Software Requirements Specification for Helmholtz-Coil-Current-Calculator-CAS741: Three-axis Helmholtz Coil System Current Calculator and Target Magnetic Force or Magnetic Torque

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Contents

Revision History

Date	Version	Notes
Date 1	1.0	Notes
Date 2	1.1	Notes

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit and the SI name.

symbol	unit	SI
m	length	metre
A	electric current	Ampere
T	magnetic field	Tesla
N	force	newton

1.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units. The choice of symbols was made to be consistent with the heat transfer literature and with existing documentation for solar water heating systems. The symbols are listed in alphabetical order.

symbol	unit	description
B_x	T	Magnetic field along the x-axis
B_y	T	Magnetic field along the y-axis
B_z	T	Magnetic field along the z-axis
F	N	Magnetic force
H	A/m	Total magnetic field strength
I_x	A	Electric current through the x-axis coils
I_y	A	Electric current through the y-axis coils
I_z	A	Electric current through the z-axis coils
$Imax_x$	A	Maximum acceptable electric current through the x-axis coils
$Imax_y$	A	Maximum acceptable electric current through the y-axis coils
$Imax_z$	A	Maximum acceptable electric current through the z-axis coils
l_x	m	Distance between the coils along the x-axis
l_y	m	Distance between the coils along the y-axis
l_z	m	Distance between the coils along the z-axis

N_x		Number of turns in the x-axis coil
N_y		Number of turns in the y-axis coil
N_z		Number of turns in the z-axis coil
R_x	m	Radius of the coils along the x-axis
R_y	m	Radius of the coils along the y-axis
R_z	m	Radius of the coils along the z-axis
τ	Nm	Magnetic torque
x	m	Position along the x-axis from the midpoint
y	m	Position along the y-axis from the midpoint
z	m	Position along the z-axis from the midpoint

1.3 Abbreviations and Acronyms

symbol	**description**
A	Assumption
DD	Data Definition
GD	General Definition
GS	Goal Statement
IM	Instance Model
LC	Likely Change
PS	Physical System Description
R	Requirement
SRS	Software Requirements Specification
Helmholtz-Coil-Current-Calculator-CAS741	Three-axis Helmholtz Coil System Current Calculator and

2 Introduction

Helmholtz coils are utilized primarily for their ability to produce a nearly uniform magnetic field, a feature crucial in various scientific research and practical applications. The design consists of two identical electromagnetic coils placed symmetrically along a common axis and separated by a distance equal to their radius, having the same electric current in the same direction. It facilitates precise control over the magnetic field's strength by adjusting the electric current flowing through the coils. Alternatively, a Maxwell coil configuration is formed if currents flow in opposite directions, resulting in a uniform magnetic field gradient at the center. This precision is essential for applications that demand specific magnetic force and torque on a magnetic particle to induce desired effects on materials or biological tissues. Calculating the target magnetic field and magnetic torque based on the characteristics of a Helmholtz Coil system and magnetic particles significantly impact a wide range of scientific, medical, and industrial applications.

2.1 Purpose of Document

The primary objective of this Software Requirements Specification (SRS) document is to outline the software requirements for creating a Three-axis Helmholtz Coil System Current Calculator for Target Magnetic Force and Magnetic Torque application. This document endeavors to provide a thorough understanding of the system's architecture, focusing on the project's objectives, operational principles, and essential definitions without focusing on the implementation specifics. It aims to establish a clear overview to facilitate software development, detailing the system's context, constraints, and the problem the project intends to solve. Furthermore, the document considers possible future enhancements and modifications, ensuring the system's adaptability and scalability to meet evolving requirements.

2.2 Scope of Requirements

The project's scope is concentrated on developing a current calculator for a Three-axis Helmholtz Coil System that precisely determines the currents required to achieve a target magnetic force and torque at the system's central point. This calculator assumes an idealized scenario where the coil system is entirely isolated from any external magnetic fields, ensuring that calculations are unaffected by outside magnetic interference. The software's focus is on theoretical predictions and is not concerned with the physical implementation or the dynamic adaptation to environmental changes. The resulting tool will be critical for applications necessitating precise magnetic field manipulation, serving as a foundational resource for further experimental and practical exploration.

