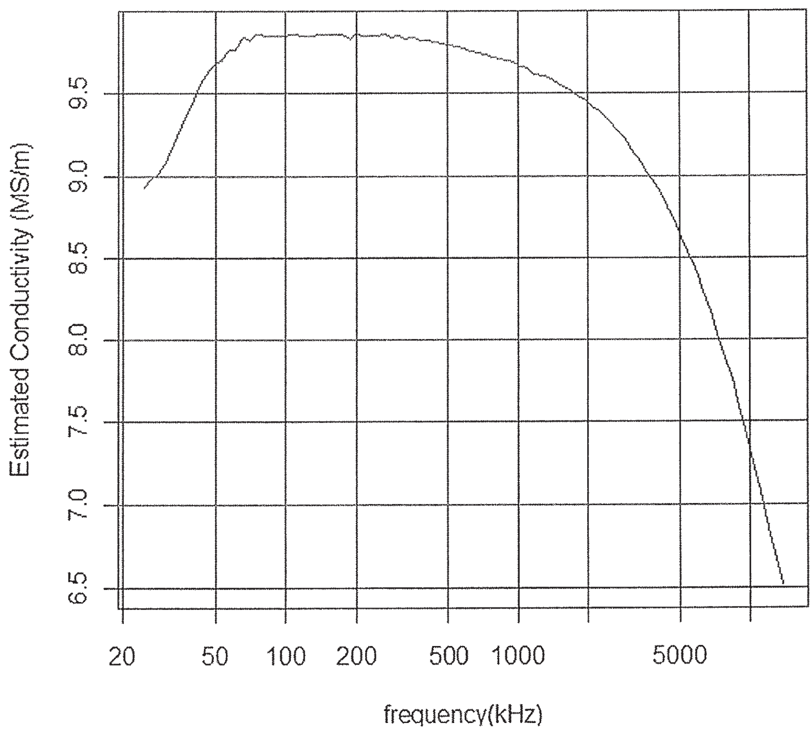

Figure 13. Back estimated conductivity for RR1-3 coil and "metal2".

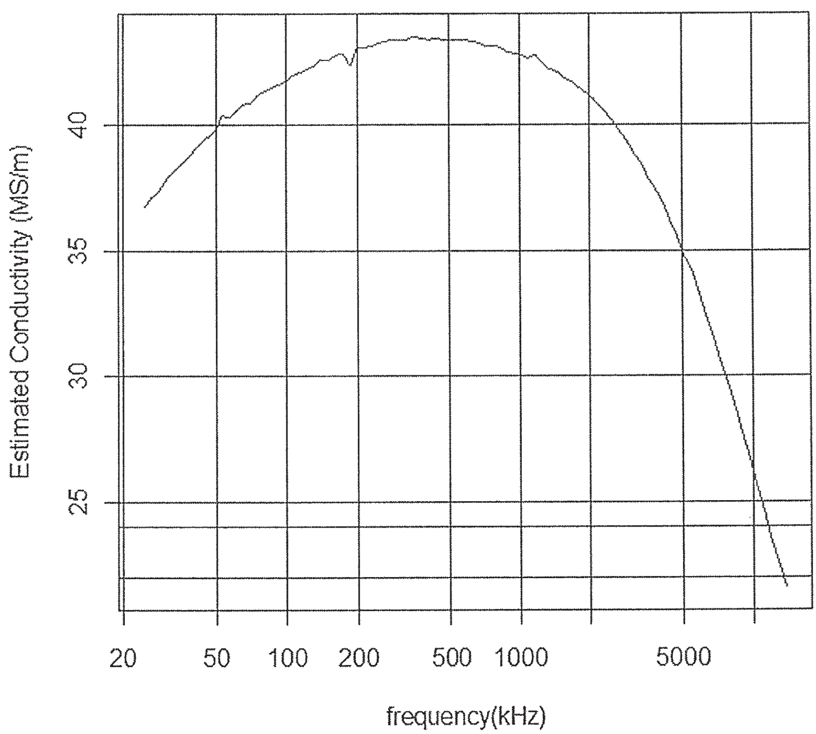

Figure 14. Back estimated conductivity for RR1-3 coil and "metal3".

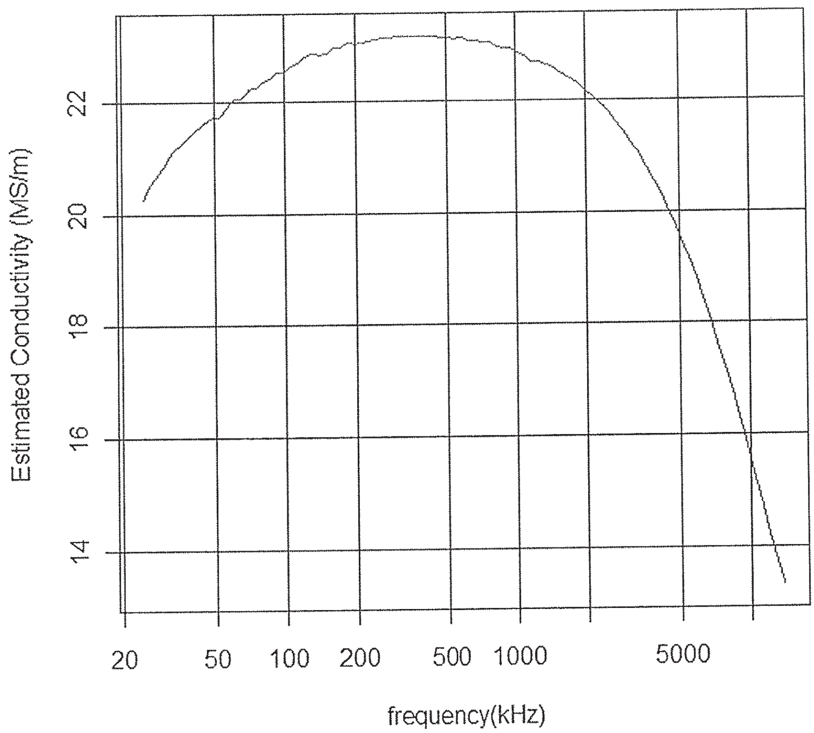

Figure 15. Back estimated conductivity for RR1-3 coil and "metal4".

electrical conductivity measurement. N14 can be used up to 500 kHz and RR1-3 up to 10 MHz measurements. At higher frequencies, corrections should be introduced to correct systematic frequency response errors.

4 FEM-SIMULATIONS

To validate the used direct- and reverse models, additionally to fitting the experimental data to theoretical (Dodd-Deeds etc) models, also a FEM simulation of the measurement setup (coil above the metal plate) has been done for RR1-3 coil above "metal2" (Nordic gold). COMSOL multiphysics-FEM simulation software package has been sued for such simulation. Got by COMSOL impedance results were used as input to the reverse model of Dodd-Deeds etc, and the results (Fig. 16) show the good correspondence of the models.

5 EXPERIMENTAL MEASUREMENT OF COINS

As PCB based coil array is more reasonable technologically and also has wider frequency range, so the RR1-3 coil was further investigated to be used for coin validation. So, the impedance (real and imaginary parts) against various Euro-coins (5 cent, 50 cents and 1 Euro and 2 Euros) has been measured (at frequencies up to 500 kHz and up to 10 MHz) (Fig. 17–21) and also the "effective" conductivity has been estimated back, according to Dodd-Deeds models, as described before (Figs. 21–24).

The investigation shows the benefits of using of various (at least two different) frequencies, to distinguish various coins. One possibility (according to Fig. 17–20) seems to be using of one frequency about of 20–30 kHz or another of 100 or 200 kHz. Also adding of a frequency of eg. 5 MHz could be useful.

