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Magnetic Imaging: a New Tool for UK National Nuclear Security

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Combating illicit trafficking of Special Nuclear Material may require the ability to image through electromagnetic shields. This is the case when the trafficking involves cargo containers. Thus, suitable detection techniques are required to penetrate a ferromagnetic enclosure. The present study considers techniques that employ an electromagnetic based principle of detection. It is generally assumed that a ferromagnetic metallic enclosure will effectively act as a Faraday cage to electromagnetic radiation and therefore screen any form of interrogating electromagnetic radiation from penetrating, thus denying the detection of any eventual hidden material. In contrast, we demonstrate that it is actually possible to capture magnetic images of a conductive object through a set of metallic ferromagnetic enclosures. This validates electromagnetic interrogation techniques as a potential detection tool for National Nuclear Security applications.

Illicit trafficking of Special Nuclear Material (SNM) and certain radiological materials remains an ongoing threat to homeland security[1]. As a response to such threats the Home Office (HO) and the Ministry of Defence (MoD) in combination with the Atomic Weapons Establishment (AWE) have established a UK National Nuclear Security (NNS) programme to enhance the UK capability in the detection of illicitly trafficked SNM and radiological materials[2,3]. To enhance the UK's capability, detection using different physical principles is continually being identified. The UK NNS programme covers a wide variety of active and passive interrogation techniques ranging from conventional radiation detection methods to muon scattering tomography[2–4]. As trafficking of SNM materials may involve cargo containers, suitable detection techniques are required to penetrate a ferromagnetic enclosure. We consider here techniques that employ an electromagnetic based principle of detection[5–7]. It is generally assumed that a ferromagnetic metallic enclosure will effectively act as a Faraday cage to electromagnetic radiation and therefore screen any form of interrogating electromagnetic radiation from penetrating, thus denying the detection of any eventual hidden material. Here we demonstrate that it is actually possible to capture magnetic images of a conductive object through a set of metallic ferromagnetic enclosures. This validates electromagnetic interrogation techniques as a potential SNM detection tool for NNS applications.

Our imaging system is based on the principles of electromagnetic induction, and on the technique used in Magnetic Induction Tomography (MIT)[5–7]. The imaging system operates by applying a primary alternating magnetic field to induce circulating eddy currents, according to Faraday's law of induction, within the conductive objects being imaged. In response, these induced eddy currents produce secondary magnetic fields opposing the cause of their generation. The measurement of the amplitude and phase of the additional magnetic fields associated with the eddy currents provides access to the electrical and magnetic properties of the object. Position-resolved measurements allow the reconstruction of an image of an object, as detailed below. In our approach, the position-resolved measurements are taken with the help of a 20×20 planar array of sensor coils. The planar arrangement allows us to extract images from the measurements without having to solve a computationally intensive inverse problem, as is the case for other geometries. Further details of our experimental set-up are given in the supplementary information provided.

Each sensor coil measures at its position, the oscillating magnetic field, consisting of the sum of the primary field and secondary magnetic fields containing image information. The output of each coil was analysed with a dual-phase lock-in amplifier at frequencies between 200 and 500 Hz. The dual-phase capability of the lock-in amplifier permitted measurement of both magnitude and phase-difference ϕ between array coils and driver. By repeating measurements for each sensor of the array, the phase-difference data at each (x, y) sensor position is determined. An image of an object is generated by initially measuring the background phase $\phi_0(x, y)$, i.e. a measurement in the absence of any object in the imaging plane. This is followed by a phase measurement $\phi(x, y)$ in the presence of an object, whereupon the phase difference $\Delta\phi(x, y) = \phi(x, y) - \phi_0(x, y)$ produces a representative magnetic image of the object. For materials with large conductivities and low magnetic permeabilities, as the ones considered in this work, phase difference $\Delta\phi(x, y)$ is determined by the conductivity of the object, and magnetic images can be considered as proportional conductivity maps that we refer to as magnetic images.

