A PRELIMINARY TEST ON THE FEASIBILITY OF LOCATING AN IRON RESTORATION PIN IN A STATUE BY MEASURING THE TMF ANOMALY WITH A TRIAXIAL MEMS MAGNETOMETER

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FOREWORD

Non-Destructive Testing (NDT) techniques have gained a growing role in Cultural Heritage Conservation. In the last years many scientists and technicians have been testing this increasing role (e.g. Livingston, 2001; Grimberg, 2009; Binda and Siasi, 2009). Recently (Cosentino et al., 2011) the faint border between NDT and Geophysics has been "officially" broken in consideration of the large overlap of the methodologies used in both the disciplines.

With respect to the testing of art artefact such as statues or architectural fragments four types of physical methods are available: sound (mechanical waves), penetrating radiation (X-ray, γ-rays), light (visible, near-visible), electromagnetic (magnetic, electrical impedance, electromagnetic induction, radar).

A particular application of the NDT technique is the location of iron or steel reinforcements or pins.

Many times the purpose of the NDT inspection is to find out not only the presence but also the size and the position of the metal pins to understand if they can properly perform their structural function. Ancient iron pins instead of having a reinforcement function can sometimes contribute to the failure of the restoration work (Jain et al., 1988). This negative effect can derive from different causes: because of rust and/or a wrong positioning of the pins. When the iron rusts the consequent expansion of the oxides generates stresses within the stone and cracks can occur. Sometimes the pins have not been placed in the centre of the volume that had to be connected, this turns out to be especially dangerous for the moving of statues inasmuch as high stress can be generated and concentrated near the surface with consequent rupture.

Iron or steel pins can be revealed and located with electromagnetic induction techniques even if the location can be sufficiently precise and reliable only when very simple geometries occur: pins parallel to a flat surface (pachometers for concrete rebar detection). On purpose Ground Penetrating radar (GPR) systems and software have been developed to rebar detection and by properly using these systems a 3D reconstruction of the rebar grid is possible. On the other hand, as for the pachometers, single pins of some centimetre length, with a diameter of some millimeter, nearly random oriented in volume with complex geometries such as a statue, cannot be reliably located mainly because of the size of the antennas and the wavelengths of the GPR pulses. Presently the shortest wavelengths that propagate in ornamental stones with GPR are around 5cm (Vaccaneo et al., 2004). This means that even if the presence of a metal pin can be detected, its size and position cannot be reasonably estimated.

Despite the large amount of mathematical tools developed to process potential field data, the analysis of static magnetic field for testing artifacts is, at our knowledge, not used. Very likely one of the main reasons of this lack of application is due to the small volumes that have to be investigated compared to the larger size of traditionally employed magnetometers, such as fluxgate, proton, etc. However, in recent years we assisted to the development and diffusion of a new type of miniaturized sensor and actuator devices based on the semiconductor technology. These devices, known as Micro Electro-Mechanical Systems (MEMS), include accelerometers, gyroscopes, pressure sensors, displays, microfluidic equipment, optical switches, and magnetometers. Miniaturized triaxial MEMS magnetometers are normally used as digital compasses (in combinations with accelerometers) in consumer applications, such as augmented positioning and navigation systems (to facilitate the dead-reckoning navigation) and mobile smart phones.

THE MAGNETOMETER

MEMS-based magnetic field sensors can offer small-size solution for magnetic field sensing. Smaller devices can be placed closer to the measurement spots, thereby achieving higher spatial resolution. Additionally, MEMS magnetic field sensors do not involve the microfabrication of magnetic material: therefore, the cost of the sensor can be largely reduced. Integration of MEMS sensor and microelectronics can further reduce the size of the entire magnetic field sensing system.

MEMS magnetic field sensors can be based on two different principles: Lorentz-force or Anisotropic Magneto Resistance (AMR) materials. In the former case, the sensor relies on the mechanical motion of the MEMS structure due to the Lorentz force acting on the current-carrying conductor in the magnetic field. The mechanical motion of the micro-structure is sensed either electronically or optically. The mechanical structure is often driven to its resonance in order to obtain the maximum output signal.

In the latter case, AMR effects, which are commonly found in both magnetic and ferromagnetic materials, are enhanced using a specific geometry of the magnetic element, such that a net residual magnetization is induced by the balance among energetic terms (magnetostatic, magnetoelastic, magnetocrystalline). Anisometric thin films exhibit a strong effect and enable the realization of simple, cost-effective sensors where the electrical resistance is a function of the angle between magnetization (function of the external magnetic field) and current density.

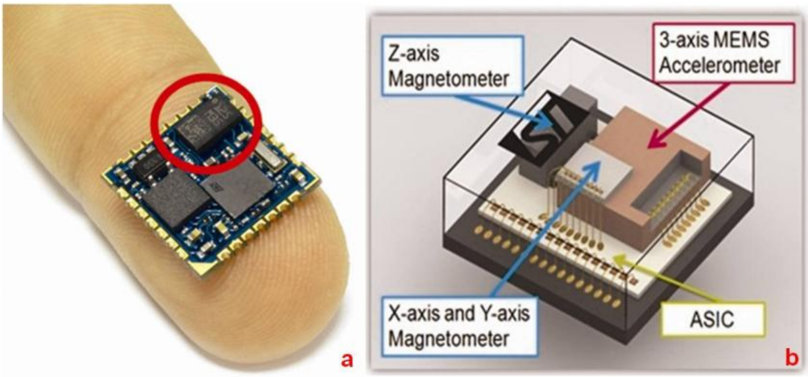

Figure 1: The STMircoelectronics iNEMO-M1 board (a) hosting the triaxial magnetometer/accelerometer LSM303DHLC (b, within the red circle in a).

