Coupling **magnetic sensors** with **accelerometers** to **capture** motion

By coupling magnetic microsensors with microaccelerometers, researchers can now offer the medical establishment, and even the general public, portable attitude control systems similar to the inertial navigation systems that equip the latest and most sophisticated vehicles.

It was the Chinese who first invented the compass in the 1st century AD. Generally consisting of a **magnetised** needle rotating freely in a horizontal plane, a compass automatically aligns itself with the Earth's **magnetic field lines**. As such, the compass may be considered as the very first magnetic sensor, an instrument of pivotal importance in the development of maritime navigation. Navigation involves the analysis of motion in a horizontal plane, using a reference point that is freely available at any location, namely the **Earth's magnetic field** (Focus D, ***The Earth's magnetic field, weak but vital***, p. 99). Groundbreaking developments in microelectronics and micro-systems have paved the way to manufacturing magnetic microsensors that use a variety of measurement methods, such as the **Hall effect**, micro-fluxgate (see *The micro-fluxgate, or how to combine precision and economy in a magnetometer*, p. 111), or **giant magnetoresistance**. The millimetre-scale dimensions involved make it possible to incorporate these sensors in objects such as wrist watches.

The Earth's second field is the **gravitational** field generated by the Earth's gravitational pull. Bricklayers have been using this force for years to guarantee the verticality of their walls, using the famous 'plumb line'. Likewise, movement in relation to a vertical plane can be estimated using a pendulum. The present-day method for measuring gravitational force employs an accelerometer which, provided it has a static configuration, will measure only this force. Like magnetic sensors, microaccelerometers are manufactured via collective production technologies derived from microelectronics (microelectricians often talk of MEMS: Micro-Electro-Mechanical Systems when referring to mechanical microsensors). Microaccelerometers are largely used in the impact detection systems equipping automobile airbags.

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Star Watch system designed by the LETI. This miniature attitude control system, shown here incorporated in a wrist watch, features micromagnetometers and a **radiofrequency** module via which it transmits its data to a central processing unit.

Combining magnetic field measurement sensors with accelerometers produces a system that is sensitive to both rotational motion in the horizontal plane and to tilt motion in the vertical plane. Engineers can mathematically calculate angles of rotation in a three-dimensional reference system, i.e. angles of yaw, pitch and roll (Figure 1), using data fusion.

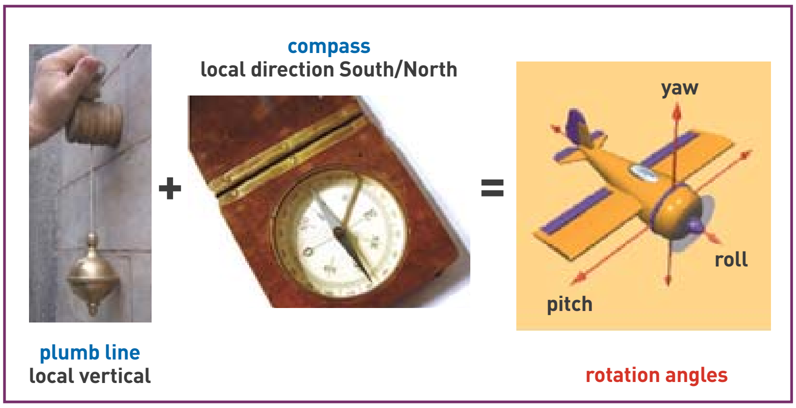

Figure 1.
Method for evaluating rotation angles in a three-dimensional reference system, based on measurements of verticality and rotation in relation to magnetic north.