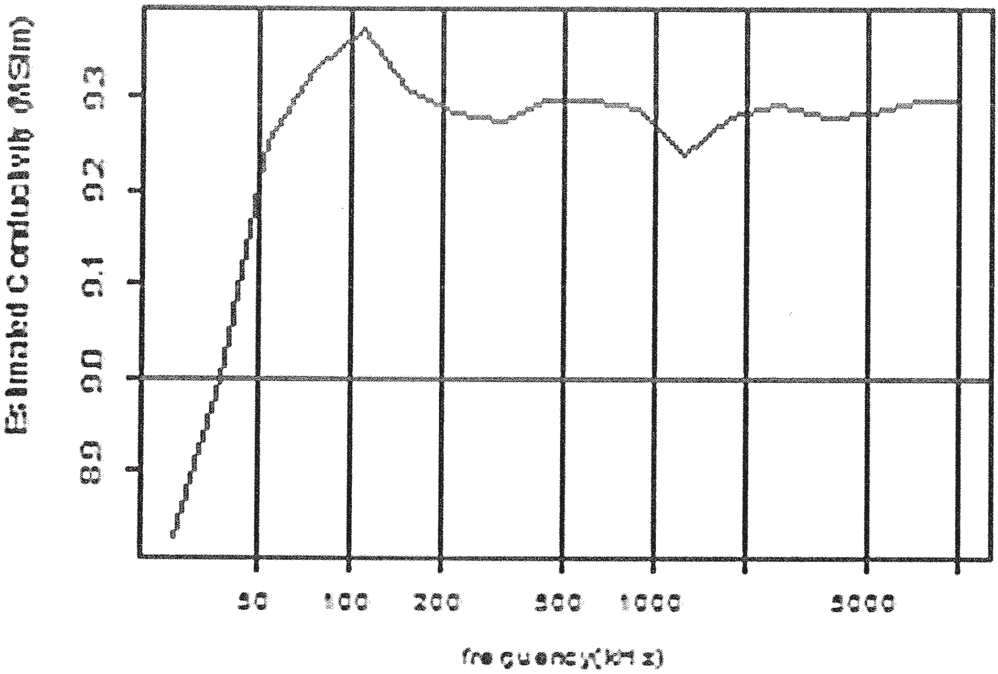

Figure 16.   Back estimated conductivity from COMSOL multiphysics..

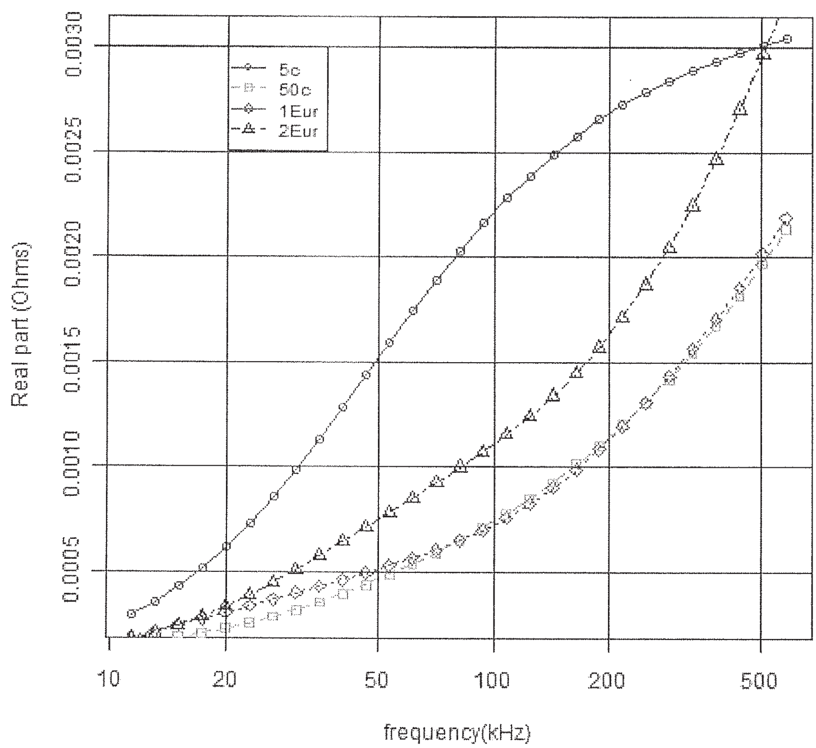

Figure 17.   Real part of the RR1-3 coil impedance, up to 500 kHz.

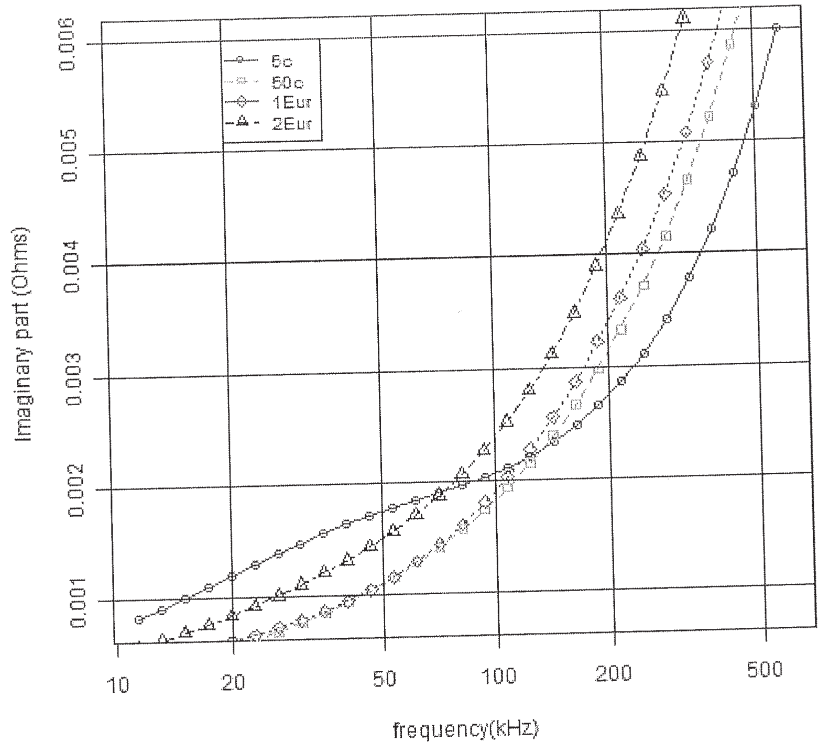

Figure 18. Imaginary part of the RR1-3 coil impedance, up to 500 kHz.

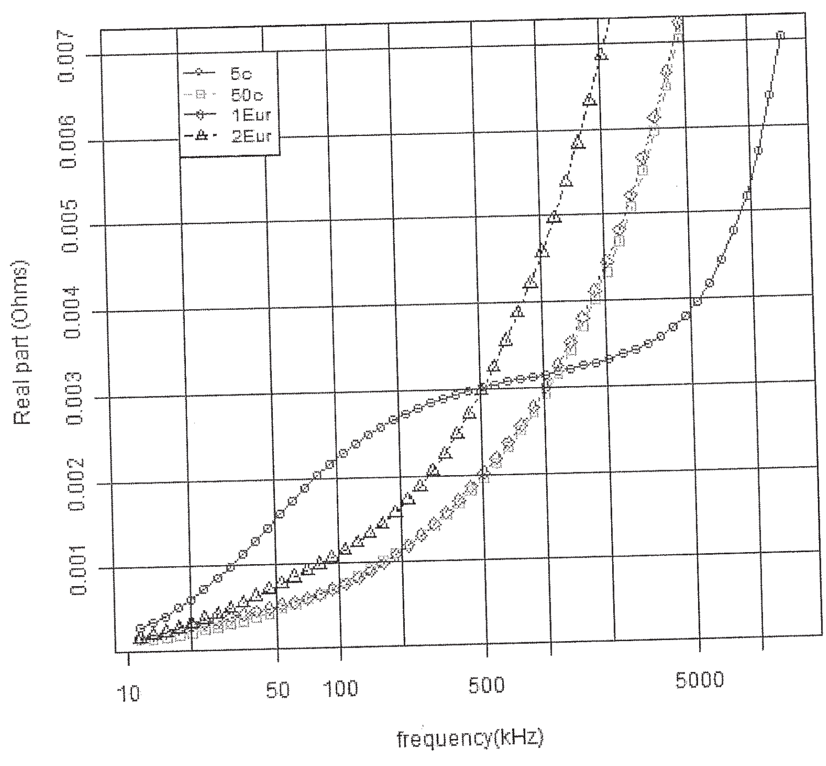

Figure 19. Real part of the RR1-3 coil impedance, up to 10 MHz.

