Using Image Processing and A new SAFT Algorithm for Ultrasonic Flaw Imaging in Concrete

Heydar T. Shandiz MSc. and Patrick Gaydecki PhD‡

Keywords: Ultrasonic Inspection, Ultrasonic imaging, SAFT

Abstract

The Synthetic Aperture Focusing Technique (SAFT) is well established for ultrasonic imaging purposes, for example in non-destructive testing (NDT) of materials. The ultrasonic inspection of concrete is notoriously difficult however, due to its combined attenuating and scattering characteristics, especially at high frequencies. Since low frequency transducers must be used, inspection has traditionally been limited to rather simple measurements conducted in the time domain, such as the ultrasonic pulse velocity. Since the propagation velocity is related to the modulus and density, and hence indirectly to the strength of concrete, the pulse-velocity method has been established as possibly the only standard technique of non-destructive testing of concrete. It is of limited value when attempting to establish the internal condition of the material. For cases where the interrogation frequency is very low (below 250kHz), normally the transducers do not have a broadband freqquency response, which causes prolonged ringing in the time domain. Recently however, advances in transducer technology and signal processing have enabled the direct visualisation of internal defects both by using pulse-echo systems and SAFT the development and application of an enhanced time-domain SAFT algorithm that uses a correlation technique to perform the coherence summation. Not only is this method faster, by an order of magnitude, than equivalent time-domain SAFT algorithms, it produces images of defects within the concrete that are unobtainable by other means of processing the ultrasonic signals.

1-Introduction

There are many methods for the NDT of concrete. Based on the source, which is used for inspecting concrete, they can be classified as ultrasonic, microwave, X-and Gamma ray; and magnetic and electrical methods [1]. Any method has some restrictions and some advantages over other methods. When only one surface of the concrete is accessible for testing, the X- and Gamma ray methods cannot be used. For finding cracks and non-metallic flaw(s) the Ultrasonic methods are the only suitable techniques.

In this work the ultrasonic method and SAFT algorithm is used to reconstruct images of flaw(s). Image processing algorithms such as negative image, edge detection and equalisation are then used to make the images more clear.

2- Methods and Materials

In any ultrasonic inspection system, the scanning method, number of transducers and method of analysis data are important.
There are many methods of scanning classified by the manner of data collection. When data is collected at different points along a single line, the method is called B-scan. In the C-scan method, data is collected from points on a two-dimensional test surface [2]. If the spread angle of the transducer is enough to cover all the test area in one scan line, the B-scan method may be used. In this work the C-scan method was used, because

‡ Authors address:

Heydar T. Shandiz and Dr. Patrick Gaydecki
Department of Instrumentation and Analytical Science (DIAS), UMIST, PO Box 88, Manchester M60 1QD, United Kingdom
E-mail: h_t_shandiz@hotmail.com
Patrick@fs3.in.umist.ac.uk

the spread angle of the transducer was about 76.16 degree and so too small for C-scan.

The minimum distance measurable by a single transducer (in pulse-echo mode) d_{min}, is given by:

$$d_{\min} = v.T/2 \qquad (1)$$

In which the v is the velocity of ultrasound in the concrete media and the T is the ringing time of the transducer.

For distances below d_{min}, transmitter and receiver transducers are required. Figure 1 shows the ringing of the transducer after one excitation. The ringing time is 50μsec (see Fig. 1). The velocity of ultrasound through the concrete is about 4500 m/s [3]. Equation 1 shows that the minimum distance measurable is 112.5mm in this circumstance. For the following reasons any crack or void, which is less that 100mm under the surface must be recognised.