2.3 Characteristics of Intended Reader

The reader should have a strong foundation in physics, particularly in electromagnetism. A university-level understanding, at least at the undergraduate level, is expected. Familiarity with differential calculus and vector analysis is necessary since the project involves calculating magnetic field gradients and currents.

2.4 Organization of Document

The document is organized into several key sections to present the software requirements specification systematically. After the introduction, which outlines the document's purpose, scope, and definitions, the general system description provides an overview of the system's context and interactions. Subsequently, The system description discusses the problem, assumptions, and dependencies. The requirements section details the functional and nonfunctional requirements, followed by a discussion on likely and unlikely changes to the system. The document also includes traceability matrices to illustrate the relationships between different components of the SRS, ensuring clear reference and maintenance.

3 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics and lists the system constraints.

3.1 System Context

The Figure 1 illustrates the user and software interaction. Users input the specifications of a three-axis Helmholtz Coil system, along with the desired magnetic force, torque, and the magnetic moment of the targeted particle. The software processes these inputs to calculate the precise current needed for each coil to achieve the specified magnetic torque and magnetic force. Then, it outputs this information back to the user.

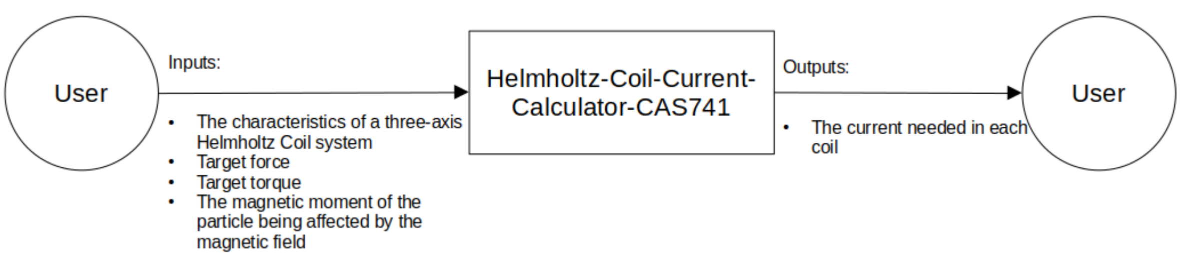

Figure 1: System Context

- User Responsibilities:
  - Provide accurate and precise input data, such as the characteristics of the Helmholtz coil system, target force, target torque, and magnetic moment.
- Helmholtz-Coil-Current-Calculator-CAS741 Responsibilities:
  - Accurately calculate the current required in each coil based on the user-provided input data.
  - Present the calculated data in a clear and understandable format to the user.
  - Verify that the calculated current is within the operational range of the system, ensuring the values are practical and safe for real-world application.

The Helmholz-Coil-Current-Calculator-CAS741 software is primarily utilized by researchers and scientists engaged in designing and working with Helmholtz coil systems. These professionals rely on the software to accurately generate specific magnetic forces and torques for experimental and investigative purposes in laboratory settings. While the software plays a crucial role in the research and development phase, it is not typically classified as mission-critical or safety-critical; however, it does demand high precision and reliability to ensure the validity of scientific experiments and the integrity of data collected.

3.2 User Characteristics

The users of this program are typically researchers and scientists with a solid foundation in physics, particularly in electromagnetism. They are expected to have experience with magnetic coil systems and a good grasp of mathematical concepts required to understand and utilize the software's calculations. Their expertise allows them to interpret the software's output accurately and integrate it into their scientific work, applying the calculated forces and torques to their specific applications in research and experimental setups.

3.3 System Constraints

There is no system constraint for this program.

4 Specific System Description

This section presents the problem at a high-level concept, followed by the solution characteristics specification which includes assumptions, theories, definitions, and instance models.

4.1 Problem Description

The problem description for the Helmholz-Coil-Current-Calculator-CAS741 project addresses the challenge of calculating the precise currents needed for a three-axis Helmholtz coil system to generate specific magnetic forces and torques. This complex task requires integrating electromagnetic theory and applying mathematical models to control the magnetic field within the coil setup. The solution must be precise, reliable, and user-friendly to support scientific research and experimentation where accurate magnetic field manipulation is critical.

