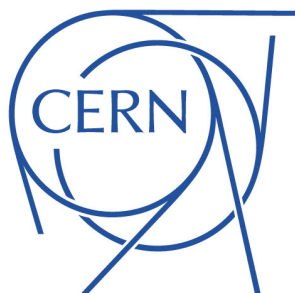


Graduation internship report
Double Master's Degree
Idir Berg Ould-Saada

ANALYSIS AND AUTOMATION OF CALIBRATION PROCESS FOR MEASUREMENT COILS FOR PARTICLE ACCELERATOR MAGNETS



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Geneva, Switzerland

2017

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PROJET DE FIN D'ETUDES

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CERN, Geneva, Switzerland

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Double Degree program in Innovation Management with IAE Toulouse

2017

Acknowledgements

The work presented in this report was carried out at CERN in the context of the Technical Student program, within the Magnetic Measurements section. This internship counted as my last semester of studies at INSA Toulouse and IAE Toulouse School of Management. I am grateful to all of these establishments for allowing me to develop my intellectual curiosity and learn at an extraordinary research institution.

More specifically, I would like to thank my CERN supervisor Carlo Petrone, who has been an excellent teacher, advisor, colleague, and friend throughout my internship. He always welcomed me in his office when I needed it, and I could not have dreamt of better supervision. Thanks also go to my section leader Stephan Russenschuck, who provided a lot of help and guidance, especially concerning theoretical aspects of my work. Next, I would like to thank Richard Beltron and his team of technicians with whom it was a pleasure to collaborate extensively. I also thank the rest of my colleagues who have been great sparring partners and friends through my stay at CERN. Then, I would like to thank my academic supervisor from IAE, Jamal Azzam, who provided valuable advice and guidance to shape the outcome of my work. I also thank my INSA supervisor Elodie Chanthery, who provided helpful feedback and direction.

Moreover, I would like to thank all my friends who have supported me and contributed to making my stay at CERN a memorable experience. Special thanks go out to the Norwegian group at CERN and all others with whom I shared countless lunches, adventures, and discussions.

Furthermore, I would like to thank my girlfriend Sara who encouraged and inspired me through this work and makes every day spent with her an amazing experience.

Finally, I would like to thank my mother and father who provided invaluable support, encouragement, and inspiration through my internship and my years of study. None of this would be possible without them. I would also like to thank the rest of my family for continuous support. Special thoughts go to my grandmother in Algeria who has taught me the power of hard work and education.

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Glossary

BPMN Business Process Model and Notation (BPMN) is a tool for representing the internal business processes of a company using a standard graphical notation.

Calibration The precise characterization of a measurement device to fit its output to a standard reference.

DAI Internal Purchase Requisition or DAI (Demande d'Achat Interne) is a tool for submitting procurement requests at CERN.

EDMS CERN's Engineering Data Management Service.

FFMM Flexible Framework for Magnetic Measurements, framework used to develop software operating magnetic measurements.

GPIB General Purpose Interface Bus, communication protocol used for several devices in the MM section.

High-Luminosity LHC Upgrade of the LHC planned for 2025 with the goal of increasing the luminosity by a factor of ten.

LHC Large Hadron Collider, the world's biggest particle accelerator.

MeCoM Measurement Coordination Meeting, meeting held every two weeks in the MM section to coordinate activity.

MIS Management Information System.

MM Engineer Magnetic Measurement Engineer, equivalent to project manager for measurements.

MM Section Magnetic Measurements Section at CERN.

PDI Portable Digital Integrator, used to make magnetic flux measurements in the Rotating Coil calibration procedure.

R&D Research and development.

Rotating Coil Magnetic field sensor based on the concept of induction used for many measurements at CERN.

Sensitivity factors Factors describing the geometric characteristics of a coil. Used to compute magnetic field characteristics from raw data coming from Rotating Coils .

Tacit knowledge Knowledge that is difficult to codify and transfer to another person.

Technical Engineer Person responsible for the design and conception of new tools.

Technician Person, often specialized in mechanics, associated to the MM section via an external firm.

Value Chain Model for representing the processes of a firm with long-linked technology.

Value Network Model for representing the processes of a firm with mediating technology.

Value Shop Model for representing the processes of a firm with intensive technology.

Executive Summary

English

In the context of my final year of studies in engineering and management, I completed an internship at CERN within the Magnetic Measurements (MM) section. After an initial assessment of some internal processes and problem areas, three main tasks emerged and were assigned to me.