The device employed for the experiment is LSM303DHLC, manufactured by STMicroelectronics. It is a system-in-package featuring a triaxial digital linear acceleration sensor and a triaxial digital magnetic sensor based on AMR. The magnetic full-scale is selectable from 130,000 to 810,000 nT, with a maximum sensitivity of 90 nT/digit. The device also includes readout circuitry providing a digital output, easy to be employed in a microprocessor-based system. Its size is 3x5x1mm and its average power consumption is under 400 μW.

THE EXPERIMENT

We made a model of a “restored arm” with a bioclastite cylindrical sample (height= 18 cm; diameter=10 cm) in which an iron pin (length= 9 cm; diameter= 5 mm) was inserted out of the sample axis and obliquely (Figure 2a). A rotating platform surrounded by a graduated scale allowed us to rotate the sample in step of 10°. A sliding beam was used to move vertically the magnetometer so that, combining the two movements, the sample was scanned along horizontal circles 1 cm apart along its height (Figure 2 b) . At each measuring point we recorded 50 times at 50 Sample/s the three magnetic components (Vertical, Radial and Tangent) with the height and the angle. At each point mean, standard deviation and standard deviation of the mean over the 50 readings were calculated and the means were then taken as raw data. With this experimental setup, aimed to perform a preliminary test of the effectiveness of the sensor, the pin rotated within the sample and was always south of the sensor, therefore we did not get the reconstruction of the magnetic field around the sample as it would be in an acquisition, for example, around a statue arm.

Figure 2: The physical model of a limestone statue “restored arm” with the iron pin fitted inside (a). The system, with the vertical sliding arm and the rotating platform, made to realize the cylindrical scanning of the model (b).

RESULTS

With a software developed in Matlab© we plotted on cylindrical surfaces all of the components and the modulus. By subtracting the average value of each component, we estimated the anomaly caused by the iron pin. Among the many representations we made of the results the most meaningful with respect to the question “where and how long is the iron pin” seem to be the plots of the total field TF (Figure 3a) and the horizontal vector H (Figure 3b) anomalies onto a cylindrical surface mapping the lateral surface of the sample. The TF vector imaging seems to reasonably describe the magnetic field flux plus some noise. The top view of all the vectors is more suitable to guess the position of the pin with respect to the sample axis. In Figure 3b some of the horizontal vector (black segments) taken at the top of the sample, and other horizontal vectors collected to a lower height (red segments), are stretched toward the sample centre. With a fair approximation the intersection areas of the black and red segments match, respectively, the top and the bottom end of the iron pin.

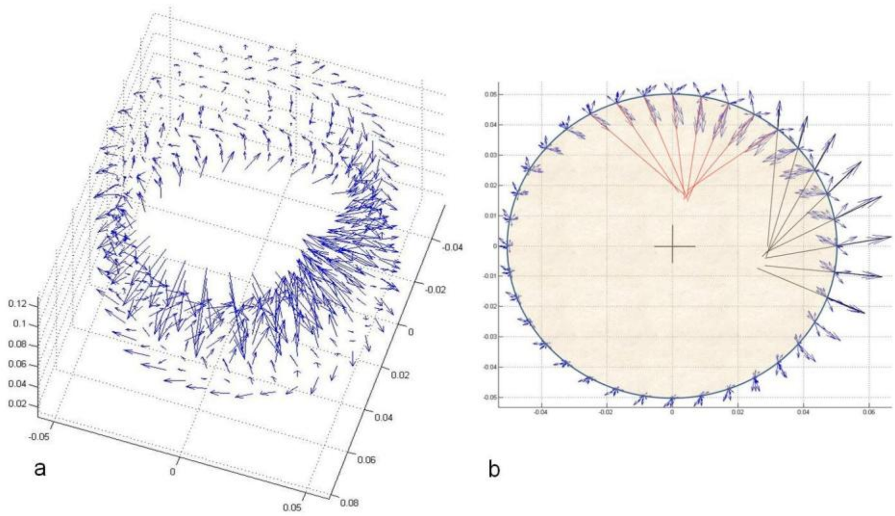

Figure 3: Two of the most meaningful representation of the results. The total field vectors (a) and the top side view of all the measured horizontal component (b) plotted at each scanning height and angle.

COMMENTS AND CONCLUSIONS

Some comments on the whole experiment are mandatory. It must be considered that: the test was carried out at the ST-POLITO office in the Politecnico of Turin, a magnetically noisy environment; the results, according to the acquisition procedure we made up, do not represent the magnetic field around the sample. However the intensity of the anomaly and the vicinity of the sensor to the anomalous body concurred to the promising results of the test. On the side of the acquisition, a set of measurements with two triaxial sensors radially separated, in order to acquire a radial gradient, has been already done always with the rotation of the sample and a static sensor. A configuration with four sensor able to measure the gradient tensor is planned as well as measurements with the sensor moved around the sample. On the site of data interpretation we are currently working at finding algorithms for data inversion. Finally it seems reasonable, giving the raw data imaging obtained, to confirm the feasibility of sizing and locating iron restoration pins within statue, with satisfying approximation, by static magnetic field anomaly measurements.

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