As illustration of the ability of the imaging system to resolve an object's shape, figure 1 shows sample images for different objects, namely an aluminium disk, square and triangle of thickness 2 mm with radius/side equal to 15 cm. A comparison between the magnetic images and photographs of the actual objects provides an immediate proof of the ability of our instrument of reproducing shape well in an image. A more complete characterization of the imaging capabilities of our instrument can be found in the supplementary information provided.

The first research question addressed in our investigation is, whether magnetic field interrogation can penetrate a metallic enclosure enough to create clear images of the enclosure interior, thus overcoming the detrimental effects of Faraday-cage screening. It is furthermore necessary to establish whether the proposed imaging modality is suitable for extracting images of eventual objects within the enclosure. Addressing these challenges was considered essential in any decisions made for future National Nuclear Security applications. The penetrating power of the imaging system was demonstrated, by imaging a copper disk through the 0.2 mm thick walls, of a closed ferromagnetic metallic enclosure, manufactured from a commonly used plated mild-steel sheet. Images of the 30 mm diameter and 2 mm thick copper disk were captured, whilst it was positioned at several locations within the 75 mm × 77 mm × 15 mm enclosure. For this study, images were captured whilst the driver coil was operated at a low frequency of 200 Hz to further increase the magnetic field penetration through the walls of the enclosure. The magnitude of the magnetic flux density at the level of the sensor coils was equal to (0.42 ± 0.02) mT RMS. The results of these measurements, presented in Figure 2, demonstrate firstly, that the copper disk appears to leave a clear magnetic signature in the image that allows the identification of its presence and position to be known. Importantly, these results additionally demonstrate that our magnetic array imaging modality is sensitive to the presence and position of this magnetic signature of the copper disk.

The penetrating power of our magnetic imaging array was further demonstrated, to an even greater degree by imaging a 40 mm diameter, by 3 mm thick copper disk, through a double ferromagnetic enclosure, using the same strength and frequency of magnetic field of the single enclosure interrogation. The copper disk was placed in a small ferromagnetic enclosure, and this enclosure containing the disk, was placed in a larger enclosure. Both enclosures were manufactured from the commonly used plated mild-steel-sheet, previously described. The smaller enclosure had dimensions of 88 mm × 89 mm × 9 mm, with material thickness (0.24 ± 0.01) mm. Whereas, the larger enclosure had dimensions of 145 mm × 113 mm × 17 mm, with material thickness (0.33 ± 0.01) mm. Magnetic images of the disk, at different relative positions within the inner enclosure were captured and presented in figure 3. Figure 3(ai) presents, a magnetic image of the closed empty double-ferromagnetic-enclosure, a photograph of which is shown in (aii). Figures 3(bi) through to (di), show that magnetic images of the double enclosure, did not clearly reveal the content of the inner enclosure. A key result of our work was that such an image does actually contain a magnetic signature of the concealed copper disk, and further there is sufficient information in such an image, with which to determine disk size and position. This can be shown by the following procedure. First, a magnetic image, i.e. the phase readings, of the empty enclosure assembly is captured. Then, such an image of the empty container is subtracted from phase readings of the double enclosure with the copper disk inside. The resultant image, shown in figure 3(bii) through to (dii) clearly reveals the disk, identifying its position within the double enclosure. This clearly demonstrates firstly, that a weak magnetic signature contains enough information to create