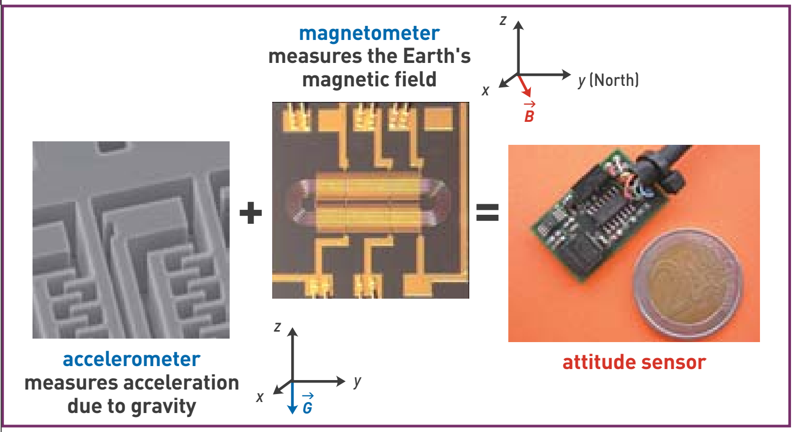

Figure 2.
Method for producing an attitude control system using sensors such as three-axis accelerometers and magnetometers.

A winning combination

Starting with this simple physical principle, the Laboratory of Electronics and Information Technologies (CEA-LETI) has pioneered a miniature attitude control system (Figure 2) that measures rotational motion in a three-dimensional reference system. This system boasts a host of potential applications in the mainstream domain, such as 3D computer interfaces or sports motion measurement and analysis systems, as well as a number of healthcare applications.

Improving man-machine interfaces

The interface used most often with a computer is the optical mouse. This relatively user-friendly device is, however, only suited to a single movement in one plane, that used in desktops in the physical world. Using an attitude control system would open up further motion options, which would be particularly useful for applications related to motion in space. Take the example of a 3D database like the IGN geographic database covering France. In this case, the attitude control system can be quite simply interfaced with a navigation software engine. This provides the operator with a highly intuitive means of exploring a digital 3D representation of France just as if they were piloting an aircraft. In the video game domain, the designers of the Wii gaming console have already taken the step by integrating inertial MEMS (in this case, accelerometers) designed to capture player motion. This groundbreaking development has proved a hit and is now paving the way to other improvements. In all likelihood the next step will involve using magnetometers to better integrate all the movements made. Indeed, such magnetometers would be able to effectively complete the inertial MEMS dataset by supplying the absolute orientation with respect to the Earth's magnetic field, without being affected by motion dynamics.

A final example of an interface able to make use of magnetometer technology is, in a more general sense, everyday portable electronic devices (mobile phone, PDA, GPS, etc.). The electronic architectures, memories and screens in these devices now offer the means to store, exchange and display an increasingly varied amount of data. In future, some of these devices will most likely be used as veritable interface controls with our surrounding environment. If these developments are to come about, user interfaces will have to be engineered to factor in this new complexity. Inertial and orientation sensors are set to play a key role in driving these developments forward. For example, they will make it easier to navigate a complex document tree structure, act as a remote control interfacing with the physical environment, like downloading information on a show just by scrolling over a display, or will help pedestrians find their way around a town or a building, etc.

Motion capture systems

Attitude control systems can also be exploited in the motion capture domain. Although the market already offers a number of devices that reproduce human motion, they are all based on highly expensive optical systems that require a dedicated infrastructure. In practice, these are employed in production studios for animated film and video game applications. A far simpler way forward, set to be unveiled in the very near future, consists in using portable inertial systems[1], i.e. systems worn on the body. By merging incoming signals via a biomechanical **model**, engineers can reproduce the motion of a sports player without the burden of having to employ a complex

Interface with a 3D IGN database. Its navigational function follows the handle's spatial orientation.

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set of equipment. Likewise, increasing the number of dynamic measurement points would make it possible to analyse and quantify the parameters governing certain motion such as rotation angles, the accelerations of certain parts of the body, and so on. The LETI is currently focusing its research on sports such as skiing, rowing and athletics. To achieve this goal, engineers have pioneered a wireless miniature attitude control system, called *Star Watch*, designed to be easily worn by athletes. No bigger than a wrist watch, this system transmits its measurement data to a central processing unit some metres away. The central processing unit can dialogue with up to 16 Star Watch systems at any one time. A key advantage of this type of system is that it is relatively unobtrusive and fully automated. It also opens the way to a number of other applications, especially in the healthcare domain.

