9-3-2008

Quantum mechanics and electromagnetics of weak magnetic field sensing, storage and retrieval in biosystems and engineered systems

Sergey Lyshevski

Follow this and additional works at: http://scholarworks.rit.edu/other

Recommended Citation

This Conference Proceeding is brought to you for free and open access by RIT Scholar Works. It has been accepted for inclusion in Presentations and other scholarship by an authorized administrator of RIT Scholar Works. For more information, please contact ritscholarworks@rit.edu.
Quantum Mechanics and Electromagnetics of Weak Magnetic Field Sensing, Storage and Retrieval in Biosystems and Engineered Systems

Sergey Edward Lyshevski
Department of Electrical Engineering, Rochester Institute of Technology, Rochester, NY 14623-5603, USA
E-mail: Sergey.Lyshevski@mail.rit.edu Web: http://people.rit.edu/seleee

Abstract – We study phenomena and effects which can be utilized to sense weak magnetic fields by engineered systems. Possible mechanisms and phenomena utilized by living systems are outlined and discussed. Assuming the macroscopic device physics, it is found that only fluidic engineered devices can typify a magnetoreception premise believed to be utilized by some living systems. It is found that the mechanical properties of silicon-technology solid devices may not coherently utilize possible behavioral transitions and functionality exhibited by natural systems. Hybrid microdevices is an alternative solution which we examine in details. Fundamental, applied, experimental and technological findings are reported.

I. INTRODUCTION

The magnetic properties of the closely-spaced biomineralized magnetite chains (~50 nm in diameter and length magnetites with ~5 nm separation) are utilized by magnetotactic bacteria for propulsion [1, 2]. The iron oxide particles and their complexes are found in various living organisms, including central and peripheries nervous systems. These facts led to a hypothesis that intracellular biomineralized iron oxides could interact with the geomagnetic field thereby sensing its direction, variations, intensity and gradient. The cornerstone processes and mechanisms, utilized by living systems to detect the geomagnetic field, have been debated and are under extensive studies [3-18]. There are many facts, reported in [3-18] and other publications, which provide an evidence that some bacteria, migrating ants, bees, birds, fish, lobsters, salamanders, sea turtles and other living organisms likely exhibit the ability to sense the Earth’s magnetic field and utilize the topographical mapping of the geomagnetic field for navigation, homing, foraging, etc. Designing engineered devices and systems, one may not be able mimic natural systems because device physics and overall functionality are unknown or not sufficiently understood. We research the fundamentals and cornerstone principles for sensing weak magnetic fields in biological and engineered systems at room temperature. Our major goals are to research biophysics and apply fundamentals of physics to examine the existing premises and devise sound alternatives. Various solid (silicon), fluidic and hybrid microdevices are documented. These devices exhibit and utilize macroscopic physics behavior, phenomena and effects.

II. MECHANISMS OF SENSING AND ITS IMPLICATIONS

We outline differences between microscopic and macroscopic systems from fundamental and practical prospective. Assuming the validity of the magnetic field sensing premise by biosystems, there are many distinct phenomena, effects and mechanisms which potentially can be utilized. They range from quantum mechanics (metastable states, energy quantization, spin-orbit interaction, interference, etc.) to classical electromagnetics and fluidics. For example, an electron may have a spin magnetic dipole moment \( \mathbf{m}_{\text{spin}} \approx 9.27 \times 10^{-24} \text{ A}\cdot\text{m}^2 \) with the alignment aiding or opposing an external magnetic field. As illustrated in Figure 1, there are small variations of the geomagnetic field which imply very small behavioral and quantitative variations. Though these changes can be utilized by microscopic (atomic and molecular) systems ensuring overall functionality and soundness, the resulting changes and transitions may or may not be observed and characterized due to fundamental and technological limits. The Heisenberg uncertainty principle provides the position-momentum and energy-time limits on the measurements. We recall that

\[ \sigma_x \sigma_p \geq \frac{\hbar}{2} \quad \text{and} \quad \sigma_\mathcal{E} \sigma_t \geq \frac{\hbar}{2}. \]

For example, \( \sigma_x \sigma_p \geq \frac{\hbar}{2} \) specifies the uncertainties on the standard deviation on the energy \( \mathcal{E} \) yielding limits on \( \sigma_x \). The observable variables (momentum \( \mathbf{p} \), displacement \( \mathbf{r} \) and other) are affected by the abilities to test and characterize devices. Even if quantum phenomena can be exhibited and utilized by natural systems, there are significant challenges to use or prototype these phenomena in engineered systems which must be characterizable.