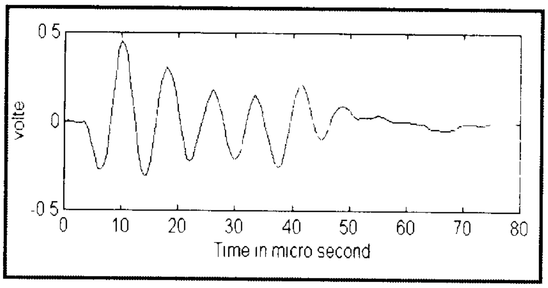


Figure 1. Ringing of transducer

Concrete has a high compressive strength but low strength under tensile or shear loading. Its tensile strength is about 10 percent of its compressive strength [4]. Reinforcing with steel bars (Rebars, with standard diameters, which are 5,6,8,10,12,16,20, 25, 32 and 40 cm) strengthens concrete under tensile loads. Reinforcement bars are arranged in a grid pattern, whose dimensions will vary, but bar spacings of the order of 120 mm are not uncommon. Concrete cover over such mesh under normal circumstances is between 40 mm and 80 mm. Carbonation and chlorinate are the main agents of corrosion. Cracks and voids can permit oxygen and moisture to reach surface of the rebars, which causes rapid corrosion. In addition the big size of flaw(s) can change the characteristic of material mixture, which affects the compressive strength of concrete structure. In this work the flaws were located in a region 40 mm to 70 mm below the surface. Therefore a single transducer with the ringing characteristics specified previously could not be used.

Using separate transducers for transmitting and receiving ultrasound, allows the use of different transducer configurations. It could be possible to fix the transmitter in place and move the receiver around the surface. But when inspecting concrete, the lateral transmission between two transducers precludes this. In this piece of work the transmitting and receiving transducers were fixed together, with a constant separation whilst being scanned over the concrete surface.

The data was analysed by using a SAFT algorithm. The US Nuclear Regulator Commission (NRC) began development of SAFT in 1974. This method produced a full volumetric image at high resolution with a high signal-to-noise ratio. The physical aperture area on any imaging system is limited. The SAFT method is an imaging method, which was developed to overcome some of the limitations caused by physical apertures size [5]. It can be performed in two ways, in the time domain or in the transfer domain [6]. In the time domain the following formula is used to reconstruct the image of flaw(s):

$$I[x,y,z] = \frac{1}{N}\sum_{i=1}^{N} X_i[\frac{r_i}{v}] \qquad (2)$$

I is the ultrasound reflected intensity from point (x,y,z), N is number of measuring points or receiving transducers, X_i represent the measured signal by the ith transducer, r_i is the distance between the transmitter and receiver i at position (x,y,z) and v is the velocity of ultrasound in media [7].

Theoretical basis of SAFT is valid for homogenous media. Concrete is built up from coarse-grained materials. Therefore the SAFT algorithm must be modified to gain better results for imaging purpose [8]. In previous studies Koehler B. et al made improvements in the pulse echo testing of concrete, by using signal conditioning methods and a scanning laser vibrometer. Techniques such as using specially designed ultrasonic probes, pulse compression, ultrasonic wave detection by laser Doppler interferometer, random speckle modulation and space time signal processing methods were also employed. In their work 3D-SAFT reconstruction increased the signal to noise ratio further and lead to a 3D-image of a reflector distributions inside the specimen [9]. Schickert M. et al, used the longitudinal waves for inspecting concrete as usual. They found any object must be larger than the concrete aggregates to be detected. Strong signal attenuation arose at high frequencies, coarser aggregate added to the amplitude of deterministic noise. It was also found that by increasing the sound path the shape of the transmitted pulse changed, this was due to frequency dependence of the phase velocity. They suggested the following improvements for overcoming the mentioned problems and obtaining better images. 1) Measuring a reference signal without an object and then subtracted this from all data to correct for late oscillation of the transducer. 2) Adjusting amplitude manually for certain records to remove effect of variations of transducer coupling on image quality. 3) Considering the diverge angle of the transducers to reduce the noise. 4) A non-linear time scaling to compensate the change in pulse velocity with increasing the depth. 5) Finally amplitude depth correction to equalise scattering and absorption losses. In their experimentation they tried to find two drill holes 55mm in diameter, which are located on 113 mm and 191 mm under the surface. For 8 mm aggregate grain size, the holes were image successfully. But with 16 mm grain size the image is less clear and for a 32mm grain size there is no clear image of the drill holes [10]. Jansohn R. and Schickert M. improved the above images by using object interpretation of the brightness distribution in statistical image processing. They knew that the grain noise could not be removed by time averaging or matched filtering, because it was correlated with the time-invariant position of the aggregate. But it is possible to assume a random position for aggregates in space. By using the central limit theorem, which states *Gaussian distributions occur in random processes when the number of statistically independent single events is increased to infinity.* They believed the unwanted ultrasonic echoes, which are generated by scattering at non-homogenous materials showed some similarity to thermal noise. For smaller resolution cells the central limit theorem is not valid. Therefore for such cells the family of Weibull-distribusions or log-normal was used. By knowing the amplitude distribution of grain noise, an appropriate threshold value was found and the false alarm probability was computed. After computing the threshold functions any value of the image matrix had to be compared against the threshold value corresponding to its depth. If the image value exceeded the threshold it remained unchanged, otherwise it was changed to the median of its row [11]. Burr E et al, use a modified SAFT-algorithm in simulation. The plane wave was used in their simulation, this wave is difficult to transmit through concrete. As they said it is not a very useful simulation from the experimental point of view [8].

