Development of a solid-state multi-sensor array camera for real time imaging of magnetic fields

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Abstract. The development of a real-time magnetic field imaging camera based on solid-state sensors is described. The final laboratory comprises a 2D array of 33 x 33 solid state, tri-axial magneto-inductive sensors, and is located within a large current-carrying coil. This may be excited to produce either a steady or time-varying magnetic field. Outputs from several rows of sensors are routed to a sub-master controller and all sub-masters route to a master-controller responsible for data coordination and signal pre-processing. The data are finally streamed to a host computer via a USB interface and the image generated and displayed at a rate of several frames per second. Accurate image generation is predicated on a knowledge of the sensor response, magnetic field perturbations and the nature of the target respecting permeability and conductivity. To this end, the development of the instrumentation has been complemented by extensive numerical modelling of field distribution patterns using boundary element methods. Although it was originally intended for deployment in the nondestructive evaluation (NDE) of reinforced concrete, it was soon realised during the course of the work that the magnetic field imaging system had many potential applications, for example, in medicine, security screening, quality assurance (such as the food industry), other areas of nondestructive evaluation (NDE), designs associated with magnetic fields, teaching and research.

1. Introduction
Visualization and determination of the magnetic field distribution emitted by either permanent or variable geometries are useful and illuminating tasks in research and design applications. Several simulation software packages are commercially available for modeling magnetic field distributions. These include boundary element, finite difference, finite element and finite integration methods [1]. Similarly, several mechanical scanner driven systems have been previously reported in the literature for imaging magneto static fields [1], these hardware systems enable the validation of the numerical calculations and provide valuable insight not obtainable through simulation. However, all these systems require a motorized 2D scanner system to position a single sensing scanning head along the surface to be analyzed and therefore the entire process is time consuming. It was recognized that in theory [1, 2], the electromechanical scanning assembly could be replaced by a 2D array of solid state sensors, to produce live, streaming-video of magnetic field distributions.

Over the last fourteen years, our research group has developed several systems capable of imaging steel reinforced bars embedded in concrete structures [2-5]. In early laboratory electromagnetic induction-based instruments, the image was formed by performing a 2D scanning over the concrete surface. Recently, we have also developed a new generation of imaging instrument based on
commercially available solid-state magneto-inductive (MI) sensors for imaging steel reinforcing bars in concrete [4, 5]. This system is capable of producing real-time, live video images of the distribution of the magnetic field emitted by either permanent magnets or geometries carrying current. Although this system was initially developed for the nondestructive evaluation (NDE) arena, it could also be used in many other fields, including medicine, security, manufacturing, quality assurance and design involving magnetic fields. Figure 1 shows a schematic concept representation of the real-time magnetic imaging system, an array of sensors capture the magnetic field distribution in the desired scanning area and display it in real time in the screen of the PC.

![Schematic concept representation of the real-time magnetic imaging system](image)

**Figure 1.** Schematic concept representation of the real-time magnetic imaging system

2. The imaging system

Figure 1 shows a schematic representation of the imaging system. The final laboratory system comprises a 2D array of 33 x 33 solid state, tri-axial magneto-inductive sensors covering an approximate area of 300 by 300 mm, and is located within a large current-carrying coil. This may be excited to produce either a steady or time-varying magnetic field. This coil is used to imaging metallic objects. However, it is not used to generate images of the distribution of the magnetic field of objects capable of producing its own magnetic field or to imaging magnetization residuals in objects.

The 2D array is arranged in matrix form as illustrated in the Block diagram representation of Figure 2. Twelve rows of sensors are routed to a sub-master controller and all sub-masters route to a master-controller responsible for data coordination and signal pre-processing. The data are finally streamed to a host computer via a USB interface and the image generated and displayed at a rate of five frames per second.

The research has been characterized by gradual evolution; first, a single solid state sensor was evaluated [5]; next, a single row or 1D line array of 33 sensors was then fabricated [4], which allowed the generation of an image using a single pass of the electromechanical scanner as illustrated in Figure 3. Figure 4 shows the 1D sensor array in detail. Figure 5 illustrates the full 2D system, which comprise 1089 individual sensors. The scientific and technological challenges of this programme have been formidable, regarding magnetic field theory, modelling, image reconstruction, electronic systems design and system coordination. The system can now generate in seconds, images that at one time
required over two hours to produce; with the deployment of the 2D array, it is possible to stream video-rate images to the dedicated control unit and display these in real-time on the graphics screen.

2.1.1. Solid-state sensor array. To implement the sensor array we use a novel commercially available solid state MI sensor (PNI Corp. PNI Sen-s65) [6]. Each MI sensor has a total field range from $-11$ to $+11$ gauss, with a typical resolution of approximately $0.015 \, \mu T$. Each row of sensors is constructed by 33 sensing elements, spaced at 10 mm each and aligned in the same orientation to measure the magnetic field parallel to its orientation. In this case, oriented to measure the $B_z$ component of the magnetic flux density, since previous studies have demonstrated that it is the most favourable for image generation [5, 7].

![Figure 2. Block diagram of the real-time magnetic imaging system design.](image)

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![Figure 3. Experimental Setup. a. 3D mechanical scanner system. b. The sensing head. c. Magnetic field source generated by passing DC current through a ring coil.](image)

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3. Experimentation and Results

In order to generate images, several 2D scans were conducted over different objects at different distances from the centre axis of the coil. The magnetostatic fields emitted by a ring coil with DC current excitation are shown in Figure 6. To qualitatively compare with the experimental results, numerical predictions were also generated using FARADAY 3D modelling software [8]. All the results were further processed and analyzed using MATLAB. The results depict the $B_z$ of the 2D magnetic flux density distribution. All measurement points were standardized and normalized to millimetres. All the measurements were corrected by measuring and subtracting the background and residual magnetic field such as terrestrial magnetism or other magnetic fields caused by electrical machinery near the sensor probe in the calibration process. In order to generate images with a resolution of 150×150 pixels, an image interpolation procedure [2, 9] was applied to the original low-resolution images of 33×33 pixels. The Images shown in Figure 6 clearly demonstrated that the system described in this work is capable of imaging and enables visualization of the magnetic field in 2D space.

Similarly the system is capable of generate images of ferrous targets. In this case a steady-state magnetic field is typically employed. The magnetic field distortion that arises due to the introduction of ferrous targets within the field region at distances greater than 100 mm is exceedingly small, and baseline correction must be performed if usable images are to be produced. Figure 7, Figure 2 depicts sample outputs.
Figure 6. Simulated and experimental results obtained by the system for the magnetic field emanated by a ring coil with DC current excitation.

4. Conclusion
A complete real-time, solid state scanner, which is capable of producing live, streaming video of magnetic field distributions and metal target embedded within any opaque medium has been produced and presented in this paper. It contains no moving parts and is intrinsically safe to operate. It comprises the scanner head, a small electronic control unit and a notebook computer. This instrument can be used in the field on real structures, not just in the laboratory. The system not only captures magnetic fields emitted by various sources, it also enables validation of results obtained from numerical simulation.

Figure 7. Sample images from the system. Top: 12 mm bar mesh at a depth of 85 mm before and after residual field compensation and interpolation. Middle: hammer at a depth of 25 mm. Bottom: various metal targets.
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