![Figure 1. Variation in the Earth's magnetic field and some living systems (fire ant, rainbow trout, sockeye salmon and homing pigeon)](image-url)
For microscopic systems, the developments on sensing, processing and memory storage may be centered on subatomic particles, individual molecules or their assemblies studying specific quantum effects, bond formation/braking, isomerization, conformation and other phenomena which are exhibited and may be utilized. However, these premises may be based on unverifiable hypotheses, limiting these developments mainly to theoretical studies. These advancements, although having an essential theoretical importance, may not be expected to be materialized as a feasible technology in near future. We focus on the conventional electromagnetics for meso- and macroscopic systems for which well-developed technologies (microelectronics, micromachining, synthetic chemistry and other) exist.

The biomineralized magnetic iron oxides and corresponding receptors could constitute magnetoreceptor cellular assemblies within the peripheral and central nervous systems. Theoretically, these magnetoreceptors can sense the geomagnetic field, accomplish memory storage and ensure data retrieval. A great variety of biomineralized iron oxide particles (maghemite \(\gamma\)-Fe\(_2\)O\(_3\) and \(\varepsilon\)-Fe\(_2\)O\(_3\), magnetite Fe\(_3\)O\(_4\), hematite \(\alpha\)-Fe\(_2\)O\(_3\) and \(\beta\)-Fe\(_2\)O\(_3\), wuestite FeO and other) were found within distinct orientation, patterns, etc. The size, shape, morphology, crystallography, spacing, magnetic moment orientation (single-domain, two-domain, superparamagnetic, etc.), magnetic dipole moment, magnetic and thermal stability, as well as other properties of biomineralized and synthesized iron oxide particles and clusters vary.

The various aspects of macroscopic magnetoreception (possible mechanisms, phenomena, effects, system organization, etc.) are important due to possible implications to engineered systems. To potentially contribute to the biophysics of natural systems and apply the results to engineered systems, we study the interactive electromagnetic-mechanical phenomena of clustered magnets (magnetic particles) with molecular (microscopic), mesoscopic and macroscopic (bulk) receptor and sensor assemblies. It is found that weak magnetic field variations result in sufficient behavioral and transitional changes in the mesoscopic and macroscopic fluidic systems. These state transitions of various variables (displacement, velocity, current and voltage) can be utilized guaranteeing the overall functionality.

The sensing mechanism can be based on the changes of physical quantities (variations of strain, charge, conformation, etc.) caused by the interaction of magnetic clusters, which have the magnetic dipole moment \(m(r)\), with the field \(B\). We quantitatively and qualitatively examine various devices focusing on overall soundness and practicality.

### III. Electromagnetics of Macroscopic Devices

The magnetic clusters cause electromagnetic interactions. The resulting forces may be exerted on biomolecular assemblies which can form biological receptors. A ferromagnetic magnetite (the orbital and spin magnetic dipole moments obey \(|m_{\text{orb}}|>|m_{\text{sp}}|\)) exhibits a response to an external magnetic field.

We consider:

1. Electromagnetic interactions of macroscopic ferromagnetic and superparamagnetic particles/clusters which lead to electromagnetic-mechanically induced transitions in biomolecular assemblies. For example, single-domain magnetite has been localized in the nervous system of various living organisms. Correspondingly, electromagnetic interactions may result in the subcellular level of sensing, memory and processing;

2. Microfluidics. The ordered, disordered and controlled dynamic and static behavior of particles (~10 nm to ~10 \(\mu\)m) and particle-assembly interactions can be utilized resulting in electromagnetic field-induced viscoelastic, strain-caused and other transitions. The behavior of magnetite clusters and assemblies (mesoscopic and macroscopic) can be examined and utilized in engineered systems.

The translational and torsional-mechanical motion of magnetic clusters in the magnetic field is examined. The electromagnetic translational and rotational transitions result due to the force and torque developed. The torque \(T\) tends to align \(m\) with \(B\), and we have

\[ T = m \times B. \]

For a magnetic rod with the length \(l\) and the pole strength \(Q_m\), the magnetic moment is \(m = Q_m l\), while the force is \(F = Q_m B\). The electromagnetic torque is found to be

\[ T = 2F/\sin \alpha = Q_m l B \sin \alpha = m B \sin \alpha. \]

Thus, one obtains

\[ T = a_m \times m \times B = Q_m a_m \times B, \]

where \(a_m\) is the unit vector in the magnetic moment direction.

With the average magnetic field of the Earth ~50 \(\mu\)T, which varies \(\pm0.5 \mu\)T, the torque on a movable member in a mesoscopic device is estimated to be ~1 \(pN\cdot m\), and \(T_{\text{max}}\) reaches ~100 \(pN\cdot m\).