Three core healthcare applications

In the healthcare domain, subject motion analysis is critical to establishing a proper diagnosis. This analysis is generally performed visually by the doctor who watches the patient carry out a task. There is a growing need to quantify these motion analyses in order to improve both their level of precision and also their reproducibility over time. The miniature attitude control system is an excellent candidate for quantifying human motion. The LETI is currently working on a raft of projects in the gerontology, neurology and rehabilitation domains.
With elderly subjects, physical movement and activity are excellent criteria on which to base an assessment of the subject's general condition and any changes in this condition over time. In clinical practice, the patient carries out a series of standardised tests which are scored, such as the Up&Go test. The patient starts the test sitting down on an armchair, then stands up, walks a distance of five metres, turns around, walks back to the chair, walks around it and then sits down again. During this test, the doctor scores various qualitative criteria such as the ease with which the patient was able to get up from the chair, the speed at which they completed the test, how well they were able to walk. By fixing a Star Watch-type miniature attitude control system to the subject's upper body, doctors can record their movements during the test, and then calculate the quantitative criteria describing how well the test was performed. This measurement therefore gains in precision, can now be reproduced, and is completely independent of any subjective interpretation by the doctor.
The analysis of abnormal motion is crucial to establishing a diagnosis in neurology. If we take epilepsy, for example, doctors can record seizures during the diagnosis phases by placing motion sensors onto the subject's body, usually on the arms and torso. The data collected thus is used to draw up a comparison of the seizures and refine the diagnosis via a precise analysis of the subject's clinical motor signs. Such a

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Clinical diagnosis of an activity analysis for an elderly person. The subject's movements are recorded using a miniature attitude control system attached to the upper body.

system is currently undergoing trials at the Grenoble University Hospital.
Lastly, functional rehabilitation is a natural candidate for motion analysis programmes. The first application to be developed is the range-of-motion evaluation carried out by a physiotherapist, for example, to evaluate the range of motion in a given articulation before and after a series of rehabilitation sessions. However, it is also possible to develop applications that provide the user with visual feedback, so they can see exactly how they moved or to suggest they carry out certain movements with a specific goal in mind.

A promising outlook for magnetic sensors

This article has deliberately focused on applications where magnetic sensors can be seen to provide a valuable extension to inertial sensors, such as accelerometers. Indeed, it has been shown that this combination will open up a rich seam of possible applications. From healthcare applications to man-machine interfaces and through to sports motion analysis, there is a wealth of domains where attitude control systems can offer groundbreaking instruments for capturing human motion. To sum up, note that the market now offers a range of highly cost-effective sensor systems. These obviously target mainstream markets.
This is why researchers believe that motion analysis and capture systems will be of key importance in the years to come, and that magnetic microsensors will be core components in most applications. If we further extend this argument, we could even consider that a whole new scientific domain may be on the horizon. Just like with image or sound processing, motion capture systems could pave the way to specific sensor-dedicated technological developments as well as opening up an entirely new signal processing field. If so, then scientists are set to engage on an extensive programme of research and development.

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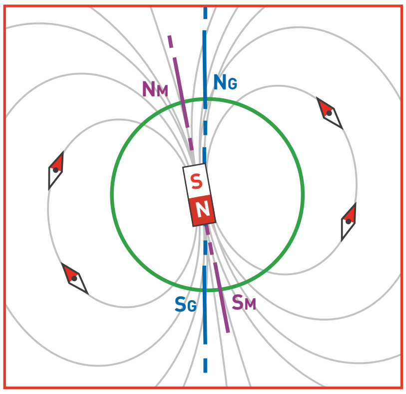
(1) Inertial system: navigation device comprising a gyrostabilised platform which provides a reference system and is designed to carry accelerometers that give real-time measurements of the accelerations of the mobile body to which it is fitted along three axes (roll, pitch and yaw). A preliminary data input gives the vector-velocity components, while a second gives the body's spatial position and orientation.