In this work the following modified SAFT formula was used:

$$R_{Iy}(0) = R_{yX_1}(\tau_1) + R_{yX_2}(\tau_2) + \dots + R_{yX_N}(\tau_N) \qquad (3)$$

In which N is the number of transducers or receiving points, R_{Iy} shows the cross-correlation between the reflected signal from point *(x,y,z)* and pattern signal y. The terms on right-hand side show the cross-correlation between the pattern signal and *ith* transducer recorded data in time τ_i [7]. This method has many advantages over the other methods. First, it requires simple and easy to use equipment. Second, no data pre-processing is required. Third, time domain data is used therefore it is fast. Forth, all processing steps can be computerised.

3- Experimental set up

Figure 2 shows the test system configuration. As it is shown the transmitter and receiver are

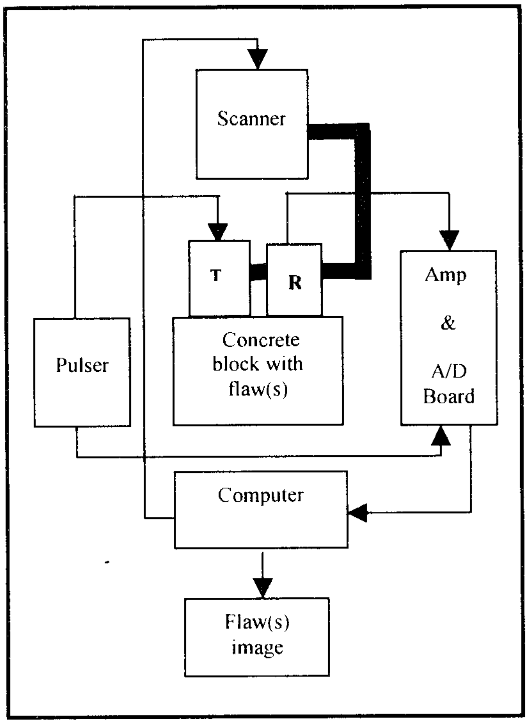
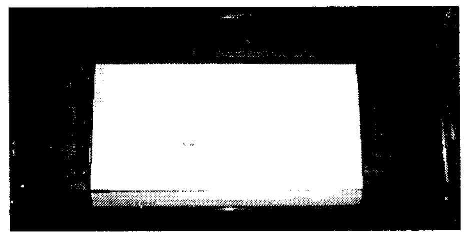


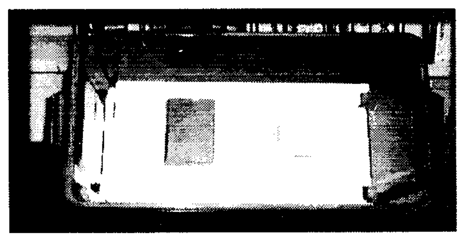
Figure 2. System test configuration

fixed together. The transmitter is a spatial high damped low frequency transducer. Its nominal frequency is 125KHz with 75KHz bandwidth. The scanner moves around the test surface, while the transmitter send ultrasound through the block and receiver produced a voltage proportional to the reflected ultrasound wave. This voltage goes through an amplifier. After 20dB amplification, it is sent to an analogue to digital (A/D) board to change to discrete value. The board has 12 bits resolution and input level is ±10 volts. Therefore, the $20/4096= 4.883\times10^{-3}$ volt is the quantum resolution or less significant bit (LSB) of the board. The sampling frequency is 2MHz, although, 400KHz would be enough. But the higher sampling frequency, the greater lateral resolution. The pulser is used to stimulate the transmitter. This device also produces a trigger pulse for triggering the A/D board. This trigger signals guarantees the transmitting ultrasound wave and recording the reflection simultaneously, which is important in SAFT algorithm. Computer has a supervisory and processing role in the system. It controls the scanner movement, acquisition data and does process in data to reconstruct the flaw(s) image. After reconstructing the image some other image processing algorithms, such as negative, edge detection and equalisation algorithms are used to make the image clearer. Figure 3 shows the configuration of flaw(s) before pouring concrete on the casts.