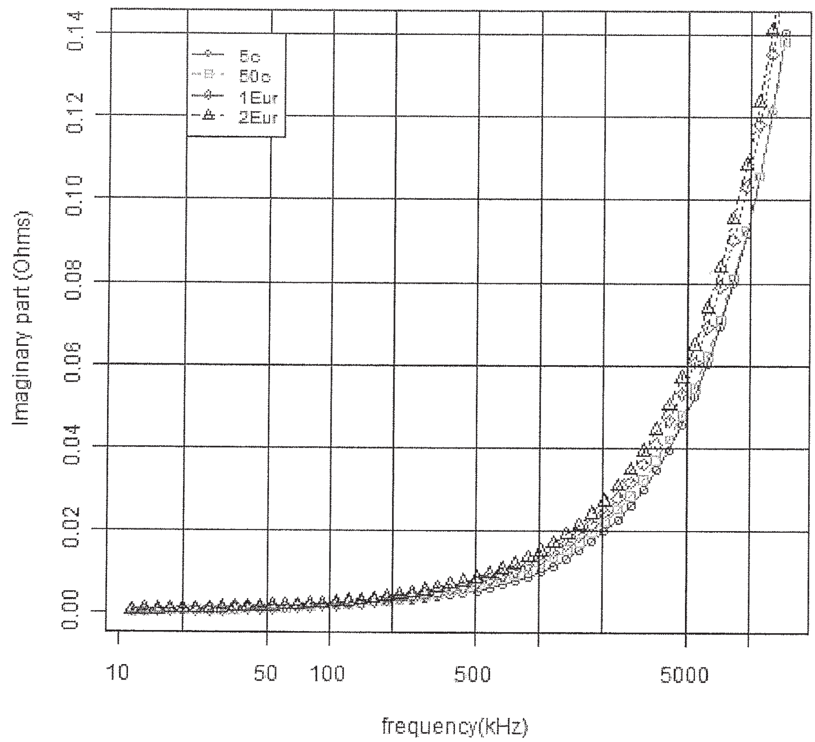

Figure 20. Imaginary part of the RR1-3, up to 10 MHz.

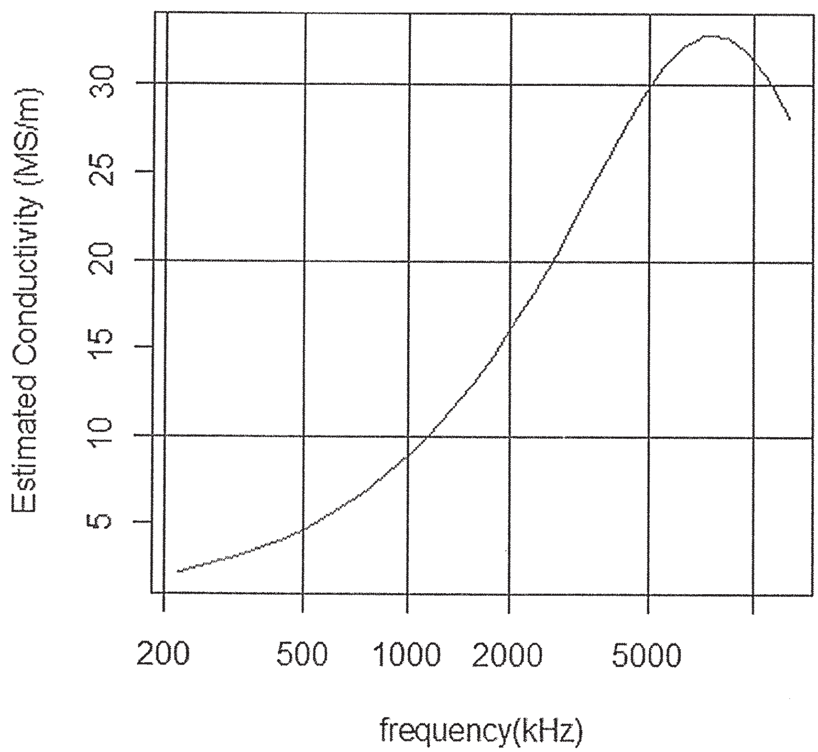

Figure 21. Back estimated conductivity for 5 cent coin.

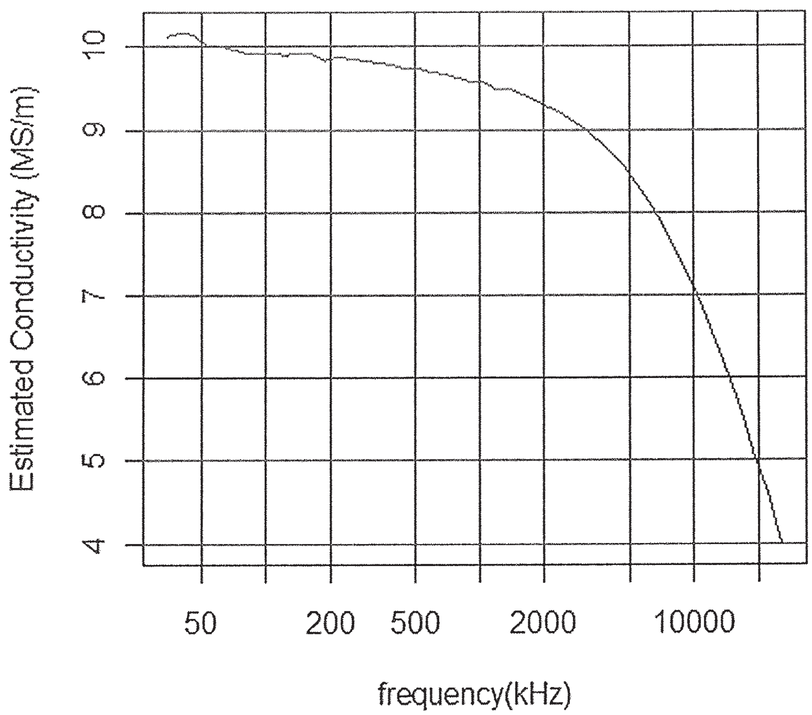

Figure 22. Back estimated conductivity for 50 cent coin.

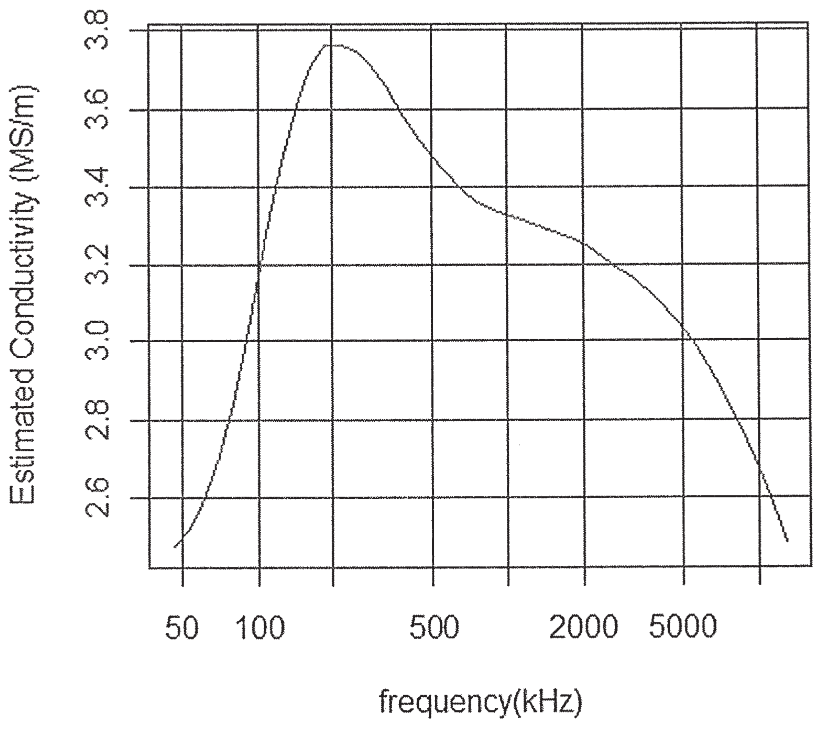

Figure 23. Back estimated conductivity for 1 Euro coin.