4.1.1 Terminology and Definitions

This subsection provides a list of terms used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements:

- Magnetic Field: A magnetic field is a vector field produced by a current flow or a magnetized material
- Magnetic Moment: The magnetic moment is a vector quantity that represents the magnetic strength and orientation of a magnet or other object that produces a magnetic field. It's a fundamental property of magnetic materials and is typically caused by the orbital and spin motions of electrons within atoms.
- Coil: A coil, in the context of a Helmholtz coil, it specifically refers to a configuration of wire loops designed to create a uniform magnetic field within the volume of the coil.
- Magnetic torque: The Magnetic torque is a measure of the turning force on an object caused by the magnetic field and the magnetic moment of the object. It determines how strongly an object (which has a magnetic moment) will align with the magnetic field.
- Magnetic force: The Magnetic force refers to the force exerted by a magnetic field on a moving charge, a current-carrying wire, or a material with a magnetic moment.

4.1.2 Physical System Description

The physical system of Three-axis Helmholtz Coil System, as shown in Figure 2, includes the following elements:

PS1: two coils along the x-axis

PS2: two coils along the y-axis

PS3: two coils along the z-axis

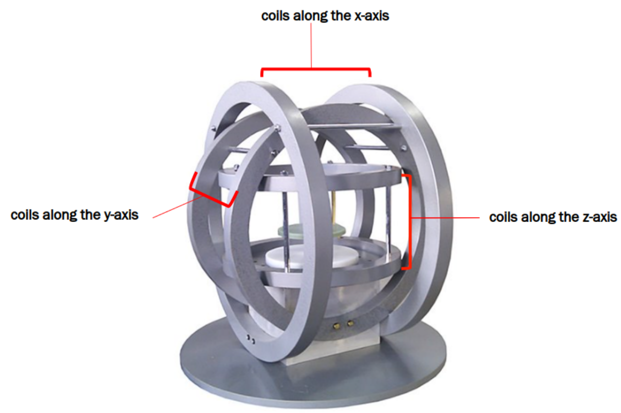

Figure 2: Three-axis Helmholtz Coil System

4.1.3 Goal Statements

Given the parameters of a Three-axis Helmholtz coil system, which include the number of turns on each coil, the radius of each coil, the distance between the coils, the maximum current each coil has access to, and the desired magnetic field strength the goal statement is:

GS1: Calculate the current required for each coil to achieve the target magnetic force at the center

GS2: Calculate the current required for each coil to achieve the target magnetic torque at the center

4.2 Solution Characteristics Specification

The instance models that govern Helmholtz-Coil-Current-Calculator-CAS741 are presented in Subsection 4.2.5. The information to understand the meaning of the instance models and their derivation is also presented, so that the instance models can be verified.

4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [TM], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

A1: The system is assumed to be powered by a direct current source, ensuring that the generated magnetic field is steady.

A2: It is assumed there are no significant external magnetic fields present that could interfere with the magnetic field generated by the Helmholtz coil system. This ensures that the magnetic field within the operational area is solely due to the coils themselves.

A3: We assume that the target magnetic force and torque is to be generated within the center of the Helmholtz coil.

4.2.2 Theoretical Models

This section focuses on the general equations and laws that Helmholtz-Coil-Current-Calculator-CAS741 is based on.

RefName: **TM:FBD**

Label: Force on a magnetic dipole

Equation:

$$\vec{F} = (\vec{m} \cdot \nabla)\vec{B} \tag{1}$$

Description: The equation represents the force on a magnetic dipole in an inhomogeneous magnetic field. Here, $\mathbf{F}$(N) is the force, $\mathbf{m}$($\mathrm{A\,m^2}$) is the magnetic moment,$\mathbf{B}$(T) is the magnetic field.

Notes: None.

