# Design and simulation of a superconducting magnetic system for milli/microrobotics applications

Julien Leclerc and Aaron Becker
Dept. of Electrical and Computer Engineering,
University of Houston,
Houston, TX 70004, USA
Emails: jleclerc@uh.edu
atbecker@central.uh.edu

Nikolaos Tsekos
Dept. of Computer Science,
University of Houston,
Houston, TX 70004, USA
Email: nvtsekos@uh.edu

Kévin Berger and Jean Lévêque
GREEN Laboratory,
University of Lorraine,
Vandoeuvre ls Nancy, 54506, France
Emails: kevin.berger@univ-lorraine.fr
jean.leveque@univ-lorraine.fr

***Abstract*—Magnetically actuated robots are currently being studied as a potential technology for navigation within a human body to deliver drugs or perform minimally invasive surgery. Ex vivo applications like microconstruction or micro sensing are also considered. Superconducting materials offer the advantages of being able to carry large current densities with low losses compared to regular conductors. This drastically increases the energy efficiency of the system while reducing its size. It also allows producing higher magnetic field. This paper presents the different elements that need to be taken into consideration when designing a superconducting system for milli/microrobotics applications.**

## I. Introduction

Magnetic actuation is a technology enabling tetherless control and miniaturization of robots. They are particularly well suited for medical applications and Magnetic Resonance Imaging scanner (MRI) can be used to produce the desired magnetic field. They could navigate through body fluids to access a location to deliver highly localized therapy or perform minimally invasive surgery [1].

The MRI scanner is the most prevalent micro/robotic system using superconductors. However, it only uses superconductivity for the constant $B_0$ field, and its large size prohibits it use in most academic labs. This paper examines the trade-offs required for a laboratory-size electromagnetic system for milli/microrobotics. A comparison between different magnetic system designs is presented in fig. 1.

The generation of high magnetic fields with the use of electromagnets requires large current densities. With regular conducting materials energy is lost by Joule effect. The temperature of the coils cannot exceed a certain temperature that depends on the insulation thermal class. For example, enamel can withstand temperature up to 105°C. The maximum current density that can continuously be imposed to the coil depends on the cooling efficiency of the coil. Air cooled solenoid usually can withstand currents densities in the range of 3 to 5 A/mm$^2$. Water cooling can significantly increase this value. Increasing the current density results in decreasing the size of a solenoid to produce a given magnetic field.

Superconductors are materials that have a zero electrical resistivity when cooled at cryogenic temperature. They can transport large current densities with very low losses which

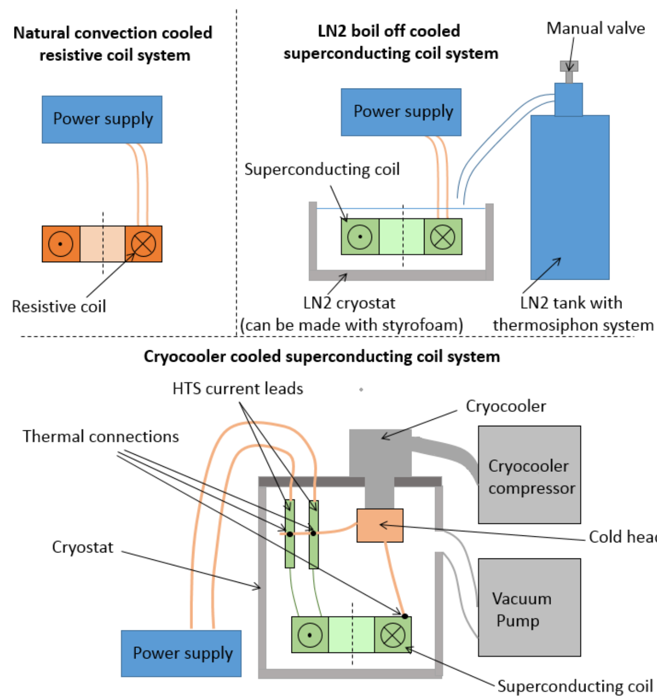


Fig. 1. Schematic representation of resistive and superconducting magnetic setups with different cooling systems.

allows to build more compacts systems. The energy efficiency is improved and smaller power supplies can be used. The maximum current density a superconductor can carry is limited by a property called critical current density ($J_c$). This value must not be exceeded. On the other hand, resistive coils current is limited by their cooling system power.

When a superconducting wire is subjected to a varying magnetic field and/or current, an electric field is created inside the material. This electric field together with the current density is a source of losses (called AC losses). Engineers must ensure that the cooling device is powerful enough to keep the superconductors at the appropriate temperature and that the heat exchanger is efficient enough to keep a small enough temperature difference between the cooling medium and the superconducting wire.