First, I developed a new software application to automate parts of the calibration procedure for magnetic field sensors called Rotating Coils. The software aimed at reducing the amount of manual tasks performed, and the operational risk associated with the previous platform, as well as making it user-friendly for non-experts to operate.

Next, a feasibility study was conducted on a new instrument to integrate signals in the same calibration procedure. The goal of the integrator was to further reduce operational risk associated with the current hardware. The programming work associated with these two technical tasks resulted in approximately 6500 lines of code.

The resulting calibration software resolved several day-to-day operational activity issues and has since been deployed in the MM section's processes. The feasibility study on the integrator could not be finalized, but the results achieved so far are a very good basis for further research beyond the scope and timescale of this internship.

Finally, the MM section's overall internal process was modelled based on the Value Shop model, which was also well received. The new model has the potential to provide an adequate tool for analyzing problems and proposing solutions within the section, and thus to lead to a more transparent organization's overview.

Paths for future prospects were suggested, including further automation of the calibration procedure, a detailed analysis to address some potential internal communication and organization issues, and the continued investigation of a new integrator.

Français

Dans le cadre de mes études en ingénierie et en management, j'ai effectué un stage de six mois au CERN dans la section de Mesures Magnétiques (MM). Après avoir fait une première analyse des processus internes et leurs problèmes potentiels, trois tâches principales m'ont été attribuées.

Tout d'abord, j'ai développé un nouveau logiciel de calibration pour des capteurs de type bobines tournantes, le but étant de réduire le nombre de tâches manuelles ainsi que les risques opérationnels associés à l'ancienne plateforme, et de rendre la procédure plus accessible et facile à opérer par des non-experts.

Ensuite, j'ai conduit une étude de faisabilité concernant l'implémentation d'un nouvel instrument de mesure pour l'intégration des signaux dans le cadre de la même procédure de calibration. La programmation associée à ces deux tâches techniques a résulté en approximativement 6500 lignes de code.

Le logiciel de calibration développé a résolu plusieurs problèmes quotidiens confrontés par les opérateurs de calibration, et a finalement été adopté par la section. L'étude de faisabilité reliée à l'intégrateur n'a pu être complétée à temps, mais a conduit à des avancements pouvant servir comme bonne base pour de plus amples études ultérieures, malheureusement au-delà de la portée de ce stage.

En plus des deux tâches techniques, j'ai développé un modèle des processus internes de la section en me basant sur un modèle de type Value Shop qui a aussi été bien reçu. Ce nouveau modèle pourrait potentiellement s'avérer un outil adéquat pour mieux analyser les processus internes, et ainsi donner un meilleur aperçu de l'organisation de la section.

Des perspectives d'avenir ont aussi été proposées, incluant une automatisation ultérieure de la procédure de calibration, une analyse organisationnelle détaillée pouvant résoudre certains problèmes de communication internes, et la continuation de l'étude de faisabilité d'un nouvel intégrateur.

Introduction

CERN, the European Organization for Nuclear Research, is one of the largest and most respected centers for scientific research in the world and is responsible for a significant number of scientific breakthroughs in a range of fields. Its engineers and physicists work together to answer important questions such as how the universe started and evolved, and what it is made of. Furthermore, the World Wide Web and medical proton therapy are examples of spin-off applications of the research and development performed at CERN. The particle accelerators and detectors used for this research are considered to be the world's largest and most complex scientific instruments [CERN, 2012a]. These instruments need a large number of very precise and technologically advanced magnets, both warm and superconducting, and it is the responsibility of the Magnetic Measurements (MM) Section to precisely perform a measurement and parameterization of the magnetic field generated by these magnets. The MM section kindly welcomed me to work and study for a six-month internship, thus giving me the opportunity to combine the fields of engineering and management in a professional research environment. The resulting work counts as the final semester in both study programs - Engineering and Management - of my Double Master's Degree.

The Double Master's Degree is a joint program between the engineering school *Institut National des Sciences Appliquées Toulouse* (INSA Toulouse), where I specialized in Automatic Control and Electronics with a major in Innovative Smart Systems for five years, and the management school *Institut d'Administration des Entreprises Toulouse* (IAE Toulouse School of Management), where I specialized in Innovation Management in parallel for the last two years of the five-year period.