Source:

Ref. By: IM1

Preconditions for TM:FBD: None

Derivation for TM:FBD: Not Applicable

RefName: **TM:TBD**

Label: Torque on a magnetic dipole

Equation:

$$\vec{\tau} = \vec{m} \times \vec{B} \tag{2}$$

Description: The equation represents magnetic torque τ (N m) experienced by a magnetic dipole in a uniform magnetic field. There the torque τ (N m)is given by the vector cross product of the magnetic moment $\mathbf{m}$(A m^2) and the magnetic field $\mathbf{B}$(T).

Notes: None.

Source:

Ref. By: IM2

Preconditions for TM:TBD: None

Derivation for TM:TBD: Not Applicable

RefName: **TM:BSL**

Label: Biot-Savart law

Equation:

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{Id\vec{l} \times \vec{r}}{r^2} \tag{3}$$

Description: The equation gives the magnetic flux density $\vec{B}$ (T) generated by a constant electric current I (A) of a current-carrying wire at position r (m) in 3D space where μ_0 is the magnetic constant (N A^{-2})and $\vec{r}$ is the position vector from the current element to the point where the field is being calculated.

Notes: None.

Source:

Ref. By: GD1

Preconditions for TM:BSL: None

Derivation for TM:BSL: Not Applicable

4.2.3 General Definitions

This section collects the laws and equations that will be used in building the instance models.

Number	GD1
Label	**Magnetic field along the axis of a coil**
SI Units	(T)
Equation	$B = \frac{N\mu_0 IR}{2(x^2+R^2)^{3/2}}$
Description	The equation represents the magnetic field B along the axis of a coil with multiple turns. • B: The magnetic field at a point along the axis of the coil(T). • N: The number of turns in the coil. Each turn contributes to the total magnetic field, so the field strength is proportional to the number of turns. • μ_0: The magnetic constant or the permeability of free space, which is $4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$ ($\mathrm{T\,m\,A^{-1}}$). • I: The current through the coil(A). • R: The radius of the coil(m). • x: The distance from the center of the coil along its axis to the point(m).
Source	
Ref. By	GD2, GD3

Detailed derivation of magnetic field along the axis of it

For a small current element $Id\mathbf{l}$ on the loop, the TM4.2.2 gives the magnetic field contribution $d\mathbf{B}$ at point x on the axis.

By symmetry, only the component of $d\mathbf{B}$ that is along the axis (the x-component) contributes to the net field at point x. The field due to each element is directed according to the right-hand rule, which, given your description, points to the right along the axis of the loop for the entire loop.

Using the Biot-Savart Law, the x-component of the field due to the element is $dB_x = dB \cdot \sin(\theta)$, where θ is the angle between $d\mathbf{l}$ and $\mathbf{r}$. Because $\sin(\theta) = \frac{r}{R}$ and $r = \sqrt{x^2 + R^2}$, the x-component of $d\mathbf{B}$ is given by:

$$dB_x = \frac{\mu_0}{4\pi} \frac{I dl R}{(x^2 + R^2)^{3/2}}$$

The integral $\int d\mathbf{l}$ around the loop gives the circumference $2\pi R$, so the net magnetic field at point x is:

$$B_x = \frac{\mu_0}{4\pi} \frac{I}{(x^2 + R^2)^{3/2}} \int d\mathbf{l} = \frac{\mu_0 I R}{2(x^2 + R^2)^{3/2}}$$

Which is the magnetic field at a distance x from the center of the loop along its axis.

For a coil with N turns, this expression is multiplied by N, since each turn contributes to the magnetic field at the point x. Therefore, the total magnetic field B_x due to a coil with N turns is

$$B_x = \frac{N \mu_0 I R^2}{2(x^2 + R^2)^{3/2}}$$

These calculations can be generalized for the y and z axis, allowing for a comprehensive analysis of the magnetic field in three-dimensional space.

