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

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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. A method to design superconducting Helmholtz coil system is detailed. This method was implemented into the software MATLAB and a design example is presented.

1. Introduction

Magnetic actuation is currently being seen as a promising technology to control miniature robots. This method removes the need for a complex embedded actuation system. Forces are instead created by external magnets. Magnetic miniature robots can, therefore, be extremely simple. This allows for an easier miniaturization and robots can be as simple as a single magnetic particle. [1].

Two main applications are foreseen for these magnetic millirobots. The first one is the micro-assembly of microscopic objects where robots are used to move, place and assemble parts together. The second application is in the medical field where robots could be used to perform highly localized drug delivery or minimally invasive surgery. A controlled magnetic field is produced around a patient to actuate a robot placed inside his body. MRI scanners can be used to produce the required magnetic field. This machine can also be used at the same time to track the position of the robot.

The MRI scanner is the most prevalent micro/nano 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.

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.

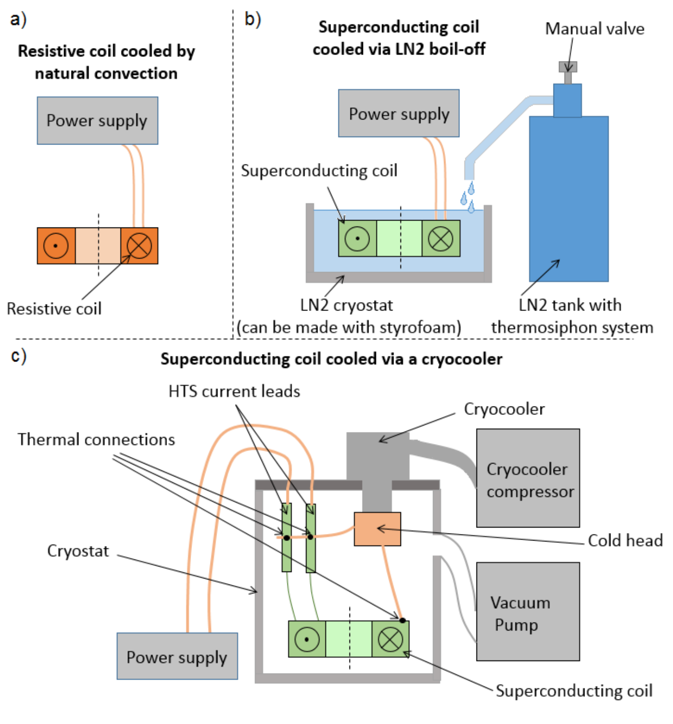

Fig. 1. Schematic representation of resistive and superconducting magnetic setups with different cooling systems.

The temperature of resistive coils cannot exceed a certain value 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 allows to build more compact 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. A comparison between different cooling systems is presented in fig. 1.

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). These losses must be calculated by engineers to select a cooling device powerful enough to keep the superconductors at the appropriate working temperature. In addition, the heat exchanger must be efficient enough to keep a small 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 are 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 is paramount to optimaly select the cooling system.

This paper reviews the key elements to take into consideration when designing a superconducting device for milli/microrobotics application. A method to design superconducting Helmholtz coil systems is presented. This method was programed into the software MATLAB and a graphical user interface was made. The computation is fully automated. The source code is attached to this paper.

Helmholtz coil systems are composed of two circular electromagnets oriented along the same axis. They are usually used to produce uniform magnetic fields. To ensure proper field uniformity, the radius of the coils should be equal to the distance separating them. In this paper, the term Helmholtz coil is used to describe the more general case where the coils can be separated by a distance different from their radius. If these values are far from each other, the magnetic field might not be homogeneous. However, having this additional degree of freedom allows to increase the design flexibility. Magnetic robots don't necessary need homogeneous field. Their small size will always allow to assume a constant applied flux density. In addition, the controller can be used to compensate the change in magnetic field when the robot changes location by changing the electromagnets current value.

2. Electromagnetic properties of Superconductors

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] presented in eq. 1.

$$\frac{\vec{E}}{E_c} = \left(\frac{\vec{J}}{J_c(\vec{B})}\right)^{n(\vec{B})} \tag{1}$$

$$\tag{2}$$

In this equation J_c is the critical current density. It 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 normative. It is equal to 0.1 μV/cm for Low Temperature Superconductors (LTS, $T_c < 30K$) and 1 μV/cm for High Temperature Superconductors (HTS, $T_c \geq 30K$). n is simply called the exponent of the power law.