Various techniques are used to measure magnetic fields within the MM section, all of which require the use of specific sensors. These sensors need to be calibrated in order to map the resulting signals to the characteristics of the magnetic field. One sensor technology, known as Rotating Coils, uses the concept of magnetic induction to measure magnetic fields and was extensively used during the construction of the largest accelerator at CERN, the Large Hadron Collider (LHC). More than 20 years later the same sensors and calibration procedures are still in

place, whereas software, readout, and data acquisition technologies have evolved meanwhile. Thus, the calibration procedure would benefit from being improved and made more stable, efficient, and technologically up-to-date. Consequently, I was given the opportunity of analyzing and modernizing the current calibration procedure in the context of my internship.

To improve the efficiency of the calibration procedure and the work processes it was first necessary to analyze them and identify potential issues and weaknesses to be further addressed. The calibration procedure mainly suffered from too many manual operations, which were potential sources of error, and from outdated readout and data acquisition software and hardware. We identified two tasks that would become the focus of my engineering work, and one task relating to my process management work. Firstly, a new software program had to be developed using a C++ framework called Flexible Framework for Magnetic Measurements (FFMM), that would automate the data acquisition and analysis. Next, a feasibility study had to be done to investigate the possibility of using a commercial multimeter as new hardware to integrate the signal coming from induction coils. Finally, as part of my management work, a modelling process was undertaken to develop a new model of the primary processes of the MM section. The new model aimed at making the section members better aware of each others tasks, roles and responsibilities, and potentially improving the internal communication. The model may also serve as a basis for assessing the impact of issues and solutions to the overall process, and a model called Value Shop proved pertinent as a template.

A wide range of technical and managerial concepts acquired throughout my studies, as well as further new concepts learned during my stay at CERN, proved to facilitate this work. The fields varied from electromagnetism, numerical analysis, optimization, algebra, geometry, statistics, C++ programming, and signal processing to organizational modeling, process modeling, and knowledge transfer. Useful product development concepts acquired through my internship experience in software consulting were also applied.

This report outlines my work and how it is related to the MM section, to CERN, and to my studies. Chapter 2 presents the context of my internship through organization and work environment, and underlines the importance of calibration in measurements. More details CERN are found in Appendix A. Then, Chapter 3 briefly outlines the theory of Rotating Coils and calibrations with support from Appendix B. This is based on papers coming from the MM section with my contributions to the calibration aspects. Chapter 4 presents an assessment of the problem areas detected within the MM section during my stay, along with possible solutions to some of them with support from Appendix D. My detailed analysis and implementations are described in Chapter 5, which sketches out how I worked on the new software, hardware, and management model and gives an assessment of their impact. Additional information related to this is found in Appendices E and C. Finally, a conclusion with considerations about the internship and suggested further work is presented in Chapter 6. An extended summary in French is available in Appendix F.

Context and goals of the internship

This chapter briefly outlines the context of my internship at CERN, where in the organization I worked, and how the work was done.

2.1 Magnetic Measurements Section

2.1.1 Organization

The Magnetic Measurements (MM) Section is part of the Magnets, Superconductors and Cryostats (MSC) Group, belonging to the Technology Department (TE) at CERN. An overview of the CERN hierarchy can be found in Figures 2.1, 2.2, and 2.3 and a complete introduction of CERN as an organization in Appendix A. Stephan Russenchuck, the MM section leader, has the responsibility for the activity of the section. A total of 10 permanent staff members work in the MM section, out of which most are engineers and researchers who carry out the day-to-day activities of the section. Furthermore, a significant amount of temporary staff, currently 10, is also found in the MM section, and consists mostly of students who are working at CERN in the context of their BSc, MSc or Ph.D. theses. These temporary staff members often work with internal R&D projects, are supervised by permanent staff, and work in the same building at CERN. Additionally, some fellows can be present on short-term contracts. Finally, there is also a group of technicians associated to the MM section who are not actual employees, but are hired from external companies. Their daily work is managed by a Head Technician who is part of the permanent staff. They are responsible for manual tasks such as installing and moving measurement benches and other equipment, manufacturing tools and calibrating tools.