Number	GD2
Label	**Magnetic field in the center of a Helmholtz Coil along the axis of it**
SI Units	(T)
Equation	$B = \frac{\mu_0 NIR^2}{2(x^2+R^2)^{\frac{3}{2}}} + \frac{\mu_0 NIR^2}{2((l-x)^2+R^2)^{\frac{3}{2}}}$
Description	In a Helmholtz coil setup, we have two identical circular coils that are spaced a distance apart. Each coil produces its own magnetic field GD1, and because the coils are arranged along the same axis and the currents flow in the same direction, the magnetic fields generated by the individual coils add up constructively in the space between them. • B: The magnetic field at a point along the axis of the coil(T). • N: The number of turns in the coil. Each turn contributes to the total magnetic field, so the field strength is proportional to the number of turns. • μ_0: The magnetic constant or the permeability of free space, which is $4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$ ($\mathrm{T\,m\,A^{-1}}$). • I: The current through the coil(A). • R: The radius of the coil(m). • x: The distance from the center of the coil along its axis to the point(m). • l: The distance between two coils(m).
Source	
Ref. By	IM2

Detailed derivation of magnetic field in the center of a Helmholtz Coil along the axis of it

In a Helmholtz coil setup, we have two identical circular coils that are spaced a distance apart equal to their radius. Each coil produces its own magnetic field GD1, and because the coils are arranged along the same axis and the currents flow in the same direction, the magnetic fields generated by the individual coils add up constructively in the space between them.

Number	GD3
Label	**Magnetic field in the center of a maxwell Coil along the axis of it**
SI Units	(T)
Equation	$B = \frac{\mu_0 N I R^2}{2(x^2+R^2)^{\frac{3}{2}}} - \frac{\mu_0 N I R^2}{2((l-x)^2+R^2)^{\frac{3}{2}}}$
Description	In a Helmholtz coil setup, we have two identical circular coils that are spaced a distance apart. Each coil produces its own magnetic field, and because the coils are arranged along the same axis and the currents flow in the same direction, the magnetic fields generated by the individual coils add up constructively in the space between them. • B: The magnetic field at a point along the axis of the coil(T). • N: The number of turns in the coil. Each turn contributes to the total magnetic field, so the field strength is proportional to the number of turns. • μ_0: The magnetic constant or the permeability of free space, which is $4\pi \times 10^{-7}\,\mathrm{T\,m\,A^{-1}}$ ($\mathrm{T\,m\,A^{-1}}$). • I: The current through the coil(A). • R: The radius of the coil(m). • x: The distance from the center of the coil along its axis to the point(m). • l: The distance between two coils(m).
Source	
Ref. By	IM1

Detailed derivation of magnetic field along the axis of a coil

In a Maxwell coil setup, we have two identical circular coils that are spaced a distance apart equal to their radius. Each coil produces its own magnetic field, and because the coils are arranged along the same axis and the currents flow in the opposite direction, the magnetic fields generated by the individual coils are oppose each other.

4.2.4 Data Definitions

This section collects and defines all the data needed to build the instance models. The dimension of each quantity is also given.

4.2.5 Instance Models

This section transforms the problem defined in Section 4.1 into one which is expressed in mathematical terms. It uses concrete symbols defined in Section 4.2.4 to replace the abstract symbols in the models identified in Sections 4.2.2 and 4.2.3.

The goals GS1 and GS2 are solved by IM1 and IM2 respectively.