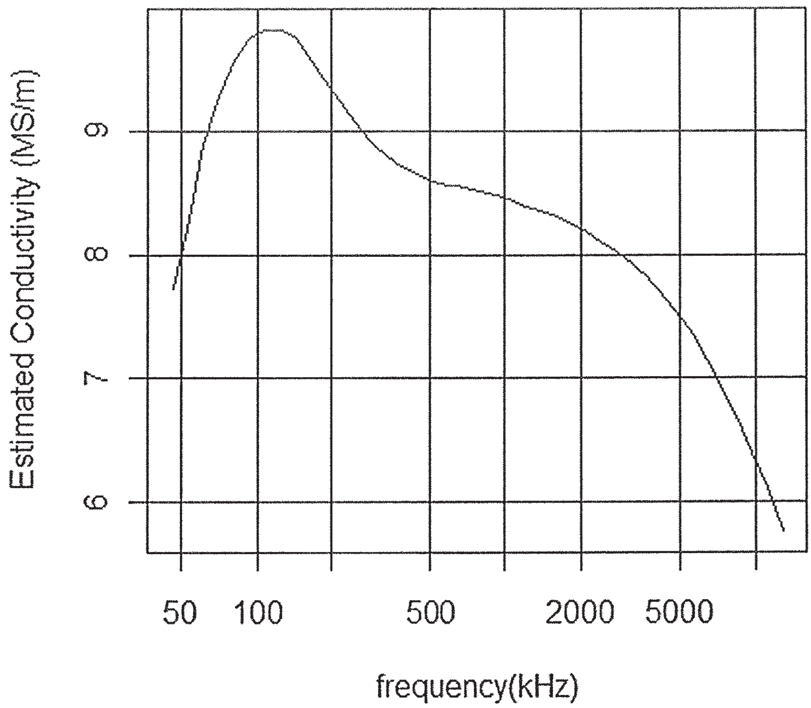

Figure 24. Back estimated conductivity for 2 Euro coin.

6 COIN VALIDATION SOLUTION

A specially designed test-equipment for having dynamical (in time) test-signals, more-or-less similar to the situation in real coin-validation devices, has been developed (Fig. 25).

Example of the measured signal, for a 20-cent coin, in the time, at 100 kHz frequency, with N14 coil, is given on figure 26 (upper line is a module of the impedance, being similar to the next- imaginary (inductive) component of the impedance and the lowest line is the real part of the coil impedance (change of the losses). The ohmic resistance of the coil is subtracted in the processing, as models deal with ideal coils.

The results show good correspondence of the measured conductivity. For example, in the described experiments, with 20 cent coin (nominal value of the conductivity is about 9.6 MS/m) in the frequency range 40 to 200 KHz, the absolute measurement error is within ±10%.

7 RESULTS, CONCLUSION AND DISCUSSION

So, as described, by using of air-core coil-based sensors (arrays of sensors), relatively high speed and precise conductivity measurement and corresponding coin-validation could be achieved, limited mainly by signal processing solution performance and smart signal approaches used to reduce the needed computational power (and energy). Relaxing the requirements to needed processing power could be achieved by using synchronous under-sampling, as proposed and implemented in (Märtens and Min 2004, Martens, Land, Gavrijaseva, and Molder 2011). Further improvements can be achieved by using of the smart signal processing, for example by using the changeable number of frequencies and sample rates, depending on the position of the coin from sensors (that means from previous measurement results). Further investigation of possibilities of smart signal processing is probably very promising in making the high-speed precise coin-validation more practical.

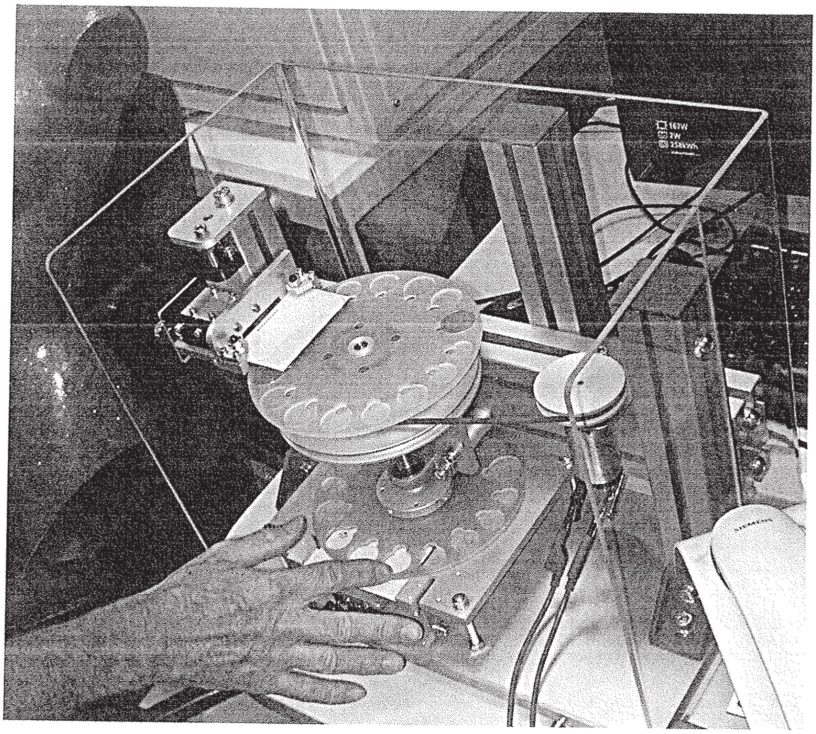

Figure 25. Auxiliary test-bench for experimental signals.

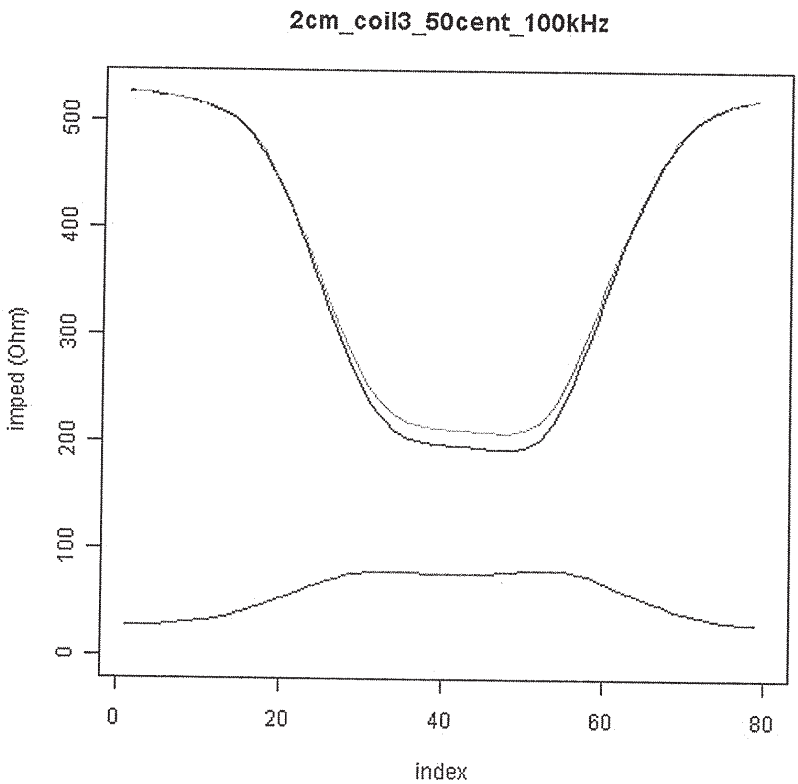

Figure 26. Measured (in the time domain) impedance signal.

ACKNOWLEDGMENTS

Current work have been supported by EU (FP7-SME project "Safemetal"), Enterprise Estonia (support of Competence Centre ELIKO), target financing SF0142737s06 and grant ETF8905 (Estonian Science Foundation) and by the European Union through the European Regional Development Fund.