2.1.2 Mandate

The goal of the Magnetic Measurements (MM) section at CERN is to perform high-quality magnetic measurements to assure the correct function of the accelerator complex. If there is any unexpected behavior from the accelerator magnets after their placement, this can have

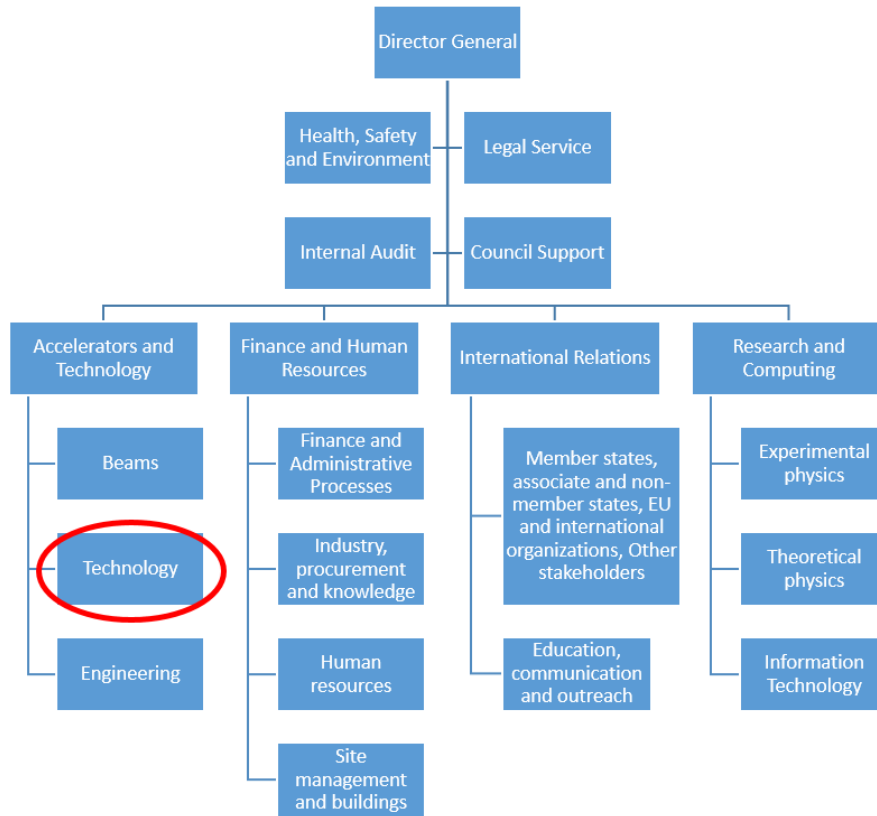


Figure 2.1: CERN hierarchy

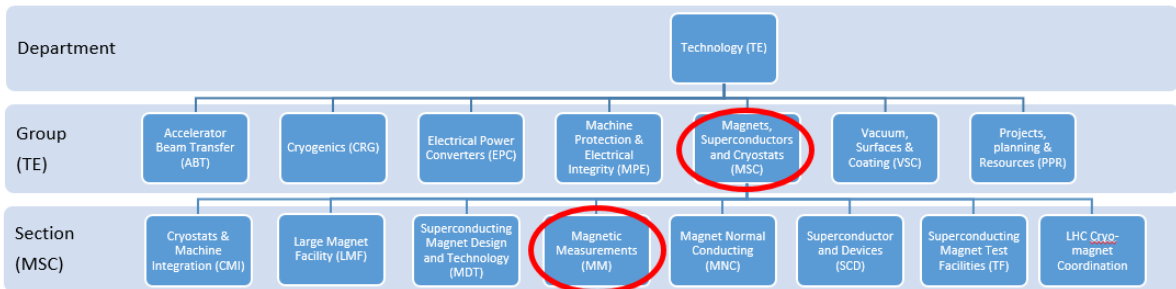


Figure 2.2: Technology Department organization

dire consequences for the experiments which are precisely and tightly scheduled. This could potentially cause significant additional costs in time and money, making the quality of the MM section's work critical.

Magnetic measurements are necessary to correctly install and align the accelerator beams, to verify tolerances, and to provide valuable information regarding the magnet's parameters for simulations [Buzio, 2013]. As schematically shown in Figure 2.4, the magnetic measurements are an important part of the magnet life-cycle in the context of design, production, and utilization of the magnet [Golluccio, 2012].