The Earth's magnetic field, weak but vital

The Earth has its own **magnetic field**, which acts like a giant **magnet**. **Geomagnetism** is the name given to the study of this field, which can be roughly described as a centred **dipole** whose axis is offset from the Earth's axis of rotation by an angle of about 11.5°. This angle varies over time in response to movements in the Earth's core (Figure). The angle between the direction of the *magnetic* and *geographic* north poles, called the



magnetic declination, varies at different points on the Earth's surface. The angle that the magnetic field vector makes with the horizontal plane at any point on the Earth's surface is called the **magnetic inclination**.

This centred dipole exhibits magnetic **field lines** that run between the north and south poles. These field lines convergent and lie vertical to the Earth's surface at two points known as the **magnetic poles**, which are currently located in Canada and Adélie Land. Compass needles align themselves with the magnetic north pole (which corresponds to the south pole of the 'magnet' at the Earth's core).

The Earth's magnetic field is a result of the **dynamo effect** generated by movements in the planet's core, and is fairly weak at around 0.5 **gauss**, i.e. 5 10^{-5} **tesla** (this is the value in Paris, for example). The magnetic north pole actually 'wanders' over the surface of the Earth, changing its location by up to a hundred kilometres every year. Despite its weakness, the Earth's dipolar field nevertheless screen the Earth from charged particles and protect all life on the planet from the harmful effects of cosmic radiation. In common with other planets in our solar system, (Mercury, Jupiter, Saturn, Uranus and Neptune), the Earth is surrounded by a **magnetosphere** that shields its surface from solar wind, although this solar wind does manage to distort the Earth's magnetic field lines.

The Earth's magnetic field is far from uniform. It is affected by **magnetic anomalies** which show up as variations in the magnetic field in relation to the global magnetic field. These anomalies can be quite large, affecting areas on a regional scale. One example is the *South Atlantic anomaly*, which affects the amount of cosmic radiation reaching the passengers and crew of any plane and spacecraft led to cross it.

The Earth's magnetic field has other, weaker, *non-dipolar* components whose effects are superimposed on the main dipole, but have far shorter time constants and so do not have any significant effect beyond the Earth's surface.

The Earth's magnetic field has fluctuated strongly over the course of geological time, suffering periods of major instability that occur with no observable regularity, and has experienced repeated reversals of its polarity. All this can be confirmed by studying the igneous or sedimentary sequences that accumulate on ocean floors. Both these rock types have the ability to acquire and lock in a magnetisation oriented parallel to the ambient geomagnetic field that existed at the time they cooled to their **Curie temperature** (**Curie point**), just below 500°C. These rocks can therefore be used to chart the polarity of the magnetic field that existed at the Earth's surface during this cooling period (or during their deposition as tiny magnetic sediment grains). This phenomenon, called **magnetic remanence**, was pivotal to the development of the field of **paleomagnetism**. The direction of the remanent field, which may be completely different from the present-day local field, provides a record of the polarity of the local field at the time the rock was formed. Volcanic rocks are first forced through the Earth's crust at a temperature higher than the Curie point of their constituent minerals. As they cool, they recross this Curie point and their constituent grains become magnetised in the direction of the ambient field. While sedimentary rocks are less sensitive to remanent magnetisation, any magnetic grains they contain will be magnetised in the direction of the Earth's magnetic field in existence at the time of their deposition. Ocean floor sediments are particularly rich in magnetic minerals, the easiest of which to identify is the famous magnetite. This magnetisation is proportional to field strength and does not vary at standard temperatures. Other factors affecting remanent magnetisation include continuous action of the Earth's magnetic field, transient high-energy fields (due to lightning, for instance), and crystallisation processes, which can modify both the strength and direction of the magnetic field locked into the magnetic mineral grains.