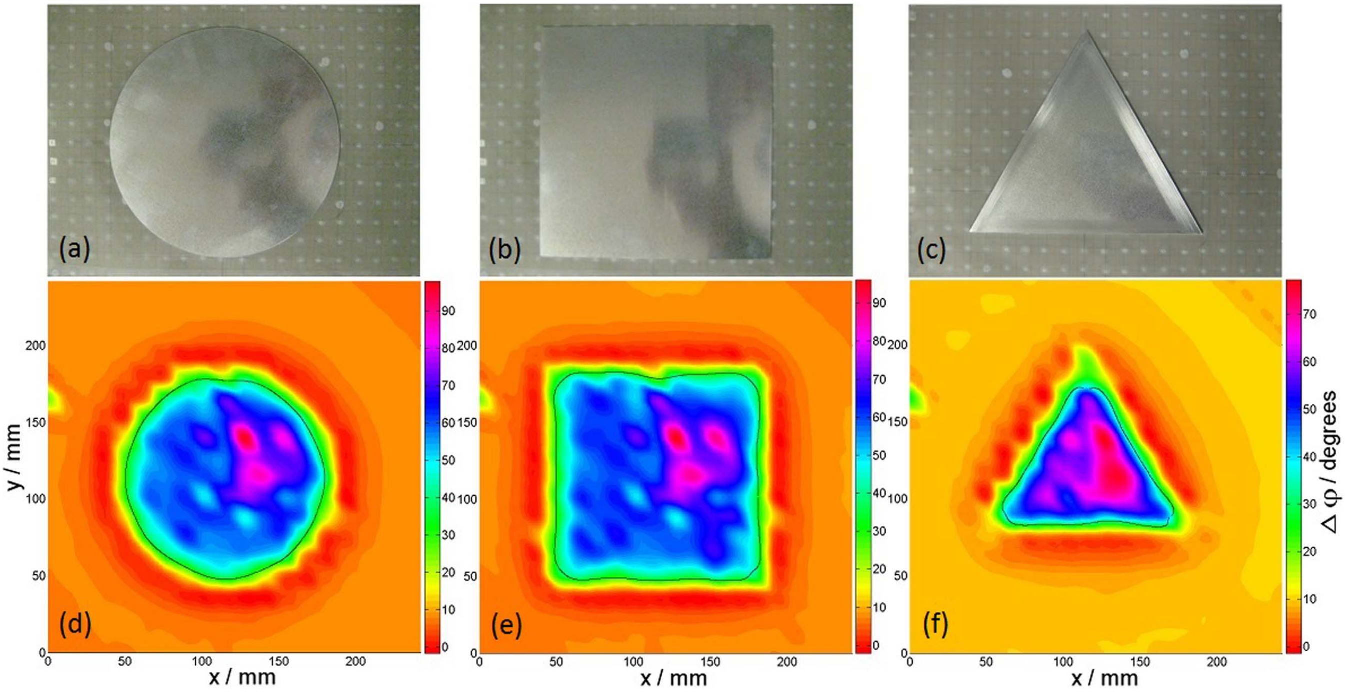

Figure 1 | Sample images. (a) through to (c) show photographs of an aluminium disk, square and triangle of thickness 2 mm with radius/side equal to 15 cm. (d) through to (f) illustrate the respective magnetic images reconstructed from phase measurements between the Helmholtz driver and 20 × 20 sensor coil array. The edges of the objects, as detected via a Canny[8–10] method, are also reported in these magnetic images (solid lines). Object photographs identify individual sensor coil positions of the array with respect to the object.