The Newtonian translational and torsional-mechanical dynamics are governed by the following differential equations

\[ \Sigma F = m_a a, \]

and

\[ \Sigma T = J \alpha, \]

where \(\Sigma F\) and \(\Sigma T\) are the net force and torque; \(a\) and \(\alpha\) are the linear and angular accelerations, \(\alpha = \frac{d^2 \theta}{dt^2}\) and \(a = \frac{d^2 r}{dt^2}\); \(m_a\) and \(J\) are the mass and moment of inertia.

Using the pole strength \(Q_m\), the force acting on a magnet is given as

\[ F = B Q_m. \]

The force between two magnets depends on the shape, magnetization, orientation, etc. The Coulomb law provides the equation for the force. For two magnetic poles, we have

\[ F = a \frac{\mu_0 Q_{m1} Q_{m2}}{4\pi r^2}, \]

where \(a\) is the unit vector along line joining poles; \(Q_{m1}\) and \(Q_{m2}\) are the pole strengths; \(r\) is the distance between poles.

The flux density at distance \(r\) from a pole with \(Q_m\) is
The magnetization is defined as the net magnetic dipole moment per unit volume, and
\[ M = \mu_0 V Q_m / 4\pi. \]

For a uniformly magnetized cylindrical magnet of length \( l \) and cross-sectional area \( A \), we have
\[ M = M_{min} l / A = M_{max} / A. \]

The pole surface density is expressed as
\[ \rho_{m} = M_{min} A = M. \]

For a cylindrical magnet with length \( l \) and radius \( r_m \), the magnetic flux density on the axis is found to be
\[ B = (\frac{1}{r_m}) \mu_0 M \left( \frac{z}{\sqrt{z^2 + r_m^2}} - \frac{z - l}{\sqrt{(z - l)^2 + r_m^2}} \right) a. \]

The reported expressions are of a significant importance because they provide the dimension-related relationships which should be used in analysis and design. The conformations of the receptors (due to the exhibited electromagnetic force) are studied for the translational and rotational devices. Some of the proof-of-concept devices are reported below. The quantitative and qualitative analysis is performed to study the magneto-receptor-centered magnetic field sensing at room temperature.

**IV. SYNTHESIS OF MAGNETIC PARTICLES AND CLUSTERS**

Magnetic properties and characteristics of biomineralized and synthesized iron oxide particles and clusters vary. For example, one may not ensure the expected ~10 mT coercivity and ~1×10\(^{-17}\) A-m\(^2\) magnetic dipole moment for a ~1 \( \mu \)m magnetite cluster. There are reasons for these results. For example, maghemite \( \gamma \)-Fe\(_2\)O\(_3\) has inherent cation vacancies \( V \) in the octahedral positions. From
\[ 4 \text{Fe}_2\text{O}_3 \rightarrow 3 \text{Fe}^{3+}\text{O} - \{\text{Fe}^{3+}_{3/2} \text{V}_{1/3}\}\text{O}_3 \]
we conclude that possible order-disorder at different sites are affected by the synthesis methods resulting in distinct properties and characteristics.

Various methods have been reported to synthesize iron oxide particles [19]. For example, ferrous chloride tetrahydrate \( \text{FeCl}_2 \cdot 4\text{H}_2\text{O} \) and ferric chloride hexahydrate \( \text{FeCl}_3 \cdot 6\text{H}_2\text{O} \) can be used. To neutralize the anionic charges on the particles surface, 1N hydrochloric acid (HCl) is used. The major steps are depicted as
\[ \text{FeCl}_2 + \text{FeCl}_3 \rightarrow \text{Fe}_2\text{O}_3 \rightarrow \gamma \text{Fe}_2\text{O}_3. \]

The resulting magnetite \( \text{Fe}_3\text{O}_4 \) is separated by applying an external magnetic field. The magnetite can be transformed into maghemite crystallites by oxidizing them at ~300\(^{\circ}\)C by aeration.

Two typical magnetization-applied filed \((M-H)\) curves (with and without hysteresis, e.g., curves 1 and 2) for ~5 nm maghemite \( \gamma \text{Fe}_2\text{O}_3 \) spherical particles, synthesized utilizing distinct procedures, are provided in Figure 2. The ferromagnetic \((M-H)\) curves with hysteresis) and superparamagnetic (no hysteresis) are observed. One recalls that
\[ B = \mu_0 (H + M), \quad M = \chi_m H, \quad B = \mu_0 H, \]
where \( \chi_m \) is the magnetic susceptibility; \( \mu_0 \) is the relative permeability, \( \mu_r = 1 + \chi_m \). For FeO, the magnetic molar susceptibility \( \chi_m V_m \) is 7.2×10\(^{3}\) cm\(^3\)/mol, where \( V_m \) is the molar volume. For the organic compounds (\( \text{C}_2\text{H}_2, \text{C}_3\text{H}_6, \text{C}_6\text{H}_{12}, \text{C}_{20}\text{H}_{12}, \) etc.), the diamagnetic molar susceptibility varies as ~[2.5 20]×10\(^{3}\) cm\(^3\)/mol.