Reversals and excursions in the Earth's magnetic field

The Earth's magnetic field records two types of instability, reversals and excursions. Reversals occur when the north and south magnetic poles switch polarity, an event that last took place some 790,000 years ago. This type of reversal was first suggested in France in 1906 by the geophysicist Bernard Bruhnes, but it was not until the 1960s that research started to pick up pace and confirm that these reversals were a global manifestation of the Earth's magnetic field. In particular, it was shown that these reversals were both erratic and unpredictable, alternating long periods of stable field polarity (lasting hundred thousand of years) with shorter periods of rapid field reversal (lasting just a few thousand years). It was also shown that the reversal rate had increased over the last hundred million years, from one reversal at the beginning of this period to four reversals per million years over the last five million years. This would seem to suggest that the current period of 'normal' polarity is 'abnormally' long. Geomagnetic excursions are simply shorter bursts of instability. While, like reversals, the polarity of the Earth's magnetic field flips over, it flips back to its initial polarity just as quickly. Research conducted by the Climate and Environmental Sciences Laboratory (LSCE, CEA-CNRS-Versailles-Saint-Quentin-en-Yvelines University) has demonstrated that excursion periods generally run for about 1,500 years, thus providing preliminary confirmation of the theory suggested by English geophysicist David Gubbins, according to which excursions only occur in the Earth's external *liquid* outer core and not in its inner *solid* core.

The different types of magnetism

The origins of magnetism lie in the properties of electrons as explained by the laws of quantum physics. Part of an electron's magnetic properties (*spin magnetism*) results from its quantum-mechanical spin state, while another part results from the orbital motion of electrons around an atom's nucleus (*orbital magnetism*) and from the magnetism of the nucleus itself (nuclear magnetism). This is put to use, in particular, for nuclear magnetic resonance imaging in the medical field. Magnetism is therefore produced by electric charges in motion. The force acting on these charges, called the Lorentz force, demonstrates the presence of a magnetic field.

Electrons have an intrinsic magnetic dipole moment (the magnetic quantum state being the Bohr *magneton*), which can be pictured as an electron's rotational motion of spin around itself in one direction or another, oriented either upwards or downwards. The *spin quantum number* (one of the four numbers that 'quantifies' the properties of an electron) equals 1/2 (+ 1/2 or - 1/2). A pair of electrons can only occupy the same *orbital* if they have opposite magnetic dipole moments.

Each atom acts like a tiny magnet carrying an intrinsic magnetic dipole moment. A nucleus (the neutron and proton individually have a half-integer spin) will have a half-integer spin if it has an odd atomic mass number; zero spin if the atomic mass number and charge are even, and an integer spin if the atomic mass number is even and the charge odd.

On a larger scale, several magnetic moments can together form magnetic domains in which all these moments are aligned in the same direction. These spatial regions are separated by domain walls. When grouped together, these domains can themselves form a macroscopic-scale magnet (Figure E1).

The type of magnetism that comes into play is determined by how these elementary constituents are ordered, and is generally associated with three main categories of material: *ferromagnetic*, *paramagnetic* and *diamagnetic*.

Any material that is not diamagnetic is by definition paramagnetic provided that its magnetic susceptibility is positive. However, ferromagnetic materials have particularly high magnetic susceptibility and therefore form a separate category.

1. Ferromagnetic materials are formed of tiny domains inside which atoms exhibiting parallel magnetisation tend to align themselves in the direction of an external magnetic field like elementary dipoles. In fact, the magnetic moments of each atom can align themselves spontaneously within these domains, even in the absence of an external magnetic field. Applying an external field triggers domain wall movement that tends to strengthen the applied field. If this field exceeds a certain value, the domain most closely oriented with the direction of the applied field will tend to grow at the expense of the other domains, eventually occupying the material's whole volume. If the field diminishes, the domain walls will move, but not symmetrically as the walls cannot fully reverse back to their original positions. This results in remanent magnetisation, which is an important feature of naturally occurring magnetite, or of magnets themselves.