Special thanks also to Dr. Theodoros P. Theodoulidis (University of Western Macedonia, Greece) for support with eddy current models.

REFERENCES

Bowler, N. and Y. Huang (2005). Electrical conductivity measurement of metal plates using broadband eddy-current and four-point methods. *Measurement Science and Technology 16*, 2193.

Carlosena, A., A. Lopez-Martin, F. Arizti, A. Martínez-de Guerenu, J. Pina-Insausti, and J. García-Sayés (2007). Sensing in coin discriminators. In *Sensors Applications Symposium, 2007. SAS'07. IEEE*, pp. 1–6. IEEE.

Dodd, C. and W. Deed (1975). Calculation of magnetic fields from time-varying currents in the presence of conductors. Technical report, OAK Ridge National Laboratory.

Dodd, C. and W. Deeds (1968). Analytical solutions to eddy-current probe-coil problems. *Journal of Applied Physics 39*(6), 2829–2838.

Harris, J., J. Churchman, D. Sharman, et al. (2007, July 17). Coin-validation arrangement. US Patent 7,243,772.

Howells, G. (2009, September 8). Coin discriminators. US Patent 7,584,833.

Martens, O., R. Land, A. Gavrijaseva, and A. Molder (2011). Adaptive-rate inductive impedance based coin validation. In *IEEE 7th International Symposium on Intelligent Signal Processing (WISP)*, pp. 1–4. IEEE.

Märtens, O. and M. Min (2004). Multifrequency bio-impedance measurement: undersampling approach. In *Proc. 6th Nordic Signal Processing Symposium. NORSIG*, Volume 2004, pp. 145–148.

Rossiter, P. (1991). *The electrical resistivity of metals and alloys.* Cambridge Univ Pr.

Snyder, P. (1995, February 28). Method and apparatus for reducing errors in eddy-current conductivity measurements due to lift-off by interpolating between a plurality of reference conductivity measurements. US Patent 5,394,084.

Theodoulidis, T. and M. Kotouzas (2000). Eddy current testing simulation on a personal computer. In *Proc. 15th World Conference on Nondestructive Testing*.

PAPER IV

"CROSS-CORRELATION-BASED IMAGE MATCHING OF COINS"

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IEEE 13th Biennial Baltic Electronics Conference,
2012, pp. 319 – 322.

2012 13th Biennial Baltic Electronics Conference (BEC2012)
Tallinn, Estonia, October 3-5, 2012

Cross-Correlation-based Image Matching of Coins

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ABSTRACT: Grey-scale multiresolution cross-correlation, combined with Canny edge detection algorithms, has been proposed and investigated for relatively simple and efficient coin recognition and matching algorithm. First experiments and investigations of the proposed solution show promising results. Also an overview of the alternative or complimentary image matching by support vector machines algorithm has been given in the paper. Finally, ideas for further improvement of the efficiency of the proposed solution are discussed.

1 Introduction

For coin recognition and validation image processing can be used, separately or in the combination with other sensors and corresponding signal processing, for example, with electromagnetic sensors.

Generally, image recognition and validation plays an important role in many applications in the industry (including automatic optical inspection), transportation etc. Furthermore, image matching results can be further used for data fusion, using signals and images from other sensors.

As complexity of 2-D image processing tasks is typically very high, main challenge here is to find reasonably simple algorithms, which could be performed on low-cost real-time target platforms (eg digital signal processors) with limited computational power and also memory size and communication bandwidth.

Various image matching algorithms have been proposed in the literature [1-2]. Approaches for image matching can include detection of different features, various search strategies, similarity metrics and achievable (sub-)pixel accuracy. One modern approach is using of wavelets [3] for image analysis, so combining time- and frequency domain processing, but main problem here is to find efficient ("optimal") parameters of wavelets. Also achieving of multi-resolution for faster signal processing can be problematic.

Correlation is widely used as an efficient similarity measure in recognition and validation tasks. In this paper an algorithm for relatively fast calculation of the grey-scale coin-template matching using cross correlation (CC) method, combined with Canny edge detection image pre-processing, and its application to the problem of coin recognition and validation is proposed.

However, it is clear that CC is not always the ideal approach since it is not invariant to imaging scale, rotation, illumination and geometrical (eg perspective) distortions. But, fortunately, normalization of the CC can significantly improve the method- in the simplest case this "conditioning" could be done by equalizing the mean values of the pixels and also the "energy" (root-mean square value of the deviation from the mean value) of the compared images or blocks. And also, often limitations of the CC can be resolved by using of more complex image processing, where CC is incorporated as a component into the system.

This paper does not suggest the using of CC instead of alternate approaches, but, rather, trying to show some of the issues involved in various approaches to feature tracking, and will conclude that CC is a reasonable choice for some applications, similarly, as done in [4], but about using the CC for specific task of the coin recognition.

From alternative or complimentary image processing and matching techniques, support vector machines algorithm (SVM) has been described in the paper.

An empirical study of five template matching algorithms in the presence of different distortions [4] have found, that normalized CC can provide the best performance in some cases.

2 Proposed CC method

First (Fig.1), the image-under-test and reference image are converted into grey-scale, to reduce the complexity of the image processing system. Then maximum and most minimum (saturated) intensity values of the pixels are discarded. Next Canny edge detector [5] is used to reduce the level information. In popular words, Canny edge detector, magnifies the intensity differences on the image, so enhancing the image, but potentially can also reduce the signal-to-noise ratio, as typical for similar high-pass-filter and differentiator algorithms. To avoid normalization process for every block, individually, CC reference image is divided into blocks, where block size is equal to coin-template size (240x240, in our example). The image pyramid [6] can be used for coin-template and reference images to reduce the size of images, in the first processing steps. Here higher-level image pyramid is represented by average of two neighbor values of the lower-level pyramid. Next the cross correlation of template- image and each block of reference image with specified step of angle rotation is calculated. The position of block with the maximum of correlation is used for next step of algorithm, carried out with smaller step (and so higher accuracy).

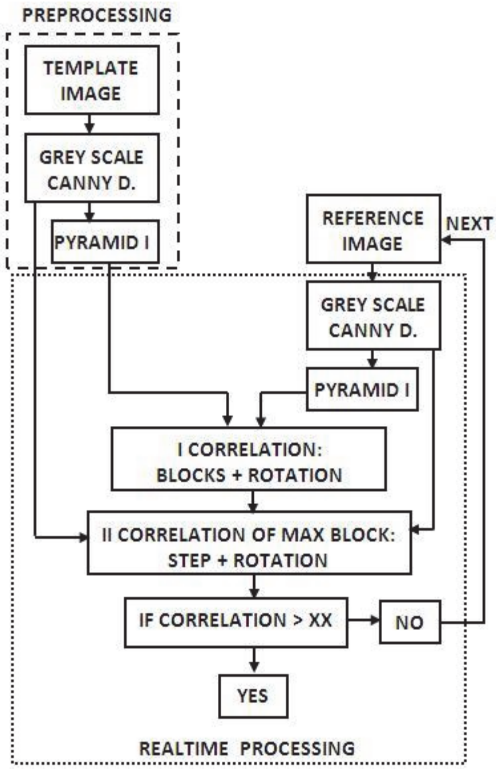

Fig 1. Image matching algorithm using CC.

The selected accuracy of the peak of correlation XX depends on the size of specified step and rotation angle: correlation criteria XX have to be smaller when step-size or rotation angle is bigger.

3 Optional complimentary SVM algorithm

Image matching CC approach can be complemented by appearance-based approaches like support vector machines (SVMs) [7, 8]. Such approach rely on learning algorithms to build a classification model that is used to classify new unknown data in one or more classes, and have been used for various image recognition applications (eg face detection) with very good results [9]. Such algorithms are trained using samples of images from each class in order to capture the variability in the appearance of the object in each class.