Figure 3. Configuration of flaws: (a) one flaw 40 mm under the surface and (b) two flaws the larger one 40 mm and small one 70mm under the surface



(a)



(b)

4- Data analysis and results

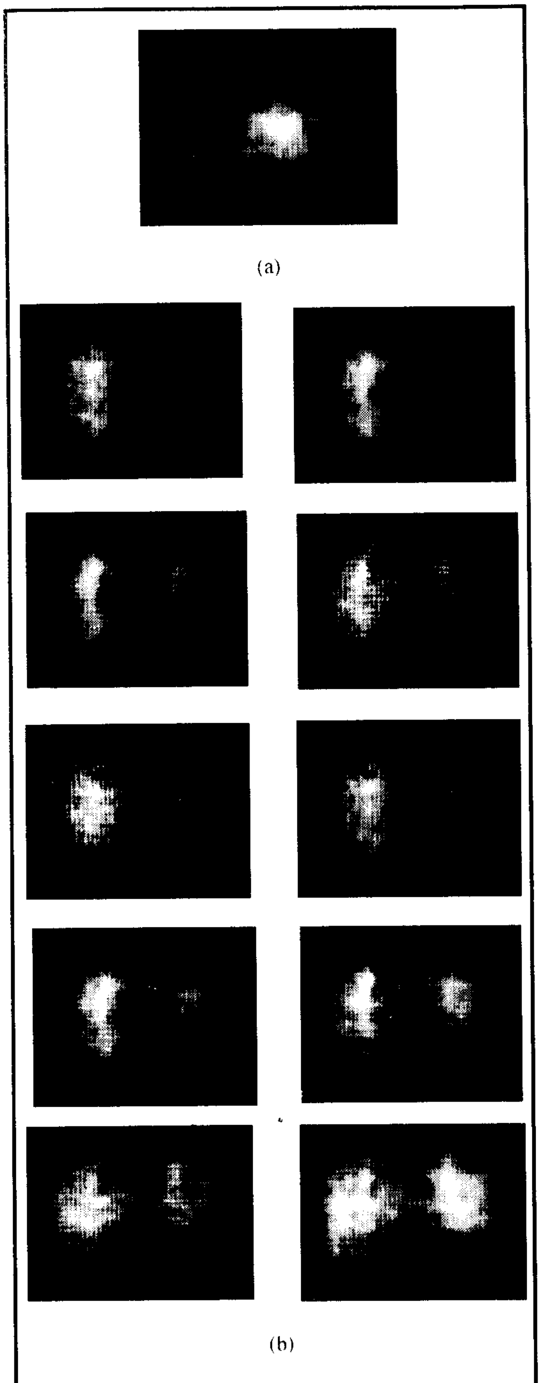


Figure 4. Reconstructing image by 2D-SAFT algorithm: (a) one flaw and (b) two flaws, in which the left image is about 50mm above the right one and first image start at 30mm below the surface.

When making volumetric images it is difficult to use 3D-SAFT, because it needs a lot of memory. To simplify the calculation 2D-SAFT is used for different planes. There are two kinds of images in this work; in one of them the image is calculated by taking depth, Z, as a constant in each 2D-image. In figure 4 the horizontal images of one and two flaws are shown. For one flaw only the second picture is shown and for two flaws, which are in different depth, 10 images are shown. These images are called horizontal, as they give information about surface of flaw(s). The other group of images are reconstructed by taking X as a constant. These images are called vertical images because they give information about vertical cross-section of flaw(s). Below one of them is shown for two blocks of concrete (see Fig. 5).