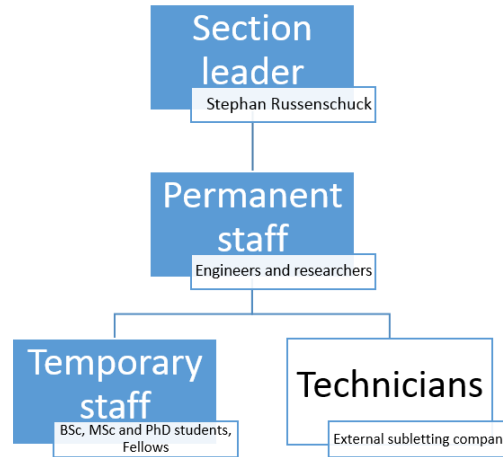


Figure 2.3: Magnetic Measurements Section organization

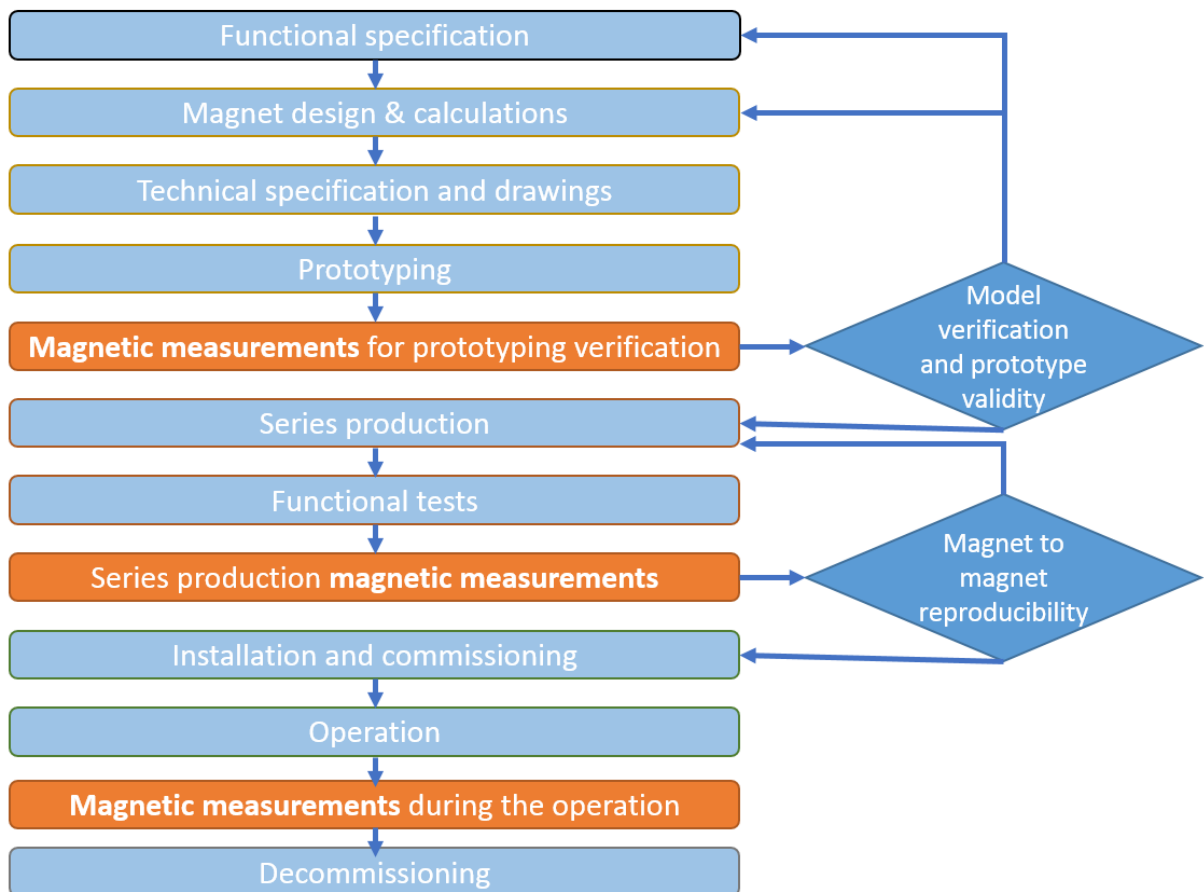


Figure 2.4: Magnet life-cycle. Adapted from [Golluccio, 2012]

2.2 The importance of calibration

Throughout the development of humankind, the need for measuring has been omnipresent. Its first purpose was to facilitate commerce and record human activity [Brown, 2016]. Several thousands of different units were used across Europe before 1789, among them the king's foot

for measuring length. It was not until after the French Revolution that the metric system was introduced. At that time, one meter was defined as one ten-millionths of the distance between the North Pole and the Equator passing through Paris. This allowed people to have one standard measurement reference for length [Barrell, 1962]. Several other measurement standards were subsequently developed, and their definitions evolved. In 1960, this resulted in the International System of Units (SI) that we use today. The base for a meter was then changed to be linked to the speed of light in vacuum, which is still the reference today.