Superconducting magnetic systems offer the following advantages:

- The size of the windings as well as power supplies is reduced.
- The energy efficiency is drastically improved.
- Higher field can be obtained when other technologies are limited by the heating of the coils.
- They can create stronger fields than permanent magnets which are limited to a few hundreds of milliTeslas.

They however have some drawbacks:

- They need to be cooled at cryogenics temperature.
- The electric current cannot exceed a critical value (temporary overcharge is not possible).

Robotic applications need fast changing magnetic fields. An accurate evaluation of the AC losses as well as a good choice of the cooling system is paramount. This paper reviews the key elements to take into consideration when designing a superconducting device for milli/microrobotics application.

## II. Superconducting coils

### A. Electric and magnetic design

Superconductors are characterized by their critical temperature $T_c$. When they are cooled below $T_c$, their electrical resistivity abruptly vanishes. They are, however, not perfect conductors. A phenomenon called flux creep [2] produces a small electric field inside the conductor. The electric field value depends on the current density value, the temperature and the magnetic field. It has a highly non-linear behavior. It is usually modeled via the well-known power law [3] (see eq. 1). Superconducting materials can be classified into two categories: Low Temperature Superconductors (LTS, $T_c < 30$ K) and High Temperature Superconductors (HTS, $T_c \geqslant 30$ K).

The critical current density $Jc$ is defined as the current density necessary to produce an electrical field inside the superconductor equal to a value called the critical electric field $E_c$. The value for $E_c$ is arbitrary. It is usually taken to be equal to 0.1 $\mu$V/cm for LTS and 1 $\mu$V/cm for HTS. $J_c$ decreases when the temperature or the magnetic field increases.

When superconductors are wound into coils, the local electric field and current density $E$ and $J$ can be used to calculate the voltage $V$ and the current $I$ of the coil using eq. (3). When designing a superconducting coil, the maximum current density $J_{max} = I_{max}/S$ present in the superconductor must stay under $J_c$. This requires calculating the maximum value of the magnetic flux density $B_{max}$ present on the superconducting winding when the maximum current $I_{max}$ is applied. Knowing $B_{max}$ and the working temperature one can calculate $J_c$ from the material properties and verify that $J_c > J_{max}$. If it is not the case, the coil current density needs to be decreased and the number of turns in the coil increased to produce the desired flux density value.

Some superconducting materials exhibit anisotropic behaviors: the reduction of the critical current density depends on the orientation of the magnetic field. In that case, the angle of the magnetic field needs to be taken into account during the calculation of $I_c$.

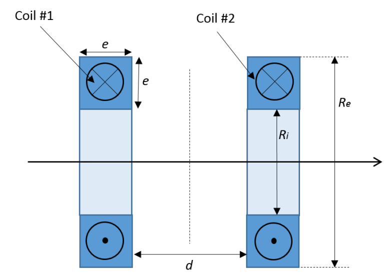


Fig. 2. Schematic representation of the Helmholtz coil system.

$$\frac{E}{E_c} = \left(\frac{J}{J_c(B,T)}\right)^{n(B,T)} \quad (1)$$

$$I = \frac{J}{S} \quad (2), \qquad V = \int_{wire\ length} E dl \quad (3)$$

### B. Practical example

Assume we want to calculate an Helmholtz coil system that produces a magnetic flux density of 1.5 T in its center. The distance between the coils $d$ is imposed and equal to 0.1 m (see fig. 2). The internal radius of the coils is chosen to be be equal to $d$ to produce an homogeneous field. The coils have a square cross-section, and the only parameter that can be adjusted to obtain the desired flux density is the length of the side of the square cross-section $e$. A security factor will be taken on the maximum current value: the coil will be designed to produce 1.875T at the critical current value. At 1.5 T the current in the coil will be equal to 80 % of the critical value.

Two main steps are needed to solve this problem. First, an algorithm able to calculate the $Jc$ of a coil for a given geometry is needed. Secondly, an optimization algorithm will be used to search for the value of $e$ that will produce the desired flux density. As seen in II-A, $J_c$ is a function of the flux density. The material considered in this study is BiSCCO. Its critical current density field dependency is modeled by eq. 4. At 30K, $J_{c0}$ is approximately equal to 500e6 A/m and $B_0$ is approximately equal to 3 T. These values have been obtained by approximating data provided by Sumitomo Electric Industries. The magnetic flux density present on the coils cross-sections is calculated via the semi-analytical method described in [4].

$$J_c(B) = \frac{J_{c0}}{1 + \frac{B}{B_0}} \quad (4)$$

The critical current of the coil needs to be calculated through an iterative process. The critical current density is a function of the current in the coil. Indeed, a change in the current changes the magnetic flux density on the windings which modify the critical current density. The critical current $I_c$ is obtained when the current density $J$ is equal to $J_c$. The minimization algorithm *fminsearch* present in Matlab was used to search $I_c$ by minimizing the quantity $(J-Jc)^2$. Once the critical current of the coils is obtained, the flux density in the center of the coil system can be calculated. An optimization algorithm can be used to search for the value of $e$ that will give the desired flux density. It was chosen to use a simple gradient descent