Specifically, for coin recognition, the proposed method is based on SVMs which are binary classifiers that construct a separating hyperplane between the samples of each class and used that hyperplane to make decisions for new samples. By combining multiple such binary classifiers, each trained for different class pairs, it is possible to perform multiclass classification. Based on this approach an image-based coin recognition method has been developed (Fig. 2) that performs classification using a three stage classification process, where each stage has a different purpose. The first classification stage aims at detecting whether the input image contains a coin by classifying between various coin and non-coin samples. If the image contains a coin the second stage is activated, and a series of classification comparisons are made in order to detect the most similar coin class to the input image. Finally, in the third stage, classification is performed between coin samples belonging to the dominant class from the previous stage and other similar looking coin samples to verify the true identity of the input coin image.

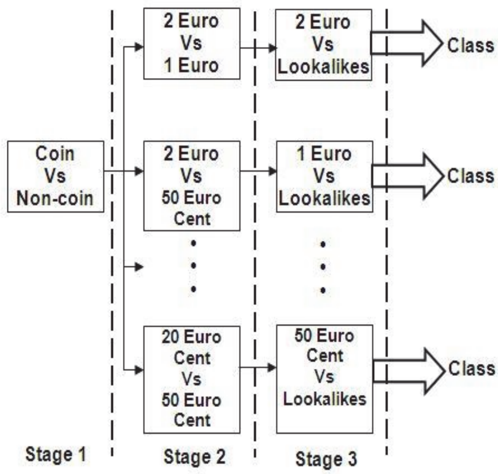

Fig 2. Coin Recognition Algorithm based on SVM.

Three stages of SVM classifiers are used:

1) Coin or other object.
2) Which coin class is closer.
3) Class verification.

4 Results

The size of the template image is 240x240 pixels and reference image is 956x936 pixels, so that reference image is divided into 16 blocks. The CC is computed for every block. Figure 3 (a, b) shows the coin-template image in grey scale and after canny filter implementation.

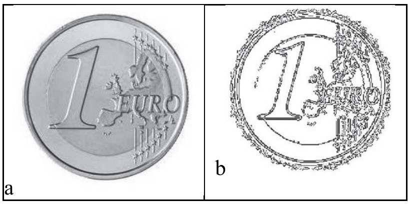

Fig 3. The coin-template image in grey scale (a) and after canny filter implementation (b).

Figure 4 (a, b) shows the reference image in grey scale and after Canny filter implementation.

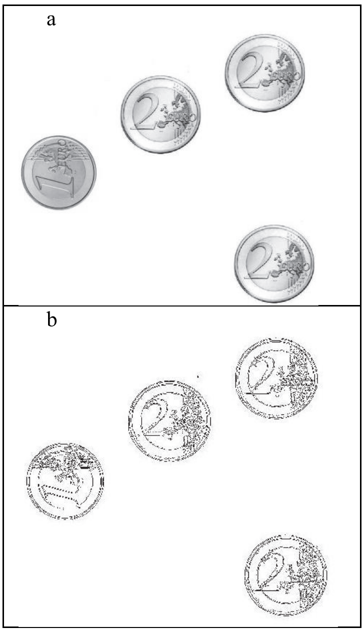

Fig 4. The reference image in grey scale (a) and after canny filter implementation (b).

The experimental results of coin-template matching of euro coin images are achieved on PC using R language program code. The step of correlation is 20 by X axis and 20 by Y axis, rotation angle is 30°. Result shows that proposed algorithm is simple, cheap in realization, real-time and effective for matching coins.

Correlation peaks after first (rough estimation) and second level (precise matching) processing can be seen on plots (Fig. 5 and 6).

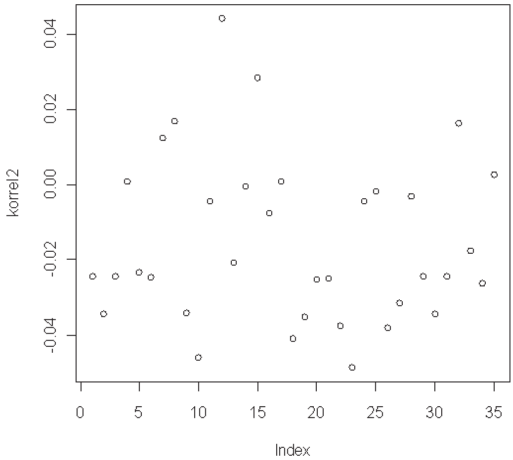

Fig 5. First level correlation map (peak at Index=12).

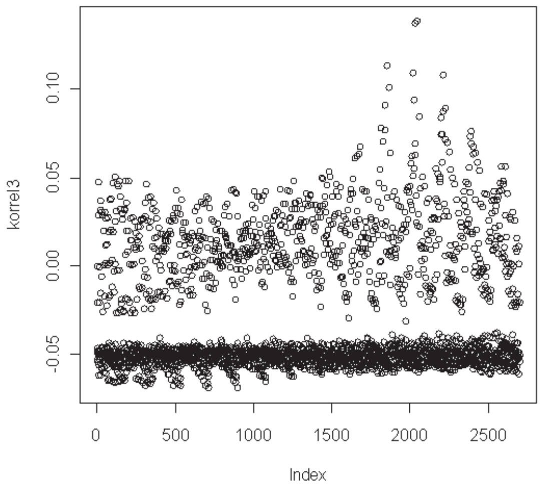

Fig 6. Second level correlation map (peak at Index=2043).

Exact possibilities of the complimentary (or also useable separately) SVM -method need more theoretical and experimental analysis.

4. Conclusions and future work

This paper presents an efficient method of coin template images matching and detection with good results. The discussed algorithm is relatively simple, cheap in realisation, real-time and effective for matching coins.

The experimental results of euro coin images demonstrate that the new method is effective for matching coins with significant rotation.

Furthermore, complimentary SVM algorithm (requiring, still further research) can improve the recognition and validation efficiency.

Further improvement of the proposed CC method can be achieved by combining the available from the literature ideas- first - approach by [9], where full calculation resolution is used only near the maximum of the cross-correlation function, but also implementing of the CC as some kind of the “fast(er)” CC algorithm [9-13]. Also using for CC of the “sum-table scheme” [14] can accelerate the calculations. Applicability of all of these methods and ideas requires additional research. Also works [15, 16] can inspire for more efficient methods.

Acknowledgements

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References

[1] W. Pratt, "Digital Image Processing", John Wiley, New York, 1978.

[2] R. C. Gonzalez and R. E. Woods, "Digital Image Processing" (third edition), Reading, Massachusetts: Addison-Wesley, 1992.

[3] A. R. Lindsey, “The Non-Existence of a Wavelet Function Admitting a Wavelet Transform Convolution Theorem of the Fourier Type", Rome Laboratory Technical Report C3BB, 1995.

[4] P. J. Burt, C. Yen and X. Xu, ”Local Correlation Measures for Motion Analysis: a Comparitive Study", IEEE Conf. Pattern Recognition Image Processing 1982, pp. 269–274.

[5] M. S. Nixon and A. S. Aguado, “Feature extraction and image processing”, Second edition, Academic Press, Elsevier, 2008, 399 pp.

[6] E. H. Adelson, C. H. Anderson, J. R. Bergen, P. J. Burt and J. M. Ogden ”Pyramid methods in image processing”, Pub. in RCA Engineer, 1984, pp. 33–41.

[7] C. J. C. Burges, “A Tutorial on Support Vector Machines for Pattern Recognition,” Data Mining and Knowledge Discovery, vol. 2, no. 2, pp. 121–167, 1998.

[8] C. Kyrkou, and T. Theocharides, "A Parallel Hardware Architecture for Real-Time Object Detection with Support Vector Machines", IEEE Transactions on Computers, vol.61, no.6, June 2012, pp. 831-842.

[9] D. I. Barnea and H. F. Silverman,”A class of algorithms for fast digital image registration", IEEE Trans. Computers, 21, 1972, pp. 179-186.

[10] R. Takei, “A New Grey-Scale Template Image Matching Algorithm Using the Cross-Sectional Histogram Correlation Method”, 2003. http://www.math.ucla.edu/~rrtakei/prevRsrch/workreport03.pdf *(last visited 6.6.2012)*

[11] J. P. Lewis, ”Fast normalized cross-correlation”, Canadian Image Processing and Pattern Recognition Society, 1995, pp. 120–123.