When designing a superconducting coil, the current density J present in the superconductor must stay under the critical value. J_c varies both with the temperature and the magnetic field. An increase in temperature or an increase of magnetic field produces a decrease of J_c. For most applications, the temperature can be assumed to be constant. The following equation presents a model for the field dependance of J_c of an isotropic superconductor:

$$J_c(\vec{B}) = \frac{J_{c0}}{1 + \frac{|\vec{B}|}{B_0}} \tag{3}$$

Superconducting wires usually have isotropic behavior, however, superconducting tapes have anisotropic electromagnetic properties and in this case the following model can be used:

$$J_c(\vec{B}) = J_c(\vec{B_\perp} + \vec{B_\parallel}) = \frac{J_{c0}}{1 + \frac{\sqrt{|\vec{B_\parallel}|^2 + k^2|\vec{B_\perp}|^2}}{B_0}} \tag{4}$$

where $\vec{B_\perp}$ and $\vec{B_\parallel}$ are the components of the magnetic flux density perpendicular and parallel to the superconducting tape respectively.

The magnetic field present on the superconductor is the sum of the external magnetic field and the self magnetic field (magnetic field produced by the superconductor on itself). The first term can in some application be non existent. However, the self magnetic field is always present and must be taken into account.

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 calculations.

The critical current density of superconducting tapes or wires is also affected by the mechanical stress it has to withstand. Superconductor manufacturers provide the value of the critical tensile strength. For example, the Sumitomo BiSCCO type H tape has a critical tensile strength of 130 MPa. This value corresponds to the tensile strength that produces a decrease of 5% of the critical current density. This value should not be exceeded.

Superconductors are also sensitive to the bending radius. Each manufacturer provide a minimum bending radius. For example, the YBCO tape from Superpower Inc. can be bent at a radius of 5.5 mm.

3. AC losses

A time-varying magnetic field present on the superconductor produces an electric field which, together with the current density produces AC losses. 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 calculations [4]. Models are derived from the critical state assumption which assume an infinite value for n. This leads to a calculation errors that are large for low n values but decreases to zero when the value of n tends to infinity. The main advantage of this method is that predictions are fast to compute.

The second method is based on finite elements calculation [5]. 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. This method is accurate but slow.

The last possibility is to use empirical models based on FEM simulations. These models are build by fitting large amount of data generated via FEM computation. In [6] an artificial neural network was trained to fit losses data calculated for a superconducting filament submitted to a rotating, pulsating or elliptical magnetic field. This type of model is long to build because a lot of numerical simulations must be computed. However, once the parameters of the model are found, the predictions are fast and accurate.

4. 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 LHe 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. LHe is expensive and evaporated gas must be stored to be reliquified. On the other hand, LN2 is cheap and easy to handle.

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, the AL125 refrigerator from Cryomech uses 3,900 W of electric power to extract 100 W of heat at 65K while the AL325, which is designed to work at lower temperature, uses of electric power 11,22 W to extract the same heat at 25 K [7]. 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.

There is three ways to thermally connect a Superconducting coil to a cryocooler:

- Thermal connection via conduction: the coil and the cold head of the cryocooler are placed under vacuum. A highly thermally conductive part connects the coil to the cold head. This part is often a copper braid with a large section.
- Thermal connection via convection: A cryogenic gas (usually Helium gas) circulates between the superconducting coil and the crycooler cold head. A heat exchanger is present in both sides. A cryogenic fan is usually used to force the convection.

- Thermal connection via boil off of cryogenic liquid: The Superconducting coil is placed into a cryogenic liquid bath. The energy dissipated into the coil produces the evaporation of liquid. The cryocooler is used to re-condensate the evaporated liquid. This method is used in zero-boil off MRI scanners.

5. Design of a Superconducting Helmholtz coil system

5.1. *Magnetic field computation*

As stated in section 2, the critical current density of superconductors varies with the magnetic field. One therefore have to calculate its value. The system is axisymmetric. It was chosen to perform the calculations in a 2d axisymmetric coordinate system (see Fig. 2). The total magnetic field is the sum of the external and self magnetic field (see Section 2). The external magnetic field depends on the environment. The self magnetic field is produced by the coil itself and must be computed.