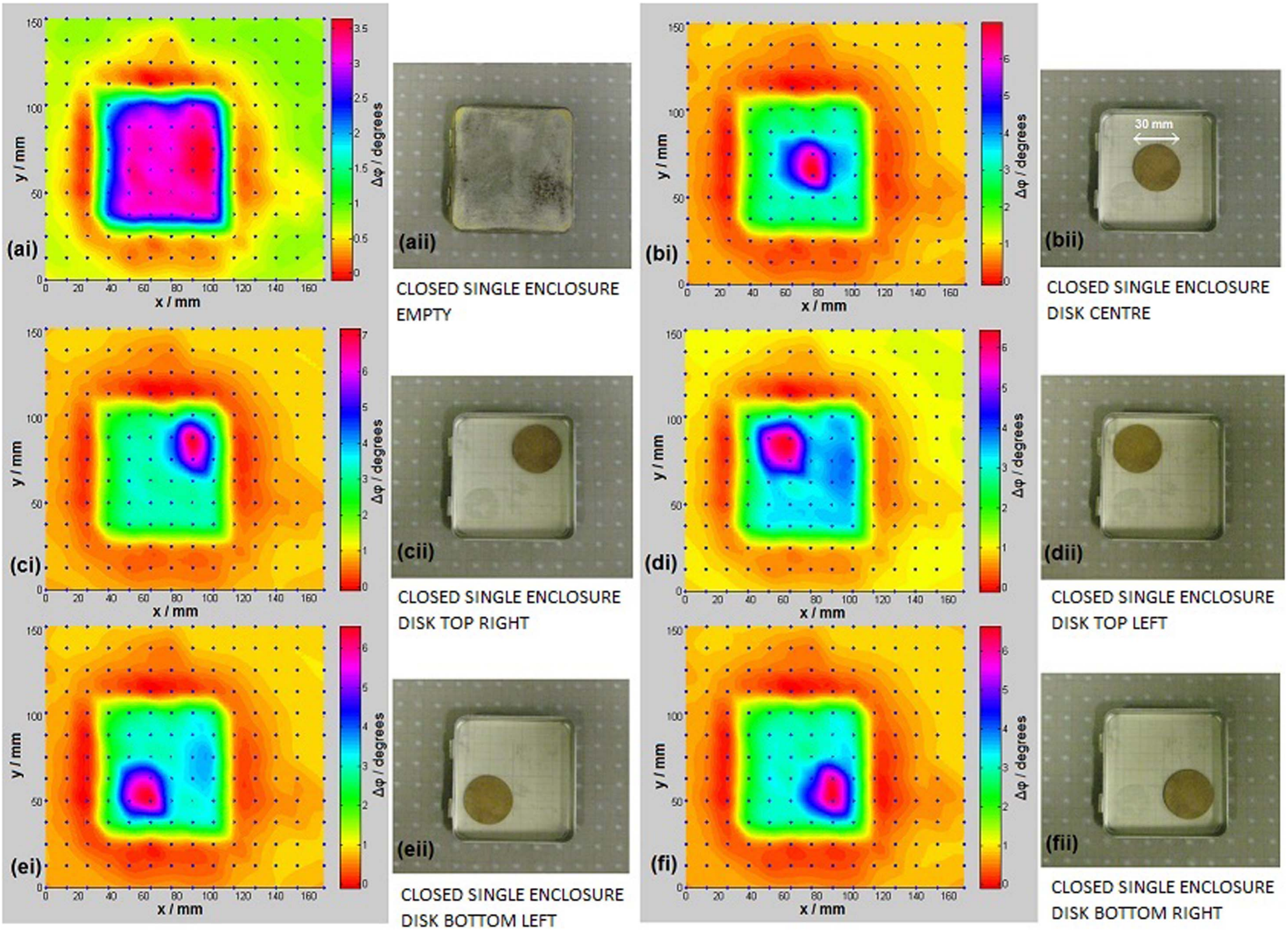

Figure 2 | Magnetic image capture through a single ferromagnetic enclosure. (ai) Magnetic image and (aii) photograph of the closed empty ferromagnetic enclosure. (bi) through to (fi) illustrate reconstructed magnetic images of the same closed enclosure concealing a 30 mm diameter, 2 mm thick copper disk in the 5 different positions stated, where photographs (bii) through to (fii) show, respectively, the disk position within the enclosure when opened. Photographs of the magnetic enclosures were taken with the enclosure lid off to allow identification of disk positions; magnetic images however were captured whilst the enclosure was closed.

detailed images, of a concealed object within double ferromagnetic-enclosures, and secondly that our imaging system proved sensitive to these signatures.