Number	IM1
Label	**Current needed for target force**
Input	$\vec{f}$, $\vec{m}$, R_x, R_y, R_z, l_x, l_y, l_z, N_x, N_y, N_z,max_I_x, max_I_y, max_I_z
Output	$\vec{I_1} = [-\frac{2\left(\frac{l_x^2}{4}+R_x^2\right)^{5/2}}{3\mu_0 N_x R_x^2 l_x m_x}F_x, -\frac{2\left(\frac{l_y^2}{4}+R_y^2\right)^{5/2}}{3\mu_0 N_y R_y^2 l_y m_y}F_y, -\frac{2\left(\frac{l_z^2}{4}+R_z^2\right)^{5/2}}{3\mu_0 N_z R_z^2 l_z m_z}F_z]$
Description	With condisitonsA3,A2,and B from GD3 we calculate the spatial derivative of B_x with respect to x, which describes how the field changes along the axis. $\frac{d}{dx}B_x\left(x\right) = -\frac{3\mu_0 N_x I_x R_x^2 x}{2(x^2+R_x^2)^{5/2}} + \frac{3\mu_0 N_x I_x R_x^2 (x-l_x)}{2\left((l_x-x)^2+R_x^2\right)^{5/2}}$ The gradient is then evaluated at the midpoint between the two coils $x = l/2$, which is typically where measurements are taken $\frac{d}{dx}B_x\left(x\right)\Big\vert_{x=\frac{l_x}{2}} = -\frac{3\mu_0 N_x I_x R_x^2 l_x}{2\left(\frac{l_x^2}{4}+R_x^2\right)^{5/2}}$ By using GD4.2.2 we reach to the equation below. $F_x = -\frac{3\mu_0 N_x I_x R_x^2 l_x}{2\left(\frac{l_x^2}{4}+R_x^2\right)^{5/2}}m_x$ The following relationship is derived by rearranging the previous equation to isolate the current, allowing for the calculation of the current needed to achieve a specific magnetic force. $\implies I_x = -\frac{2\left(\frac{l_x^2}{4}+R_x^2\right)^{5/2}}{3\mu_0 N_x R_x^2 l_x m_x}F_x$ The same calculation can be applied for I_y and I_z $\implies I_y = -\frac{2\left(\frac{l_y^2}{4}+R_y^2\right)^{5/2}}{3\mu_0 N_y R_y^2 l_y m_y}F_y$ $\implies I_z = -\frac{2\left(\frac{l_z^2}{4}+R_z^2\right)^{5/2}}{3\mu_0 N_z R_z^2 l_z m_z}F_z$
Sources	
Ref. By	R3

Number	IM2
Label	**Current needed for target torque**
Input	$\vec{\tau}$, $\vec{m}$, R_x, R_y, R_z, l_x, l_y, l_z, N_x, N_y, N_z,max_I_x, max_I_y, max_I_z
Output	$\vec{I}_2 = \left[\frac{1}{\frac{m^2\mu_0 N_x R_x^2}{\left(\frac{l_x^2}{4}+R_x^2\right)^{3/2}}}\left[\tau_y m_z - \tau_z m_y\right], \frac{1}{\frac{m^2\mu_0 N_y R_y^2}{\left(\frac{l_y^2}{4}+R_y^2\right)^{3/2}}}\left[\tau_z m_x - \tau_x m_z\right], \frac{1}{\frac{m^2\mu_0 N_z R_z^2}{\left(\frac{l_z^2}{4}+R_z^2\right)^{3/2}}}\left[\tau_x m_y - \tau_y m_x\right]\right]$
Description	With condisitonsA3,A2,and B from GD2 we calculate the spatial derivative of B_x with respect to x, which describes how the field changes along the axis.
Sources	
Ref. By	R4

Derivation of Current needed for target torque

Initially, expressions for B specifically at $B_x\left(\frac{l_x}{2}\right)$ from B from GD2 are provided.

$$B_x(x) = \frac{\mu_0 N_x I_x R_x^2}{2(x^2+R_x^2)^{3/2}} + \frac{\mu_0 N_x I_x R_x^2}{2\left((l_x-x)^2+R_x^2\right)^{3/2}}$$

$$B_x\left(\frac{l_x}{2}\right) = \frac{\mu_0 N_x I_x R_x^2}{\left(\frac{l_x^2}{4}+R_x^2\right)^{3/2}} = C_x I_x$$

The overall magnetic field is decomposed into components parallel ($\vec{B}_\parallel$) and perpendicular ($\vec{B}_\perp$ to the magnetic moment, noting that only the perpendicular component contributes to the torque.

$$\vec{B} = \vec{B}_\perp + \vec{B}_\parallel$$
$$\vec{m}\cdot\vec{B}_\perp = 0$$
$$\vec{m}\times\vec{B}_\parallel = 0$$
$$= \vec{m}\times\vec{B}$$
$$= \vec{m}\times\left(\vec{B}_\perp + \vec{B}_\parallel\right)$$
$$\vec{\tau} = \vec{m}\times\vec{B}_\perp + \underbrace{\vec{m}\times\vec{B}_\parallel}_{=0}$$
$$= \vec{m}\times\vec{B}_\perp$$