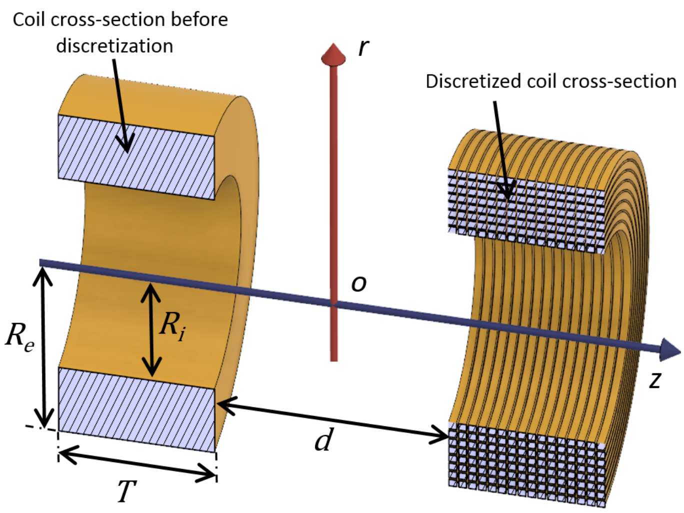

Fig. 2. Drawing of the Helmholtz coil system.

Each coil has a total number of turns equal to N. A current I_w circulates in the conductor. The current density averaged over the superconducting wire cross-section is $J_w = I_w/S_w$ where S_w is the superconducting wire cross section area. The cross-section of the coil is composed of areas occupied by the superconducting wire and area occupied by insulating material. The filling factor of the coil is $FF = N \cdot S_w/((R_e - R_i) \cdot T)$ where R_e and R_i are the external and internal radius of the coils respectively and T is the their thickness (see Fig. 2).

To perform the self magnetic field calculation, the current density is averaged over the coil cross section i.e. the non-uniformity produced by the combination of insulating and conducting material on the current density is neglected. The current density averaged over the coil cross section is denoted J_a and is calculated with $J_a = FF.J_s$.

Each coil can be decomposed into a sum of infinitesimal current loop having a cross section $dr.dz$. The magnetic flux density $dB_z(R_p, Z_p, R_m, Z_m)$ and $dB_r(R_p, Z_p, R_m, Z_m)$ produced by a current loop can be calculated using the semi-analytical equations 3, 4, 5 and 6 [8]. In these equations, the field calculation point is placed at coordinates $(R_m, 0, Z_m)$ in the cylindrical coordinate system and the current loop is placed at $z = Z_p$ and has a radius R_p. The magnetic flux density produced by the complete coil is obtained by performing the integration of $dB_z(R_p, Z_p, R_m, Z_m)$ and $dB_r(R_p, Z_p, R_m, Z_m)$ over the coil cross section (see eq. 7 and 8).

$$\begin{aligned} dB_z(R_p, Z_p, R_m, Z_m) = &\frac{\mu_0 I}{2\pi\delta^2\beta}([(R_p^2 - R_m^2 - (Zm - Zp)^2) \\ &.(E(k^2) + \delta^2 K(k^2)))] \end{aligned} \quad (5)$$

$$\begin{aligned} dB_r(R_p, Z_p, R_m, Z_m) = &\frac{\mu_0 I \cdot (Zm - Zp)}{2\pi\delta^2\beta R_m}([(R_p^2 - R_m^2 - z^2) \\ &.(E(k^2) - \delta^2 K(k^2)))] \end{aligned} \quad (6)$$

$$\delta = \sqrt{R_p^2 + R_m^2 + (Z_m - Z_p)^2 - 2R_pR_m} \quad (7)$$

$$\beta = \sqrt{R_p^2 + R_m^2 + (Z_m - Zp)^2 + 2R_pR_m} \quad (8)$$

$$Bz(R_m, Z_m) = \int_d^{d+T} \int_{R_i}^{R_e} dBz((R_p, Z_p, R_m, Z_m))dR_p dZ_p \quad (9)$$

$$Br(R_m, Z_m) = \int_d^{d+T} \int_{R_i}^{R_e} dBr((R_p, Z_p, R_m, Z_m))dR_p dZ_p \quad (10)$$

5.2. *Critical current density computation*

It is first necessary to clarify the difference between the local critical current density J_c and the coil critical current density J_{cc}. At each point on the coil, the superconductor is subjected to a different magnetic field $B(R_m, Z_m)$ [9]. The critical current is a function of the magnetic field as shown in the model presented in eq. 3. Therefore, at each location of the coil, a value for $J_c(B)$ can be calculated. It correspond to the maximum current density the superconductor can carry **at this point**. On the other hand, the value of J_{cc} corresponds to the maximum current density the conductor of **the complete coil** can carry.

In the considered Helmholtz coil problem, the only sources of magnetic field are the coils of the system. There is no external magnetic field. The two coils are connected in series and are therefore sharing the same current. The magnetic field present on the Helmholtz coils system is thus proportional to the current and is classified as self-magnetic field.