[12] J. P. Lewis, “Fast Template Matching", Vision Interface, 1995, pp. 120–123.

[13] J. Shi and C. Tomasi,”Good Features to Track", Proc. IEEE Conf. on Computer Vision and Pattern Recognition, 1994. http://www.ai.mit.edu/courses/6.891/handouts/shi94good.pdf *(last visited 6.6.2012)*

[14] K. Briechle, “Template matching using fast normalized cross correlation”, Proceedings of SPIE, 2001, pp. 95–102.

[15] M. Mori and K. Kashino, “Fast Template Matching Based on Normalized Cross Correlation Using Adaptive Block Partitioning and Initial Threshold Estimation*”,* IEEE International Symposium, 13-15 Dec. 2010, pp. 196 – 203.

[16] F. Zhao, Q. Huang and W. Gao, “Image Matching by Normalized Cross-Correlation”, IEEE International Conference, p.II-II, 24 July 2006 pp. 729–732.

PAPER V

"VARIABLE-RESOLUTION IMAGE PROCESSING FOR VALIDATION OF COINS"

O. MARTENS, T. SAAR, A. GAVRIJASEVA AND A. MOLDER,

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Variable-Resolution Image Processing for Validation of Coins

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***Abstract*—In this paper correlation-based matching solutions of images for the case of the validation of the eurocoins with relatively high-speed motion have been developed and evaluated. Image processing (combined with other -electromagnetic, optical and acoustical sensorics) is an efficient method for coin recognition and validation. From the image processing viewpoint- an universal method is finding and checking the coin image by cross-correlating it with expected (reference) image(s). Correlation is widely used as an effective similarity measure in matching tasks. However, traditional correlation based matching methods are limited by various ways. Main challenge here (additionally to "pre-conditioning" of compared images, of course) is the significant reduction of the computations, needed for finding cross-correlation values over 2-D space and for all possible rotation values. In current work usage of variable-rate subsampled (by pixel blocks) reference images has been proposed and evaluated. A special case has been considered, where most of the image blocks are sampled with zero (none) ~~or one~~ sample-values, while a few blocks (some to some tens) of the image has been sampled at the full accuracy (eg 240x240 pixels, in the used examples). The criteria, used for selection of the "specific" (unique) blocks of the reference image has been the minimum value of the maximum cross-correlation of an block of samples (eg 20x20 or 30x30 pixels) against any other (shifted or rotated) block of the same coin image. So, blocks with relatively high value of "secondary "correlation peaks at shifting and rotating are not considered as "good or unique" ones. So, sub-sampled reference images for various eurocoins has been proposed, and corresponding algorithms has been evaluated.**

Alternatively, using of set of feature-points of the images, as reference for cross-correlation, has been evaluated, for various eurocoins (with corresponding determination of reasonable feature points, for these coins).

Alternatively, using local maximum and minimum difference based interesting pixel blocks as reference blocks for cross-correlation has been discussed.

These methods have been tested on real eurocoins, the results are presented at the end of paper.

Keywords- image processing; coin validation; SIFT; pyramid; cross-correlation; sub-sampling; variable-rate; decimation; reference images

I. INTRODUCTION

Image processing (combined with electromagnetic, optical and acoustical sensors) is an efficient method for coin recognition and validation [1]. While electromagnetic (eddy current) sensors can allow relatively simple, precise and efficient solution, still some different coins, worldwide [2], can have similar electrical or magnetic properties, and so image processing-based solutions can have their place [3]. Of course, complexity of image processing part for coin validation can vary from simple image-acquisition and processing solutions [4] up to more sophisticated image acquisition [5] and processing solutions [6,7].

Generally, image matching systems consist of at least two phases: image processing and object classification. One of the first tasks are image pre-conditoning and localizing the objects from the background.

Aim is to identify eurocoins and their location in image scale space that is invariant with respect to image translation, scaling, and rotation, and is minimally affected by noise and small distortions.

There are many factors to consider in formulating an image (coin) matching strategy including acceptable precision/error limits, scene characteristics, instrument parameters, and the method of image acquisition [8]. The final goal of this work is to obtain a confident coin image match with minimal overlap at a reasonable speed.

From the image processing viewpoint - an universal method is finding and checking the coin image by cross-correlating it with expected (reference) image(s). Correlation is widely used as an effective similarity measure in matching tasks [9]. However, traditional correlation based matching methods are limited by various ways. Main challenge here (additionally to "pre-conditioning" of compared images) is the significant reduction of the computations, needed for finding cross-correlation values over 2-D space and for possible rotation values.

One general approach here could be using of "pyramid schemes", where variable resolution image versions are used in parallel. Alternative could be also "adaptive subsampling" [10, 11] or using of some kind of "rotation invariant" approaches or "multi-match" techniques, to match the object with any of many "candidate" image-versions in parallel [12].

Still, after practical experiments with various algorithms, cross-correlation has been taken as one good candidate for image matching, and ways to drastically simplify the calculation has been looked for.

An important feature of the proposed solution is that it imposes only minimal requirements on the image acquisition process. The scale detection is not restricted to a specific type of ruler and is robust with respect to the placement and orientation of the ruler [13]. Similarly, the coin segmentation works for a wide range of coins and backgrounds and is independent of the position of the coin.

II. APPROACH 1: ADAPTIVELY SUBSAMPLED CROSS-CORRELATION

In current work usage of variable-rate sub-sampled (by pixel blocks) reference images has been proposed and evaluated.

The aim of segmentation an image into parts in this system is to differentiate the region of interest from other region of the image. A special case have been considered, where most of the image blocks are sampled with zero (none) sample-values, while a few blocks (some to some tens) of the image has been sampled at the full accuracy (240 x 240 pixels, in the used examples). The criteria, used for selection of the “specific (unique) blocks” of the reference image has been the minimum value of the maximum cross-correlation of an block of samples (eg 20 x 20 or 30 x 30 pixels) against any other (shifted or rotated) block of the same coin image. So, blocks with relatively high value of “secondary “correlation peaks at shifting and rotating are not considered as “good” or “unique” ones.

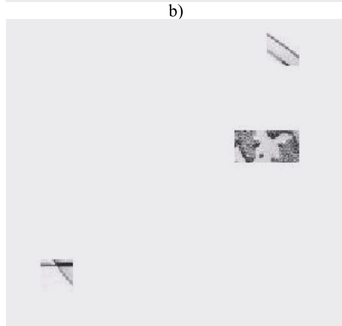
This can be computed very efficiently by building an image pyramid with re-sampling between each level. Figure 1 shows the regions with “specific (unique) blocks” of a 2-Euro coin, as an example.

So, sub-sampled reference images for various euro-coins have been proposed, and corresponding algorithms has been evaluated.

The computational complexity of proposed method is significantly reduced (with full-image correlation calculation), as only a small part of the image is considered for calculations.

a)

b)



c)

d)

Figure 1. Adaptively subsampled images of 2 Euro coin (a- 10 blocks of 20x20 ,b – 20 blocks of 20x20 -both of side A, and c-4 blocks of 20x20, 20-blocks -side B).

III. APPROACH 2: SIFT ANALYSIS

Alternatively, using of set of feature-points of the images, as reference for cross-correlation, has been evaluated, for various EuroCoins (with corresponding determination of reasonable feature points, for various coins). SIFT (Scale Invariant Feature Transform) feature points [14][15][16] have widely been used for image matching and stitching. SIFT method is invariant to image scaling, illumination changes and rotation. This makes it very suitable for coin matching (recognition).

Method is based on unique feature point calculation. For each point also features like scale and orientation are being calculated. Based on these features points on two images will be matched.

Figures 2 and 3 demonstrate image matching using feature points. On the first image (Fig.2) all coins have zero degree angle. Second image (Fig.3) represents two-euro coin which has been rotated 33 degrees. Sub-images on the right display 8 different euro coins, among others also two-euro coin. SIFT feature points have been calculated for both images. Best matches between two point sets are then calculated. Blue crosses on both images represent feature points on both images. All matched feature points are located on two euro coin. This indicates sufficient uniqueness of each point.