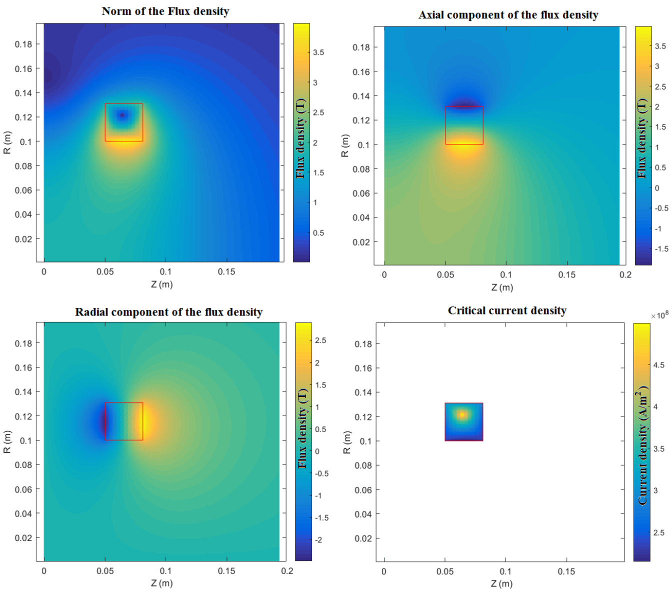


Fig. 3. Plot of the magnetic flux density and the critical current density maps obtained via Matlab simulations. This plot correspond to the optimal designed system ($d$=0.1 m and $e$=0.031 m)

algorithm to perform this optimization. The solution for the considered problem is presented in Fig. 3. It was found that the Helmholtz coils need to have a cross section side length of 0.031 m to produce 1.5 T in their center.

## III. AC LOSSES CALCULATION

To properly select the cryogenic cooling system, the amount of AC losses must be calculated. However, the highly non-linear behavior of superconductors make the task difficult. Three options are currently available to calculate AC losses.

The first method is based on analytical calculation [5]. Strong assumptions need to be made to obtain a result. This leads to inaccurate but fast predictions.

The second method is based on finite elements calculation [6]. The local variables $E$ and $J$ must be calculated at each point of the superconductor as a function of the time. The amount of losses produced per period is obtained by integrating $E \cdot J$ over the total volume of superconductor and over a period of the input signal.

The last possibility is to use empirical models based on FEM simulations. These models were build to fit large amount of data generated via FEM computation. In [7] an artificial neural network was trained to fit losses data calculated for a superconducting filament submitted to a rotating, pulsating or elliptical magnetic field.

## IV. CRYOGENIC COOLING SYSTEM

Cooling methods for superconducting devices can be classified into two categories: cooling via a cryogenic liquid and cooling via a cryocooler. Figure 1 is a schematic representation of two cooling methods for superconductors and a comparison with a natural convection cooled resistive coil.

Commonly cryogenic fluids used in superconductivity are liquid Helium (LHe, 4.2 K) and liquid Nitrogen (LN2, 77 K). Cryogenic liquids are usually used at their boiling temperature. This ensures that the system is working at a constant temperature. The heat is removed via the evaporation of the liquid. LHe, for example, has a latent heat of vaporization equal to 20.9 J/g at 4.2 K. That means that 1 g of LN2 will evaporate to extract 20.9 J of heat. With this value and knowing the quantity of losses produced, the amount of liquid evaporated per unit time can be calculated.

Cryocoolers are machines that use a thermodynamic cycle to generate low temperature. They have the advantage of being closed systems (no gas or liquid is lost). Unlike cooling with a cryogenic liquid, this system does not need regular refills. It only needs an electrical power supply to work. The coefficient of performance (COP) of cryocoolers is an important parameter. It is the ratio of the amount of heat extracted at cryogenic temperature and the amount of mechanical work needed. This characterizes the efficiency of the cooling system. The COP decreases when the working temperature decreases. For example, an ideal refrigerator would use 288 W to extract 100 W of heat at 77K while it would use 7,043 W to extract the same heat at 4.2 K. For systems producing a significant amount of AC losses, it is usually chosen to work with HTS rather than LTS to reduce the power consumption of the cooling system.

## V. CONCLUSION

Methods and tools to design superconducting magnetic systems for microrobotics applications are presented. The design approach first focuses on the design of the superconducting solenoid and the calculation of the critical current. Then, AC losses must be carefully evaluated. Microrobotics application indeed needs varying magnetic field. This produces losses inside the superconducting wire. The cooling system needs to be carefully chosen to keep the winding at the desired working temperature. Different technics are available to cool superconductors at cryogenic temperature. A cryogenic liquid like Helium or Nitrogen can be used. A cryocooler offers the advantage of lowering the operating work.

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