In real-world applications images of empty enclosures would not be easily acquirable rendering our background subtraction method impracticable. To address such a limitation, we have demonstrated that a substitute background image technique can be implemented, using magnetic images of enclosures at sufficiently high frequencies, such as to preclude enclosure penetration. This dual-frequency procedure is detailed and validated here, by imaging a 30 mm diameter by 0.71 mm thick, concealed copper-disk, inside a single ferromagnetic-enclosure. The method required two images of the enclosure containing the object to be captured; one at low frequency, 200 Hz, shown in figures 4(ai) through to 4(ci), and the other at high frequency, 2 kHz, shown in figures 4(aii) through to 4(cii). The low frequency image was rescaled by a global factor, so that at locations away from the concealed object, the phase value coincided with the value at the corresponding position in the high frequency image. The high frequency image approximated an empty enclosure and the rescaled low-frequency-image, contains the critical data of the object. We subtracted the phases of the high frequency image from the rescaled low-frequency-image, thus revealing the extracted metallic object, concealed inside the ferromagnetic enclosure in three positions, as shown in figures 4(aiii) through to 4(ciii).

Discussion

The described research, thus demonstrated that in addition to it being possible for interrogating magnetic-fields to penetrate through the walls and into a ferromagnetic-enclosure arrangement, any conductive concealed-objects enclosed, have magnetic signatures that are able to escape back out through the enclosure walls. These signatures can then be detected via the array-based imaging system introduced here, thus revealing the existence and position of the object. We also demonstrated, that even very weak signatures escaping double-ferromagnetic enclosures can be clearly resolved, by subtracting the background image corresponding to the empty enclosure. A dual-frequency procedure makes our technique suitable for real-world applications. This procedure does not require an empty enclosure background-image, therefore providing the capability to image the unknown contents of ferromagnetic enclosures, without having to open them. We anticipate that the magnetic signatures identified also contain information on material type, permitting the nature of the object to also be identified. Our demonstration of the possibility to image, along with the potential to identify objects through multiple metallic-ferromagnetic-enclosures, provides a potential threat/non-threat detection technique suitable for nuclear security applications. This demonstration has realised a principle of detection that is alternative and potentially complementary to those already identified, and the presented evidence validates