**V. DATA STORAGE AND RETRIEVAL**

The relative motion of the iron oxide particles/clusters with respect to each other can result in the longitudinal or perpendicular data storage (recording) which can be assessed and retrieved. The concept is visualized in Figure 3. For the perpendicular storage, the memory density limit is ~1000 bit/\( \mu \)m\(^2\) which may be sufficient to ensure the geomagnetic field mapping by biosystems. The magnetization of the element should be retained despite thermal fluctuations caused by the superparamagnetic limit. The energy required to reverse the magnetization of a magnetic element is proportional to the size and the magnetic coercivity of the magnet. These issues were studied and covered in previous section. Biomineralized iron oxides could possess sufficiently large coercivity ensuring thermal stability thereby preventing demagnetization.

**VI. ENGINEERED MAGNETIC FIELD SENSORS**

The fundamentals of engineered room-temperature magnetic field sensing devices are reported. The basic physics and enabling current technologies are coherently integrated. The polymer chemistry and microelectronics technology have been matured guaranteeing high-yield industrial mass-production. As reported, maghemite, magnetite, hematite, wuestite and other oxides were synthesized and characterized. Polymer microcapsules with embedded magnetic particles can be synthesized. The polymer microcapsule’s shells are formed as magnetic particles, dispersed in the hydrophobic polymer (such as NOA prepolymer), are captured into the solid polymer phase at the emulsification step with the subsequent curing and drying. The specified magnetic characteristics can be ensured.

![Figure 2](image-url)

**Figure 2.** \( M-H \) curves for ~5 nm maghemite, \( H_{max} \) is ~100 A/m

![Figure 3](image-url)

**Figure 3.** Longitudinal and perpendicular data storage utilizing electromagnetic- or pressure-induced magnetization: Demagnetizing and magnetic storage elements are in the relative motion \( r(i) \) and \( \omega(i) \).
guaranty the overall feasibility of the proposed devices.

Various oxides and microcapsules can be deposited on the movable diaphragm. The magnetic field can be sensed and measured as the membrane deflection (r) or induced emf (voltage). The micromachined structures, components, proof-of-concept devices and solid (silicon) prototypes were designed and fabricated as reported in Figure 4.a [20]. The deflection of the suspended (released) movable structures or diaphragms were measured and characterized. For example, the micromachined four polysilicon resistors, which form the Wheatstone bridge, are documented in Figure 4.b [20]. It is found that relatively weak magnetic field can be sensed. The magnetic field is measured by using the force-induced displacement-centered sensing mechanism. Figure 4.b documents the deflection of the suspended diaphragm due to 

\[ B(t) = \frac{1}{2} \left[ \text{rect}(\frac{t}{\pi}) - 1 \right] \text{ mT}. \]

Correspondingly, time-varying \( B(t) \) can be sensed. The noise \( \xi(t) \) can be filtered by ICs.

Figure 4. (a) Etched silicon structure and silicon diaphragm with ~30 µm thickness; (b) Micromachined sensors with polysilicon resistors (to measure the force-induced deflection) and Al coils on the silicon diaphragm measuring a time-varying \( B(t) \).

In addition to solid concepts, engineered fluidic weak magnetic filed sensors are currently under developments. Various magnetic particles can be coated by polymers and suspended in liquid and solid matrices. For example, the solvent-free surface-functionalized maghemite \( \gamma \text{Fe}_2\text{O}_3 \) can be functionalized by a positively-charged organosilane \( (\text{CH}_3\text{O})_3\text{Si}(\text{CH}_2)\text{N}^-\text{Cl}^- \), which forms covalent bonds with the surface hydroxyl groups. A counter anion is \( R\text{(OCH}_2\text{CH}_2)\text{O(CH}_2)\text{SO}_3^- \), \( R\text{C}_1\text{H}_{15} \) alkyl chain. This ultimately may lead to an engineered apparatus to sense the magnetic field. In addition to this inorganic solution, a natural ferritin protein, which has an antiferromagnetic 8 nm iron oxyhydroxide core Fe(O)OH with ~4500 Fe\(^{3+} \) atoms, is considered. The suspended magnetic particles and synthetic ferritins can sense the magnetic field utilizing the force generation and displacement mechanisms.

VII. CONCLUSIONS

The fundamentals of magnetic field sensing and data storage were researched. These findings may lead to alternative solutions and re-assessment of basic postulates and premises. We focused on sound, technologically feasible and practical solutions which promise to ensure desired device performance and capabilities. We advanced engineered solutions by developing alternative concepts possibly observed in living systems. The results were demonstrated and verified for macroscopic devices fabricated utilizing silicon technology.

REFERENCES