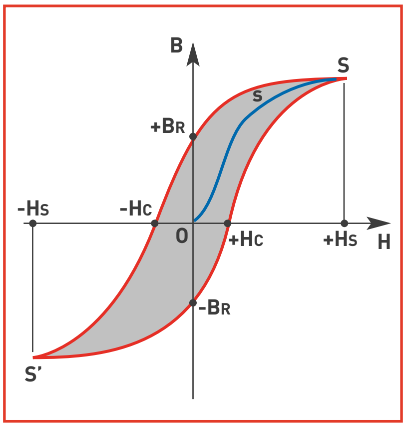


Figure E2.
The induction B of a magnetic material by a coil is not proportional to its magnetic excitation (*field H*). While the initial magnetisation forms an OsS-type curve, shown in blue in the figure, it reaches saturation at point s. Only a partial induction is retained if the field approaches zero; this remanent induction can only be cancelled out by reversing the magnetic field to a "coercive" field value. This hysteresis loop illustrates the losses due to "friction" between the magnetic domains shown on the area bounded by the magnetisation and demagnetisation curves.

The whole process forms a hysteresis loop, i.e. when the induced field is plotted against the applied field it traces out a *hysteresis curve* or *loop* where the surface area represents the amount of energy lost during the irreversible part of the process (Figure E2). In order to cancel out the induced field, a coercive field has to be applied: the materials used to make artificial permanent magnets have a high coercivity.

Ferromagnetic materials generally have a zero total magnetic moment as the domains are all oriented in different directions. This ferromagnetism disappears above a certain temperature, which is known as the Curie Temperature or Curie point.

The magnetic properties of a given material stem from the way the electrons in the metallic cores of a material or of a transition metal complex collectively couple their spins as this results in all their spin moments being aligned in the same direction.

Materials whose atoms are widely distributed throughout their crystal structure tend to better align these elementary magnets via a coupling effect. This category of materials, which is characterised by a very high positive magnetic

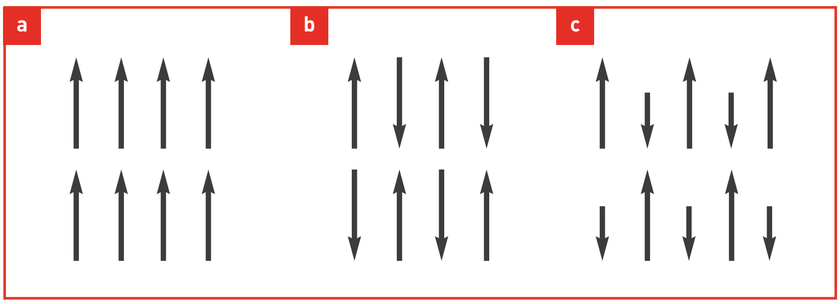


Figure E1.
Intrinsic magnetic dipole moments have parallel alignment in ferromagnetic materials (a), anti-parallel alignment but zero magnetisation in antiferromagnetic materials (b), and anti-parallel alignment with unequal moments in ferrimagnetic materials (c).

Stoiber Productions, München

A Transrapid train using magnetic levitation arriving at the Long Yang bus station in Shanghai (China). This German-built high-speed, monorail train was commissioned in 2004 to service the rail link to Pudong international airport.

susceptibility, includes iron, cobalt and nickel and their alloys, steels in particular, and some of their compounds, and, to a lesser extent, some rare earth metals and alloys with large crystal lattices, and certain combinations of elements that do not themselves belong to this category. In ferrimagnetic materials, the magnetic domains group into an anti-parallel alignment but retain a non-zero magnetic moment even in the absence of an external field. Examples include magnetite, ilmenite and iron oxides. Ferrimagnetism is a feature of materials containing two types of atoms that behave as tiny magnets with magnetic moments of unequal magnitude and anti-parallel alignment. Anti-ferromagnetism occurs when the sum of a material's parallel and anti-parallel moments is zero (e.g. chromium or haematite). In fact, when atoms are in a close configuration, the most stable magnetic arrangement is an anti-parallel alignment as each magnet balances out its neighbour so to speak (Figure E1).