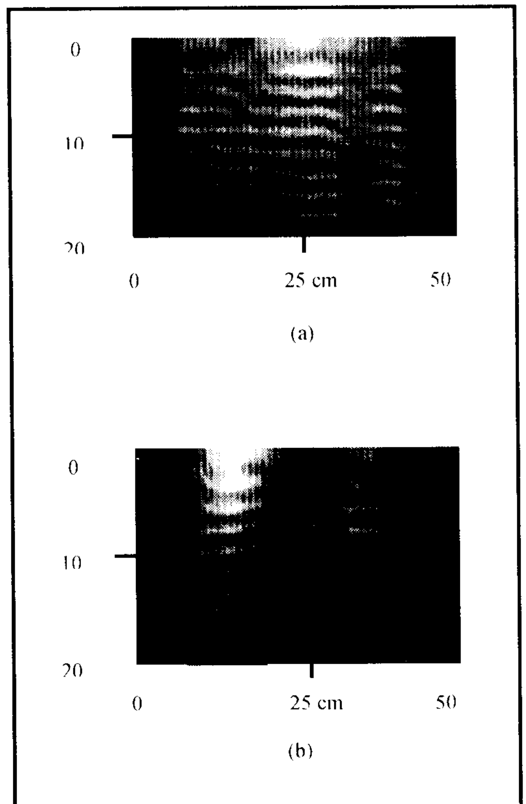


Figure 5. Vertical image: (a) one flaw and (b) two flaws

5- Image processing

To make the vertical images much clearer, the edge detection algorithm is used. In the edge detection algorithm the two-dimensional gradient is used to determine the changes in grey level in two directions. In order to build better image, the maximum grey scale in the result image is calculated. Half of this maximum is chosen as a threshold to build another image. Then the negative image algorithm is used. Finally the histogram equaliser algorithm is used to create the final clear image. Figure 6 and 7 show the result of each algorithm, when each of them is applied to the image in both one and two flaw cases.

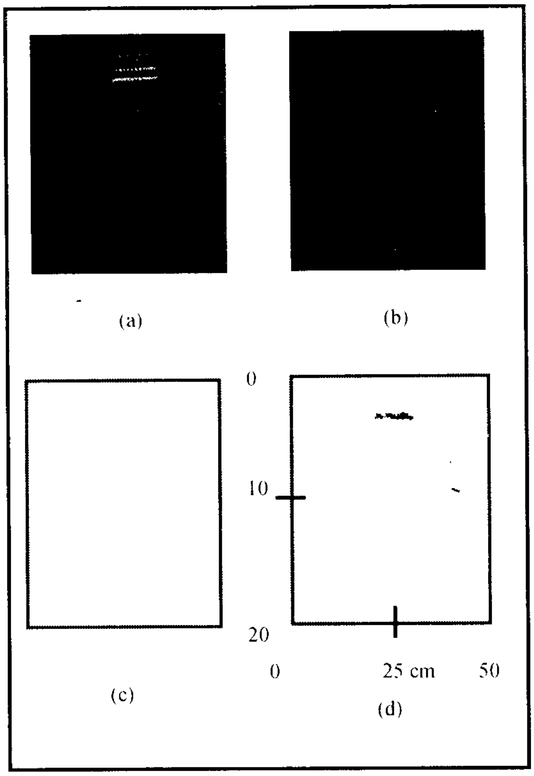


Figure 6. Applying image processing on vertical image of one flaw: (a) edge detection, (b) using half of maximum as threshold, (c) negative image and (d) using histogram equaliser algorithms.

6- Discussion

As horizontal images show the number, shape and orientation of flaw(s) are reconstructed clearly. The exact place of flaw can be recognised from vertical image. Fig. 5(a) shows the image of one flaw. It is the second and best image of ten images. As Fig 5(b) shows, for a two flaw block, first the big flaw, which is 40mm under surface is reconstructed. Then the second one, which is 70mm under surface, appears in the deeper images. It is completely clear in final image, which is in a plane 71mm under the first image. The relative difference in depth between two flaws is clear. By comparing the 5(a) and 5(b) images, it is clear that the orientation of one flaw is different from the others.

Vertical images can be used to show the exact position of a flaw. The processed image in figure 6(d) correctly shows the 40mm distance from surface for one flaw. For two flaws the figure 7(d) clearly show the position of two flaws. They are in 40mm and 70mm below the surface, respectively.