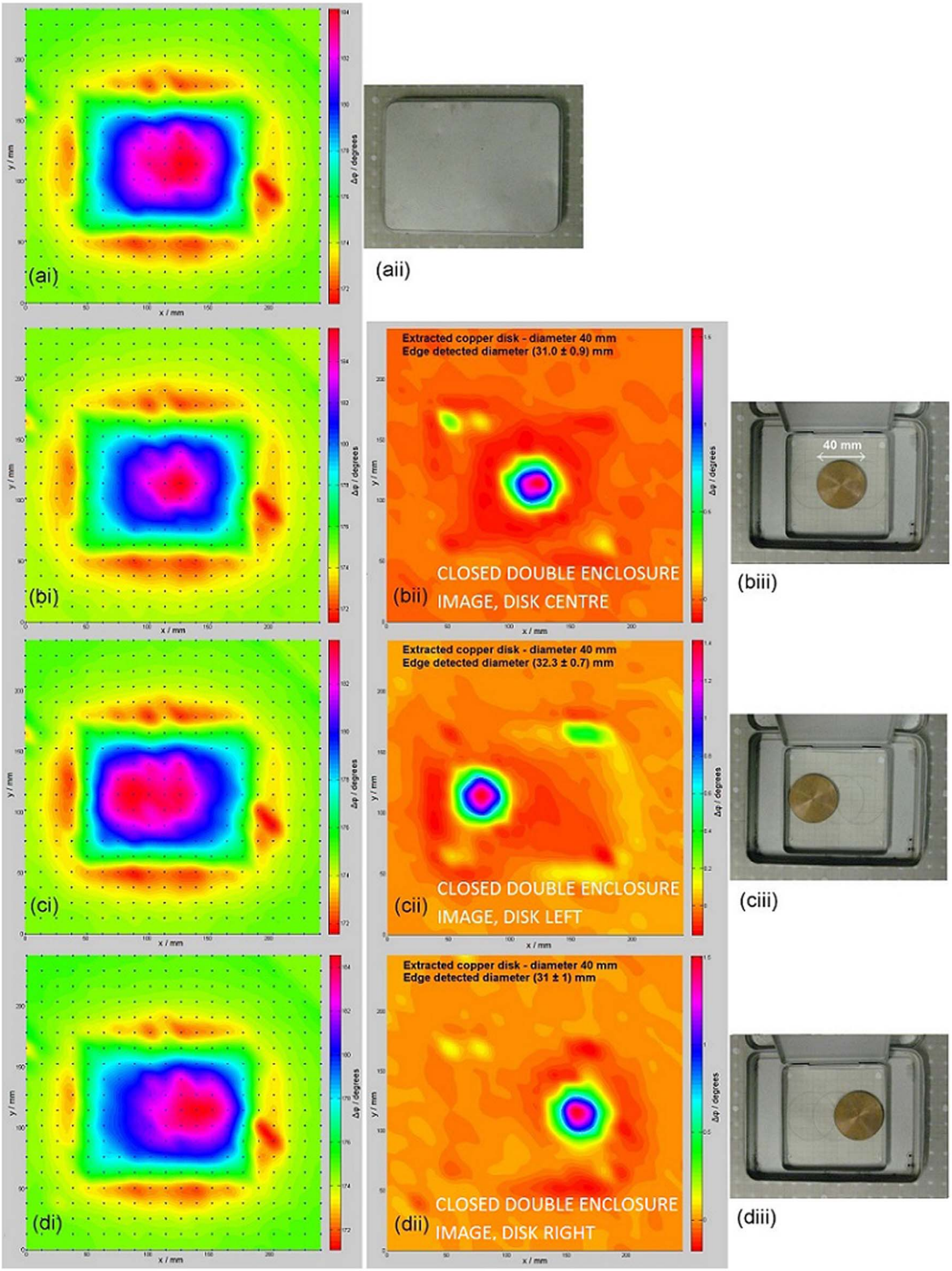

Figure 3 | Magnetic image capture through a double ferromagnetic enclosure. (ai) Magnetic image and (aii) photograph of the closed empty double-ferromagnetic enclosure. (bi) through to (di) illustrate raw magnetic images of the same closed double-enclosure concealing a 40 mm diameter, by 3 mm thick copper disk in the 3 different positions stated. (bii) through to (dii) illustrate extracted images of the concealed copper disk in 3 different positions within the enclosure. Disk images were extracted by subtraction of the phase data of the empty double- enclosure, from the double-enclosure containing the concealed disk. Photographs (biii) through to (diii) show, respectively, the disk position within the enclosure when opened. Photographs of the contents of the enclosures were taken with the enclosure lid off to allow identification of disk positions; magnetic images however were captured whilst the enclosure was closed.