J_w is constant in the in the winding since it is made with a single conductor. Therefore, much like with the weak chain link problem, the maximum current density J_{cc} that the coil can carry correspond to the minimum J_c value encountered in the winding when $J_w = min(J_c)$. The problem is not straightforward to solve: a change in the value of J_w produces a change in $min(J_c)$ which define the maximum value for J_w. An iterative calculation is therefore needed to find J_{cc} (see fig. 3 (b)).

The method used to solve this problem is the following: first, a starting value J_{w0} is chosen for J_w. The magnetic field produced at this current is calculated. From this results, J_c is calculated over the coils cross section. $min(Jc)$ is compared to J_w. If $J_w > min(J_c)$ the current density J_w needs to be decreased in the next iteration. If $J_w < min(J_c)$ the current density J_w needs to be increased in the next iteration. The process is repeated until the condition $J_w = min(J_c)$ is satisfied (or close to be satisfied) and therefore J_{cc} is found.

This algorithm was implemented in the provided MATLAB function *JcSearch.m*. The optimization algorithm *fminsearch* was used to search J_{cc}.

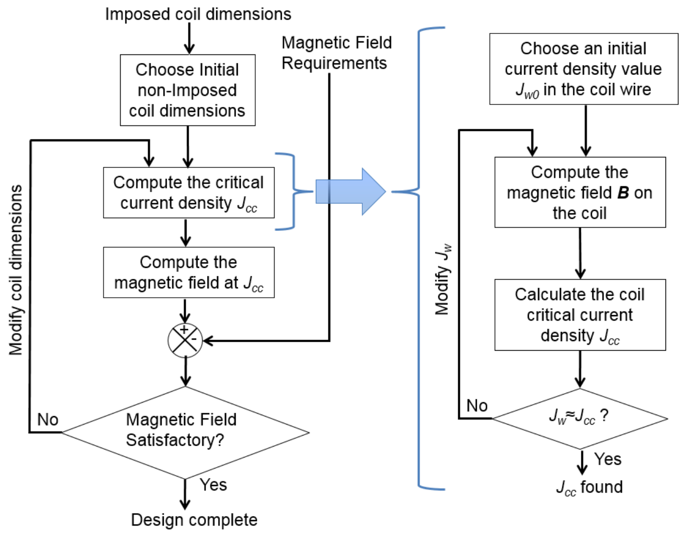

Fig. 3. Block diagram presenting the method used to compute the coil critical current density J_{cc} (b) and optimize the coils geometry (a).

5.3. *Coil geometry optimization*

Electromagnetic engineering problems often start with magnetic field requirements and some geometry constraint. Here, the case where a magnetic flux density B_{obj} needs to be generated at the center of the system will be solved. Additional geometric constraints are, imposed values for R_i and d and, a square cross section for the coils i.e. $R_e - R_i = T$. The only parameter that can be adjusted is T.

An optimization algorithm is used to find the correct value of T (see fig. 3 (a)). An initial value must first be chosen. In the provided code, the initial value is equal to R_i. Then, the developed MATLAB function *JcSearch.m* described in 5.2 is used to compute J_{cc}. The magnetic flux density can then easily be calculated at the center of the system for this current density value. The optimization algorithm compares the obtained field with the objective value. It then modify the value for T and iterates the process until a satisfactory field value is found. The optimization algorithm used is more specifically the function *fminsearch* of MATLAB. It uses the Nelder-Mead simplex algorithm [10] to generate the values for T. The cost function it minimizes is presented in eq.11. The coil geometry optimization was implemented in the provided MATLAB function *TSearch.m*.

$$CostFct = (B - B_{obj})^2 \tag{11}$$

5.4. *AC Losses computation*

The results from the magnetic field computation and critical current density can be used to evaluate the superconducting magnetization AC loses (see Section 3). It was chosen to use an analytical model to perform this calculation. The model considered is presented in [11] and equation 12 where $2a$ is the width of the superconducting tape and y is the parameter characterizing the anisotropy of the superconductors. The applied current and magnetic field are sinusoidal. The authors of this model based their calculations on the critical state assumption [12] and take into account the effect of the magnetic field angle. To test their model they calculated losses for a BSCCO tape and used a value of 10 for y.

$$W = \frac{2\mu_0 a^2 Jc^2}{3}\left(\left(\frac{3\,|B|}{\mu_0 aJc} - 2\right) + \left(\frac{|B|}{\mu_0 aJc} + \frac{2J}{Jc}\right)\frac{J}{Jc}\right) \left(y^2 cos^2(\alpha) + sin^2(\alpha)\right) \tag{12}$$

The unit of the obtained magnetization losses W is J.m^{-3}.cycle^{-1}. It corresponds to the energy dissipated into 1 m^3 of superconductor during one period of the signal. It is independent of the frequency f. The power P (in Watts) dissipated in 1 m^3 of superconductor can be easily calculated with $P = W.f$.