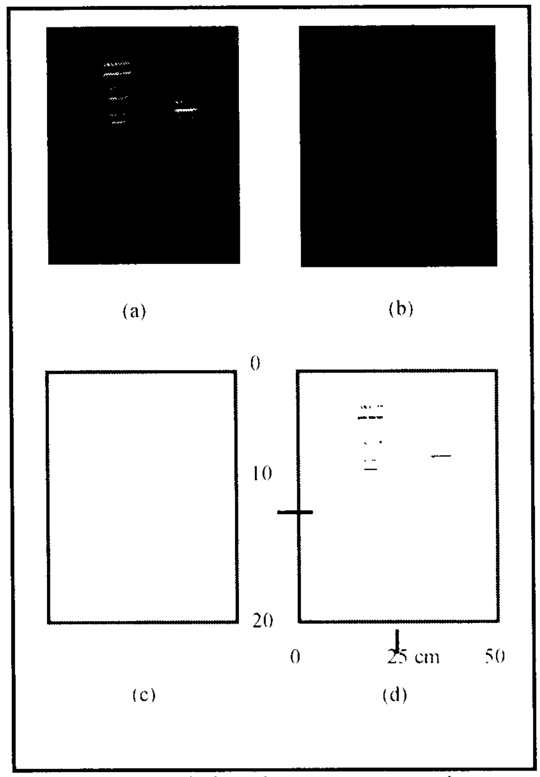


Figure 7. Applying image processing on vertical image of two flaws: (a) edge detection, b) using half of maximum as threshold, (c) negative image and (d) using histogram equaliser algorithms.

7- Conclusion

This new SAFT method can successfully reconstruct the shape, orientation and size of flaw inside blocks of concrete. The difference in depth of flaws can also be recognised.

Acknowledgement

H.T. Shandiz would like to express his thanks to his sponsor, Ministry of Culture and Higher Education in Islamic Republic of IRAN for their financial support and for giving him the chance to pursue his studies in the United Kingdom.

References

[1] P.A. Gaydecki and F.M. Burdekin Review article: Non-destructive testing of reinforced and pre-stressed concrete structures, *Journal of Non-destructive Evaluation* **14**(6) (invited paper), 1998

[2] J. Blitz and G. Simpson, Ultrasonic methods of non-destructive testing, *Chapman and Hall*, 1996.

[3] A.rosch, B.Hillemeier, Air voids, poor compaction and area of low concrete detection in concrete by pulse velocity measurement, *Technische Universitat Berlin, 1999.*

[4] J. Faber and F. Mead, reinforced concrete, *Pitman Press*, 1965.

[5] J. Pitkanen, P. Kauppinen, H. Jeskanen & V. Schmitz, Evaluation of ultrasonic indications by using PC-based synthetic aperture focusing technique (PCSAFT), *NDT.net* **2**(01), 1997.

[6] H.T. Shandis and P. Gaydecki, A new SAFT method in ultrasonic imaging with a 125KHz transducer, *ICEE-2000 IRAN*, 2000.

[7] H.T. Shandis and P. Gaydecki, Low Frequency Ultrasonic images Using Time Domain SAFT In Pitch catch method, *NDT.net* **4**(11), 1999.

[8] E. Burr, Application of a modified SAFT-algorithm on synthetic B-scans of coarse grained materials, *NDT-CE in Berlin*, 1995.

[9] B. Koehler, G. Hentges and W. Mueller, A novel technique for advance ultrasonic testing of concrete by using signal conditioning methods and a scanning laser vibrometer, *NDT.net* **2**(07), 1997.

[10] M. Schikert, Toward SAFT-imaging in ultrasonic inspection of concrete, *NDT-CE in Berlin*, 1995.

[11] R. Jansohn and M. Schickert, Objective interpretation of ultrasonic concrete image, *NDT.net* **3**(12), 1998.

Biography

Dr Patrick Gaydecki is a Senior Lecturer in the Department of Instrumentation and Analytical Science at UMIST. He gained a 1st Class Honours Degree in Computing and Biology from the University of Demontfort in 1980, and his PhD in Ecological Physics from the University of Cranfield in 1984. He is chartered physicist, a member of the Institute of Physics and the British Institute of Nondestructive Testing and is also currently Honorary Editor of the journal *Nondestructive Testing and Evaluation*. He leads a research team of ten individuals, which conducts research and development into signal and image processing solutions for nondestructive testing, medical, and audio-bandwidth signal applications. These solutions take the form of sensor design, electronic system design, in particular digital systems design, and the production of signal and image processing software. He has a keen interest in the development of real-time Digital Signal Processing (DSP) hardware and software, based around modern high MIP-rate DSP devices. He has published over 60 papers relating to signal processing, having presented his work in Europe and the Americas. He regularly presents public lectures at UMIST, and was recently been invited to give a keynote address to the *Physics Congress 2000*, an international event organized by the Institute of Physics in the UK.

H. T. Shandiz was born in Iran, in March 1964. He received the B.Sc. (1998) and M.Sc. (1991) degrees in Electrical and Electronic Engineering at Ferdowsi University of Mashed in Iran. Since 1992, he has been a lecturer at Shahroud University in Iran. At present he is finishing his PhD at UMIST. The subject of the research is ‘ DSP Solutions for SAFT Imaging’.