By using TM4.2.2:

$$\vec{\tau}\times\vec{m} = \left(\vec{m}\times\vec{B}_\perp\right)\times\vec{m}$$
$$\vec{\tau}\times\vec{m} = m^2\vec{B}_\perp$$
$$\Rightarrow \vec{B}_\perp = \frac{1}{m^2}\vec{\tau}\times\vec{m}$$
$$\vec{B}_\parallel = 0$$

$$\Rightarrow \vec{B} = \frac{1}{m^2}\vec{\tau} \times \vec{m}$$
$$B_x = \frac{1}{m^2}\left[\tau_y m_z - \tau_z m_y\right]$$
$$\Rightarrow I_x = \frac{1}{\frac{m^2 \mu_0 N_x R_x^2}{\left(\frac{l_x^2}{4}+R_x^2\right)^{3/2}}}\left[\tau_y m_z - \tau_z m_y\right]$$
$$\Rightarrow I_y = \frac{1}{\frac{m^2 \mu_0 N_y R_y^2}{\left(\frac{l_y^2}{4}+R_y^2\right)^{3/2}}}\left[\tau_z m_x - \tau_x m_z\right]$$
$$\Rightarrow I_z = \frac{1}{\frac{m^2 \mu_0 N_z R_z^2}{\left(\frac{l_z^2}{4}+R_z^2\right)^{3/2}}}\left[\tau_x m_y - \tau_y m_x\right]$$

4.2.6 Input Data Constraints

Table 1 shows the data constraints on the input output variables. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable. The column for software constraints restricts the range of inputs to reasonable values. The software constraints will be helpful in the design stage for picking suitable algorithms. The constraints are conservative, to give the user of the model the flexibility to experiment with unusual situations. The column of typical values is intended to provide a feel for a common scenario. The uncertainty column provides an estimate of the confidence with which the physical quantities can be measured. This information would be part of the input if one were performing an uncertainty quantification exercise.

Table 1: Input Variables

Var	**Physical Constraints**	**Software Constraints**	**Typical Value**	**Uncertainty**
R_x	$R_x > 0$	$R_x > 0$	0.2 m	0%
R_y	$R_y > 0$	$R_y > 0$	0.2 m	0%
R_z	$R_z > 0$	$R_z > 0$	0.2 m	0%
l_x	$l_x > 0$	$l_x > 0$	0.2 m	0%
l_y	$l_y > 0$	$l_y > 0$	0.2 m	0%
l_z	$l_z > 0$	$l_z > 0$	0.2 m	0%
N_x	$N_x \in \mathbb{Z}$	$N_x \in \mathbb{Z}$	100	0%
N_y	$N_y \in \mathbb{Z}$	$N_y \in \mathbb{Z}$	100	0%
N_z	$N_z \in \mathbb{Z}$	$N_z \in \mathbb{Z}$	100	0%
$maxI_x$	$maxI_x > 0$	$maxI_x > 0$	10 A	0%
$maxI_y$	$maxI_y > 0$	$maxI_y > 0$	10 A	0%
$maxI_z$	$maxI_z > 0$	$maxI_z > 0$	10 A	0%

4.2.7 Properties of a Correct Solution

The solution is correct if the calculated currents, once implemented in the actual coil system, produce a magnetic field that interacts with the particle's magnetic moment to generate the specified force and torque.

Table 2: Output Variables

Var	Physical Constraints
I_{1x}	$I_{1x} \leq \mathrm{m}axI_x$
I_{1y}	$I_{1y} \leq \mathrm{m}axI_y$
I_{1z}	$I_{1z} \leq \mathrm{m}axI_z$
I_{2x}	$I_{2x} \leq \mathrm{m}axI_x$
I_{2y}	$I_{2y} \leq \mathrm{m}axI_y$
I_{2z}	$I_{2z} \leq \mathrm{m}axI_z$

5 Requirements

This section provides the functional requirements, the business tasks that the software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

5.1 Functional Requirements

R1: The software shall allow users to input the target magnetic torque, magnetic force, the magnetic moment of magnetic particle, and characteristics of a three-axis Helmholtz coil system, including the number of turns in each coil, the radius of each coil, and the distance between the coils.