Feature point calculation could be used as alternative approach for cross-correlation matching algorithm. Rotation invariance makes it suitable for coin matching. More complicated processing makes it more demanding in computational power sense compared to correlation method. This method could be especially useful in cases where many coins must be recognized on a same image.

Figure 2. 2 Euro coin detection with SIFT feature method.

Figure 3. Rotated 2 Euro coin detection with SIFT feature method.

IV. APPROACH 3: LOCAL MAXIMUM AND MINIMUM DIFFERENCE BASED INTERESTING PIXEL BLOCK SELECTION

One of the simplest methods to select and determine if the pixel block has any interesting or unique features on it is the local maximum and minimum difference method. It is known that image pixel intensities in an 8 bit image vary between 0 to 255 values. If all the pixel intensities would be with the same values or with minimal pixel intensity variance then the contrast inside the pixel block is not very large and therefore the pixel block is not very characteristic or interesting. However, if the difference between the intensities inside the pixel block is relatively large then the pixel block is definitely characteristic and offers us more of an interest.

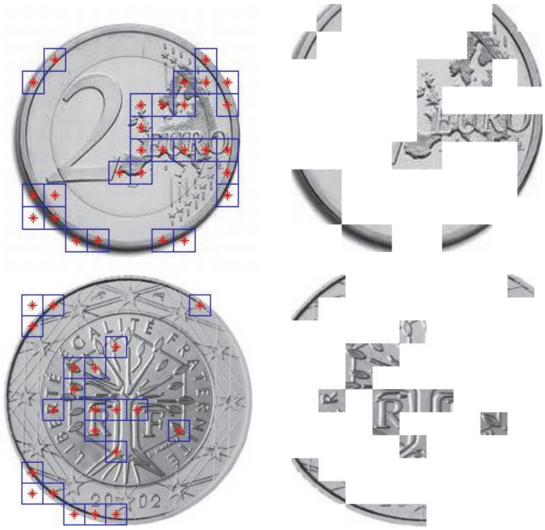


Figure 4. Adaptively sub-sampled images of 2 Euro coin based on local maximum and minimum differences (left upper image- selected pixel blocks on original image front side, left lower image- sub-sampled image front side, right up - selected pixel blocks on original image front side, right lower - sub-sampled image back side).

In order to find an interesting pixel blocks the reference image was divided into 20 x 20 pixel blocks. In every pixel block the maximum and the minimum pixel intensity values were found. The difference between the maximum and the minimum intensity values were calculated.

Threshold level for the pixel intensity difference was set to distinguish the most interesting pixel blocks from all the pixel blocks. In figure 4 a threshold level of 0.8 was used.

Local maximum and minimum difference based interesting pixel block selection method is the simplest method to determine interesting pixel blocks. Also the calculation power that is needed compared with the cross-correlation based pixel block selection is marginal.

V. RESULTS

In this paper we discussed efficient and accurate methods of coins matching and detection.

Examples of adaptively sub-sampled method, for so found reference images for the 2-euro coin, are presented here. As we have totally 144 blocks of the 240x240 image, then image is decimated, for 4 block case 38 times and for 10 block case about 15 times.

The distinct features of our proposed method from other methods are that, it is at first a hybrid scheme consisting of SIFT feature points and cross-correlation methods.

Method proposed for the segmentation of coins in images mainly focuses on present day coins. It makes special assumptions which can not be expected to be satisfied on all coin image data.

Cross-correlation could work fast in described cases and well especially by using selected local maximum and minimum difference based interesting pixel blocks.

VI. CONCLUSIONS AND DISCUSSION

This paper presents different methods of coin images matching and detection. All the coins used in these experiments are eurocoins. So, efficient algorithms with results have been proposed, allowing reasonable-speed and high accuracy.

If the width of data can be adaptive, presented methods can deal with more complex situation. All of these are our further works.

One way to improve the efficiency of the solution, is to use larger number of various sub-sampling (decimation) rates for various blocks of pixels, starting with coding of some bloks with one (eg average intensivity) „integral" value.

Future work will also include benchmarking of desribed approaches, proposed in the current paper, on various platforms (including digital signal processors and general-purpose micorcontrollers).

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REFERENCES

[1] A. Carlosena, A.J. López-Martin, F. Arizti, A. Martínez-de-Guerenu, J.L. Pina-Insausti, and J.L. García-Sayés, "Sensing in coin discriminators", *Proc. IEEE Symp.*, San Diego, CA, USA, February 6-8, 2007, pp. 1-6.

[2] The European Central Bank, official web site: *http://www.ecb.int/home/html/index.en.html*

[3] J. Karlsson (Scan Coin Industries AB), "Coin discriminating device, coin handling apparatus including such a device, and coin discriminating method", US Patent 6,761,257, July 13, 2004.

[4] M. Tresanchez, T. Pallejà, M. Teixidó, and J. Palacín, "Using the Optical Mouse Sensor as a Two-Euro Counterfeit Coin Detector", *Sensors,* 2009, no. 9(9):pp. 7083-7096.

[5] M. Kampel, and S. Zambanini, "Coin Data Acquisition for Image Recognition", *36th Conference on Computer Applications and Quantitative Methods in Archaeology*, Budapest, Hungary, April 2008.*http://www.caa.tuwien.ac.at/cvl/people/zamba/pdf/caa08.pdf*

[6] M. Zaharieva, M. Kampel, and S. Zambanini, "Image based recognition of coins – An Overview of the COINS project", *31st AAPR/OAGM Workshop*, Krumbach, Austria, pp.57–64, 2007.

[7] A. Khashman, B. Sekeroglu, and K. Dimililer, "A Novel Coin Identification System", *Intelligent Computing in Signal Processing and Pattern Recognition: Lecture Notes in Control and Information Sciences,* Vol. 345, 2006, Springer Berlin/ Heidelberg, pp. 913- 918.

[8] Ch. Heipke, "Overview of image matching techniques", *OEEPE Workshop on the Application of Digital hotogrammetric Workstations*, OEEPE Official Publications, no.33, pp.173-189, 1996.

[9] F. Zhao, Q. Huang, and W. Gao, "Image Matching by Normalized Cross-Correlation", *IEEE International Conference on Acoustics, Speech and Signal Processing*, 2006, Proc., Toulouse, ICASSP 2006, 14-19 May 2006, pp.729-732.

[10] A. Ricardo ,F. Belfor, M. P. A. Hesp, R. L. Lagendijk, and J. Biemond, "Spatially Adaptive Subsampling of Image Sequences", IEEE Transaction on Image Processing, vol. 3, no. 5 (Sept), 1994, pp.492-500.

[11] X. Zhou, E. Dorrer, "Non linear scale and orientation free correlation matching algorithm based on edge correspondence", *International Archives of Photogrammetry and Remote Sensing*, Vol. XXXIII, Part B3. Amsterdam 2000.- pp 1054-1062, http://www.isprs.org/proceedings/XXXIII/congress/part3/1054_XXXIII-part3.pdf

[12] Y. Lin, C. Chen, and C. Wei, "New method for subpixel image matching with rotation invariance by combining the parametric template method and the ring projection transform process", *Optical Engineering* , vol. 45 (2006.), no.6 (June), pp. 067202.1-067202.9.

[13] M.S. Islam, L. Kitchen, "Nonlinear Similarity Based Image Matching", *Intelligent Information Processing* III, IFIP International Federation for Information Processing, vol. 228 (2007), pp. 401-410.

[14] D.G. Lowe, "Object Recognition from Local Scale-Invariant Features", *Proc. Seventh IEEE International Conference on Computer Vision*, Corfu, Greece, 20 Sept 1999 - 27 Sept 1999, vol.2, pp. 1150 – 1157.

[15] D.G. Lowe, "Distinctive Image Features from Scale-Invariant Keypoints", *International Journal of Computer Vision*, vol.60 (2004), no. 2, pp. 91-110.

[16] D.G. Lowe, "Method and apparatus for identifying scale invariant features in an image and use of same for locating an object in an image", US patent 6,711,293, March 23, 2004.

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