Electromagnetic sensors for surgical navigation: perspectives on design and optimization

In designing and manufacturing miniature electromagnetic (EM sensors for surgical navigation applications—where precision, performance, and integration are critical - Forj Medical brings deep expertise. We understand that when it comes to sensor-enabled surgical navigation, a one-size-fits-all solution simply does not suffice. In this review, we share the fundamentals within custom EM sensor and subassembly design and outline key considerations and novel approaches to achieve optimal device efficiency and performance.

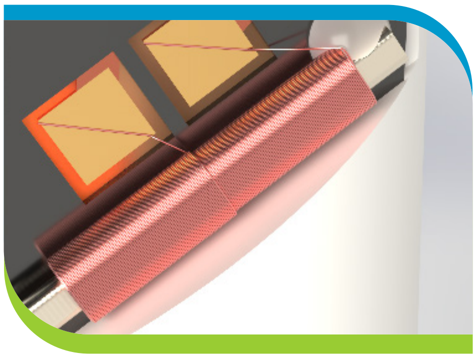

Figure 1: *Forj Medical specializes in the integration of sensors into customized components for cost efficiencies and improved manufacturability.*

Fundamentals

A custom EM sensor must optimize signal strength and maximize signal integrity within a typically minimal volume. Sensitivity describes how much signal that a sensor can transduce into voltage for a given magnetic field amplitude and frequency. Typically, larger sensitivity will lead to better localization accuracy up to a level determined by the specifics of the navigation system and surgically relevant tracking volume. Sensitivity increase can be most easily achieved by either increasing the number of winds on a coil or increasing its overall size. There are obvious limitations of increasing size within the tight constraints of an interventional device, so a core is often needed to amplify the local magnetic field perceived by the sensor. While not always necessary - such as in the case of relatively large diameter air coils or specialized sensors integrated into other device components – core choice is often of critical importance in sensor design.

Permeability

Permeability is a physical property which characterizes the degree to which a material increases a local magnetic field in response to induced magnetism when exposed to an external magnetic field. As the magnetic moments of individual electrons align with an external field[1], the overall magnetic field inside of the core increases. To counteract the discontinuous change in magnetization at the edges of the material (which goes from finite inside within the material to zero without), effective “magnetic charges” are induced at the core edges, which creates an opposing demagnetization field. When effect of these edges and associated demagnetizing fields are negligible – such as an exceptionally long cylindrical core - this amplification could theoretically lead to dramatic increases in sensitivity up to 10^6 depending on material choice. We can call this “best-case” amplification factor the intrinsic permeability.

---

[1] **The field amplification effect arises from quantum mechanical electron spin. Every electron exhibits an intrinsic magnetic dipole moment and can be imagined as a miniature bar magnet with a north and south pole. In most materials, these electron magnetic moments cancel due to quantum mechanical interactions. However, ferromagnetic materials contain an abundance of unpaired electrons which are free to align when exposed to an external magnetic field. When electron-electron interactions facilitate parallel ordering in an external magnetic field, the combined magnetic fields of individual electrons lead to high permeabilities.**

However, realistically achievable amplification factors are orders of magnitude less – we might call this the shape permeability. Clearly, aspect ratio and core shape plays a critical role in electromagnetic sensor design. In the plot shown in Figure 2, volume-averaged permeability for several cylindrical aspect ratios is shown for varying intrinsic material permeability.

The permeability curve has three main regions: the initial permeability, which dictates the low-field response of the sensor; an intermediate region which contains the peak sensitivity of the induction sensor; and the saturation region, which is the region where the intrinsic permeability curve begins to flatten at high field intensities. The general shape of this curve can be understood qualitatively in many cases.

The low initial permeability response can sometimes be correlated to crystal grain size; local forces imposed by physical grain boundaries or crystallographic defects can reduce the ability of magnetic domains to freely align in response to an external magnetic field. The domains can become temporarily "pinned", but this energy cost is overcome at stronger applied fields, cumulating in rising permeability with magnetic field strength.

The magnetic response eventually peaks and then saturation begins to occur. During saturation, electron spins rapidly approach uniform parallel alignment with the external field; benefits from increased magnetic field become progressively slighter until the core is fully magnetized.

As the mathematical transformations implemented by EM systems are typically designed for linear cores, each of these nonlinear features can cause accuracy degradation and even failure to track in EM systems. Further effects from magnetic hysteresis further complicate the pictures. As Forj Medical works to develop new sensor and sensor subassemblies with our customers, we consider factors such as core heat treatment, alloy, physical shape, amongst other concerns to provide an optimal product.