5.5. *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. 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 T. 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.

The material considered in this study is the DI-BiSCCO tape manufactured by Sumitomo Electric Industries. 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. This model takes into account the effect of the magnetic field angle with respect to the tape plane. $B_\perp$ is the component of the flux density that is perpendicular to the tape surface (called a-b plane) and $B_{||}$ is the component that is parallel to the tape surface (c-axis). The parameter y characterizing the anisotropy of the superconductor is assumed to be equal to 10 as in section 5.4.

These values were entered into the provided MATLAB graphical interface and the computation of the coil geometry was performed. The result of the calculation is presented in fig. 5.5. In this figure, part a) show the obtained flux density at maximum current. One can see that the flux density has a value of 1.88T, very close to the target.

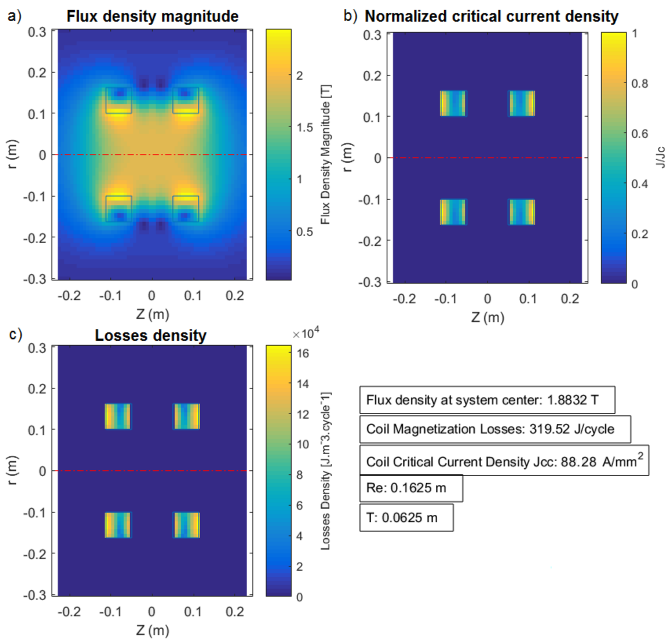

Fig. 4. Results from the geometric optimization of a superconducting Helmhotz coil system using the MATLAB program provided with this paper.

The next plot, b), shows a map of the ratio J_w/Jc. The maximum value is 1 which shows that the maximum current density is reached without exceeding it. The last graph, c), shows a map of the losses produced in the winding during each cycle. The losses are larger on the sides of the coils. Indeed, at these locations, the magnetic field has a stronger perpendicular component and, accordingly to the model used (eq. 12) more losses are generated there. The total losses obtained are equal to 319.52 J.cycle^{-1}.

6. Conclusion

Superconductors could be used advantageously to control magnetically actuated robots because of their high current density capabilities and low losses. They could allow to drastically reduce the size of the system while improving its energy efficiency. Superconductors have to be cooled at cryogenics temperature. Using cryogenic liquids such as liquid Nitrogen (77K) or liquid Helium (4.2K) is a possible solution. Cryocoolers can also be used to cool superconductors via conduction heat transfer or reliquefaction of the cryogenic fluid.

A method to design superconducting magnetic systems for microrobotics applications was presented. The design method uses an iterative algorithm to find the critical current of superconducting coils. The self magnetic field is computed and its effect is taken into account. An optimization method able to find the geometry of an Helmholtz coil system to produce a user defined magnetic field was programed. The MATLAB code and a graphical interface is attached to this paper and available for download.

Robotics applications often require fast changing magnetic fields. Under these conditions, AC losses are generated inside the superconductors. These losses must be carefully evaluated to ensure the proper sizing of the cryogenic cooling equipment.

The MATLAB program was tested to design an Helmholtz coil system able to generate 1.5T at its center. The optimum geometry was obtained and data about AC losses were computed.

Future work should include experimental measurements of AC losses in a superconducting magnetic system. A high-fidelity model for AC losses computation based on finite elements should also be implemented.

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