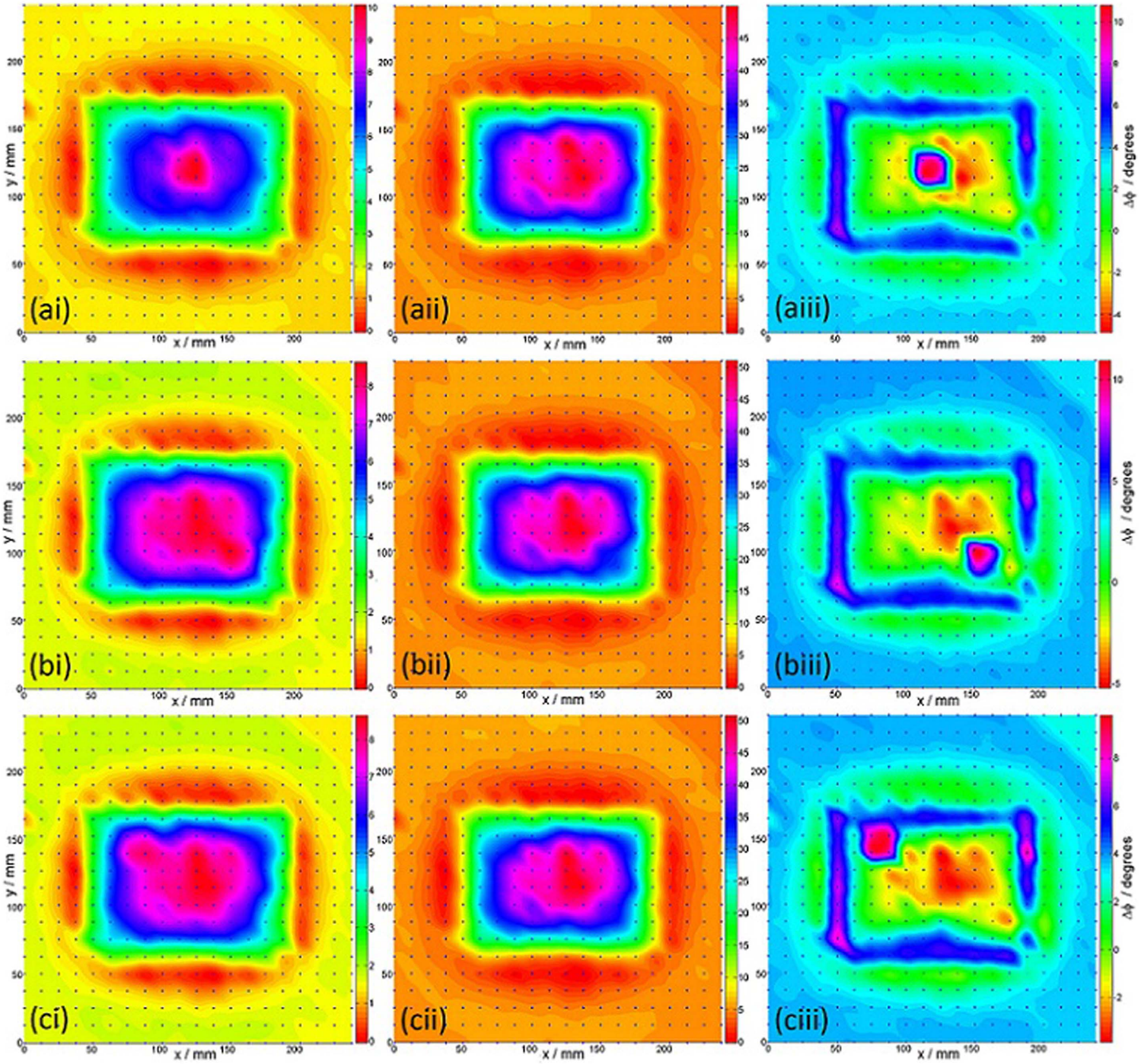

Figure 4 | Magnetic image capture through a single ferromagnetic enclosure using the dual-frequency procedure. (ai) through to (ci), magnetic images of the enclosure containing the object to be captured at low frequency (200 Hz). (aii) through to (cii), magnetic images of the previous arrangement at high frequency, 2 kHz. (aiii) through to (ciii), subtracted phases of the high frequency image from the rescaled low frequency image, thus revealing the extracted metallic object concealed inside the ferromagnetic enclosure in three positions.

electromagnetic-interrogation techniques developed within the UK NNS programme, as a valid tool for the detection of SNM.

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Author contributions

J.C.W., P.B. and F.R. designed the study. All authors participated in the design of the instrument, in the discussion and interpretation of results. B.J.D. assembled the system,

wrote the software and performed all the measurements. F.R. and J.W. wrote this manuscript with input from all the authors. Research directed by F.R.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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