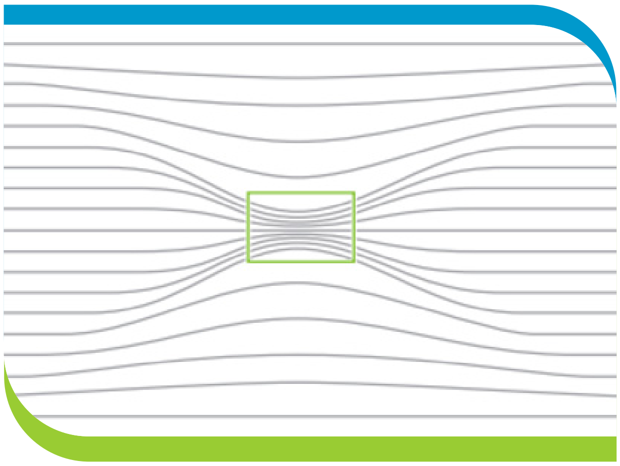

Figure 2: *Figure depicts effect of magnetic core (outlined in green) absorbing magnetic field lines in its vicinity. The lines represent the magnetic field directed from left to right, and the density of lines represents the magnetic field intensity.*

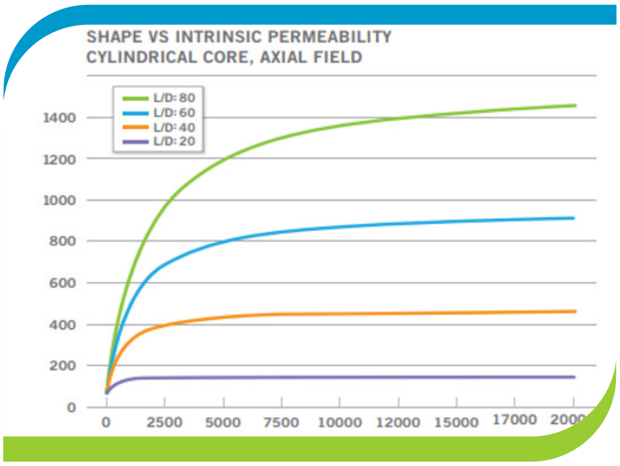

Figure 3: *Visual representation of relative intrinsic permeability vs relative shape permeability for cylindrical cores. Length-to-diameter ratio (L/D) or aspect ratio strongly impacts the shape permeability of the core.*

Let's build the future together. Visit ForjMedical.com to stay connected.

Subassembly Design for Efficiency and Electromagnetic Compatibility

Sensors are often leaded out to a fine twisted pair of wire for connectivity and sold as a simple subassembly to end users, who are then responsible for building these sensors into their assembly, whether it be a catheter, trocar needle, or other device. While this exchange is often efficient enough – and Forj Medical has extensive supplier experience in this regard – the design space is fundamentally limited. By utilizing comprehensive fine-wire connectivity resources, micro-miniature molding, pick-and-place automation, and manual assembly expertise, the development of unique low-cost subassemblies is possible. The seamless integration of EM sensors within interventional device subassemblies – placement around shafts, mounted to PCBs, and into components – can reduce overall assembly labor costs, increase durability, and open the design space for next-generation devices.

Sensor performance within a device can also differ from that of the stand-alone sensor. The mitigation of this magnetic interference is nontrivial, given the metallic components that exist in many modern interventional devices. For example, a typical interventional device will contain multiple metallic components such as braids, compression coils, pull wires and biopsy mechanisms made from 304 or 316 stainless steel, materials which are favored for their bio- and cryogenic compatibility and weak magnetic properties. Even though these steels are nonmagnetic in the heat-treated austenitic crystal phase, the cold-working and machine processes applied to alloy introduces magnetic crystalline phases. The resultant ferromagnetic properties can either amplify or attenuate the sensitivity of magnetic sensors, depending on configuration. It is usually not feasible to replace these stainless-steel components with fully nonmagnetic materials such as titanium or nitinol, which necessitates a careful consideration of sensor design and integration.

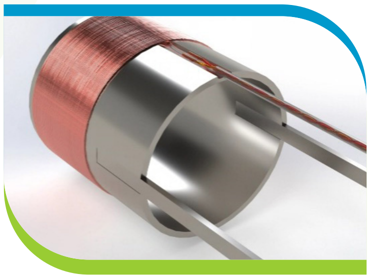

Figure 4: *Forj Medical has extensive expertise in winding sensors onto standard device components.*

Forj Medical's Expertise

With deep experience in both sensor and high-value-add subassembly design, Forj Medical is uniquely positioned to provide expert guidance throughout the entire product lifecycle—from early-stage development to high-volume manufacturing. Whether it's integrating sensors onto PCBs to enable more manufacturable wire attachment, engineering low-profile form factors through custom-molded carriers, or replacing in-tube sensors with housings that simplify production, we offer multiple paths to solve complex integration problems. We also bring a high level of thoughtfulness to the management of fine leads and contacts, including the ability to precision-wind wire directly onto components within the device's existing footprint—eliminating the need for a sensor redesign. Our vertically integrated capabilities, including precision injection molding services, allow us to design and produce custom components that improve sensor integration while meeting stringent manufacturing and performance standards. With Forj Medical's, customers gain not just a supplier, but a strategic partner committed to innovation, manufacturability, and long-term success.

FORJ MEDICAL
HEADQUARTERS
1265 Grey Fox Road
St. Paul, MN 55112
651-917-4060
info@forjmedical.com

Let's build the future together. Visit ForjMedical.com to stay connected.