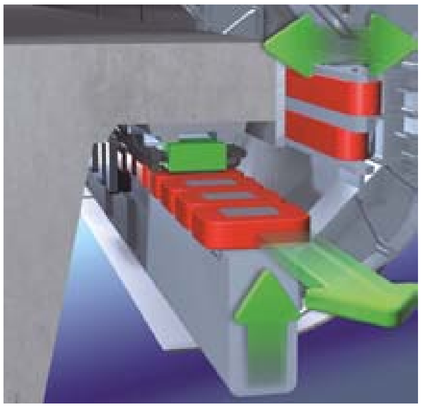
2. Paramagnetic materials behave in a similar way to ferromagnetic materials, although to a far lesser degree (they have a positive but very weak magnetic susceptibility of around 10^{-3}). Each atom in a paramagnetic material has a non-zero magnetic moment. In the presence of an external magnetic field, the magnetic moments align up, thus amplifying this field. However, this effect decreases as temperature rises since the thermal agitation disrupts the alignment of the elementary dipoles. Paramagnetic materials lose their magnetisation as soon as they are released from the magnetic field. Most metals, including alloys comprising ferromagnetic elements are paramagnetic, as are certain minerals such as pegmatite.

3. Diamagnetic materials exhibit a negative and an extremely weak magnetic susceptibility of around 10^{-5}. The magnetisation induced by a magnetic field acts in the opposite direction to this field and tends to head away from field lines towards areas of lower field strengths. A perfect diamagnetic material would offer maximum resistance to an external magnetic field and exhibit zero permeability. Metals such as silver, gold, copper, mercury or lead, plus quartz, graphite, the noble gases and the majority of organic compounds are all diamagnetic materials.

In fact, all materials exhibit diamagnetic properties to a greater or lesser extent, resulting from changes in the orbital motion of electrons around atoms in response to an external magnetic field, an effect that disappears once the external field is removed. As Michael Faraday showed all that time ago, all substances can be "magnetised" to a greater or lesser degree provided that they are placed within a sufficiently intense magnetic field.

Electromagnetism

It was the Danish physicist Hans Christian Ørsted, professor at the University of Copenhagen, who, in 1820, was first to discover the relationship between the hitherto separate fields of electricity and magnetism. Ørsted showed that a compass needle was deflected when an electric current passed through a wire, before Faraday had formulated the physical law that carries his name: the magnetic field produced is proportional to the intensity of the current. Magnetostatics is the study of static magnetic fields, i.e. fields which do not vary with time.



Close-up of the magnets used to guide and power the train.

Magnetic and electric fields together form the two components of electromagnetism. Electromagnetic waves can move freely through space, and also through most materials at pretty much every frequency band (radio waves, microwaves, infrared, visible light, ultraviolet light, X-rays and gamma rays). Electromagnetic fields therefore combine electric and magnetic force fields that may be natural (the Earth's magnetic field) or man-made (low frequencies such as electric power transmission lines and cables, or higher frequencies such as radio waves (including cell phones) or television.

Mathematically speaking, the basic laws of electromagnetism can be summarised in the four Maxwell equations (or Maxwell-Lorentz equations) which can be used to provide a coherent description of all electromagnetic phenomena from electrostatics and magnetostatics to electromagnetic wave propagation. James Clerk Maxwell set out these laws in 1873, thirty-two years before Albert Einstein incorporated the theory of electromagnetism in his *special theory of relativity*, which explained the incompatibilities with the laws of classical physics.