R2: The software shall output the calculated currents for each coil in a format that is easy for the user to interpret

R3: The software shall calculate the required current for each coil to produce a specified magnetic force by using IM1.

R4: The software shall calculate the required current for each coil to produce a specified magnetic torque by using IM2.

R5: The software shall perform calculations with an accuracy that meets the requirements of typical scientific and engineering applications.

5.2 Nonfunctional Requirements

NFR1: **Accuracy** The accuracy level of the Three-axis Helmholtz Coil System Current Calculator will be discussed in the Verification and Validation Plan.

NFR2: **Usability** The software shall be user-friendly, with a clear and intuitive interface that allows easy input, and retrieval of data

NFR3: **Maintainability** The software shall be maintainable, with a clear code structure and documentation that allows for future updates and improvements with minimum change to the implemented code.

NFR4: **Portability** The software shall be compatible with both Linux and Windows operating systems, ensuring that users can run the application on these platforms without the need for extensive modifications.

5.3 Rationale

The project focuses on designing a calculator to determine the currents required in a three-axis Helmholtz coil system for generating specific magnetic forces and torques. This scope is chosen to address the challenges in precise magnetic field manipulation, which is crucial for various scientific and industrial applications. Assumptions like direct current usage, isolation from external magnetic fields, and target magnetic field generation within the Helmholtz coil's center are made to simplify the model. These assumptions are based on typical conditions such a system operates, ensuring that the model remains relevant to real-world applications.

6 Likely Changes

None

7 Unlikely Changes

LC1: The focus on generating the target magnetic force and torque specifically at the center of the Helmholtz coil system is a fundamental design element that is not expected to change throughout the lifetime of the projectA3.

8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an "X" may have to be modified as well. Table 3 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 4 shows the dependencies of instance models, requirements, and data constraints on each other. Table 5 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions.

	TM4.2.2	TM4.2.2	TM4.2.2	GD1	GD2	GD3	IM1	IM2
TM4.2.2							X	
TM4.2.2								X
TM4.2.2								
GD1					X	X		
GD2								X
GD3							X	
IM1								
IM2								

Table 3: Traceability Matrix Showing the Connections Between Items of Different Sections

	IM1	IM2	4.2.6	R1
IM1		X		
IM2	X			
R1				
R2				
R3				
R4	X	X		
R5	X			

Table 4: Traceability Matrix Showing the Connections Between Requirements and Instance Models

The purpose of the traceability graphs is also to provide easy references on what has to be additionally modified if a certain component is changed. The arrows in the graphs represent dependencies. The component at the tail of an arrow is depended on by the component at the head of that arrow. Therefore, if a component is changed, the components that it points to should also be changed.

9 Values of Auxiliary Constants

$\mu_0 = 4\pi \times 1 \times 10^{-7}\,\mathrm{H\,m^{-1}}$

	A1	A2	A3
TM4.2.2			
TM4.2.2			
TM4.2.2			
GD1	X		X
GD2	X		X
GD3	X		X
IM1	X	X	X
IM2	X	X	X

Table 5: Traceability Matrix Showing the Connections Between Assumptions and Other Items

References

Appendix — Reflection

The information in this section will be used to evaluate the team members on the graduate attribute of Lifelong Learning. Please answer the following questions:

1. Which of the courses you have taken, or are currently taking, will help your team to be successful with your capstone project.
2. What knowledge and skills will the team collectively need to acquire to successfully complete this capstone project? Examples of possible knowledge to acquire include domain specific knowledge from the domain of your application, or software engineering knowledge, mechatronics knowledge or computer science knowledge. Skills may be related to technology, or writing, or presentation, or team management, etc. You should look to identify at least one item for each team member.
3. For each of the knowledge areas and skills identified in the previous question, what are at least two approaches to acquiring the knowledge or mastering the skill? Of the identified approaches, which will each team member pursue, and why did they make this choice?