In the same way as humans need a common reference to talk about length, we need a standard reference to talk about magnetic field characteristics. The standard unit for a magnetic field is the tesla (T). Therefore, when we measure a voltage induced in a magnetic field sensor, we need to know how this value relates to corresponding SI unit, and this is the role of the calibration procedure. A magnetic measurement can be performed using sensors based on induction coils. At the terminals of these sensors, when translated or rotated within a magnetic field, an output voltage can be measured and analyzed to determine the characteristics of the magnet. Two different types of measurements can be required for a characterization, one being a relative measurement between the different harmonic components of a magnet, and another being the absolute measurement of the field strength in teslas. For the relative measurement, thanks to the normalization done between field components measured with a single tool, the calibration is not so stringent. However, calibration is critical for the determination of the absolute value of the main field component. This is important for giving a precise value of the magnetic field for comparison with other measurements at CERN or coming from external laboratories. In the case of Rotating Coils, the sensors I focus on in my work, we need to know the exact surface area and radius to transform volts into teslas. The details of this computation are explained earlier in Chapter 4.

Hence, the calibration process is a critical step in the process of magnetic field measurements as the output numbers would have no meaning for parties outside the MM section without the use of a standard reference. The precision of this calibration therefore also has an impact on the level of accuracy of the measurements in the reference frame of the SI units.

2.3 Context and goal

Through the development of the Large Hadron Collider (Figure 2.5), the Magnetic Measurements (MM) section at CERN was ensuring field quality checks over a large number of dipole and quadrupole magnets. When the construction was done though, the same procedures and technologies remained in use, and the MM section needed to adapt to the new context. This became especially important as technology such as the software used for calibrations became outdated and exposed the procedure to operational risks. Re-adapting some of the procedures to be more flexible, extendable, and technologically up-to-date was therefore necessary.

In the context of this effort, I was given the opportunity of working with the analysis and redesigning some of these procedures, and I focused on the Rotating Coil calibration. Using my knowledge in engineering and management, I was to analyze both the MM section as a whole and the calibration procedure and propose solutions that would attempt to make them more reliable and efficient.

2.4 Work environment

The main offices of the MM section are located in a building mostly dedicated to the Technology Department in the Meyrin site, the biggest of the two CERN sites. There, I shared an office with two Ph.D. students who worked on similar projects as me. This allowed us to share ideas and collaborate in an easy way, which was very helpful throughout my stay. A laboratory optimized for magnetic measurements was at my disposal, where I spent several months developing and testing applications. I had access to a work-bench equipped with a dipole magnet generating a field of up to 1 tesla, a rack of electronic equipment for acquiring signals, a computer, as well as all other equipment required to complete my work. This laboratory was located in the tunnel previously used for the Intersecting Storage Rings (ISR) accelerator, which was the world's first hadron collider¹, operating between 1971 and 1984. The technicians, who were involved in much of my work, had a workshop located close to the measurement lab. This allowed me to easily collaborate with them, which helped me solve technical problems quickly while gaining insight into their work-environment. This proved very useful in my analysis of work processes, and allowed me to get a nuanced view on collaboration issues between them and the rest of the MM section. The multitude of workplaces required many displacements between the main offices and the laboratory. However, a computer was at my disposal in both locations, hence, I could connect remotely from one computer to the other, making my work more flexible. As CERN is an international organization, most communication was done in English. However, many technicians only spoke French, so my french skills were very helpful when interacting with them.

The work was individually driven, and I spent most of my time coding, researching or writing. However, my work required collaboration and communication skills. Through informal meetings with my supervisor, the main goals of my work for the following weeks and months were planned continuously, while the details of the work-flow were left for me to decide. I also had to plan meetings and collaboration sessions by communicating directly with the person in question. To keep track of my tasks I used Trello, a work-flow planning tool, which allowed me to get an overview of the work to be done. This was especially useful during software development.

¹In particle physics, hadrons are composite particles made of three quarks held together by the strong force

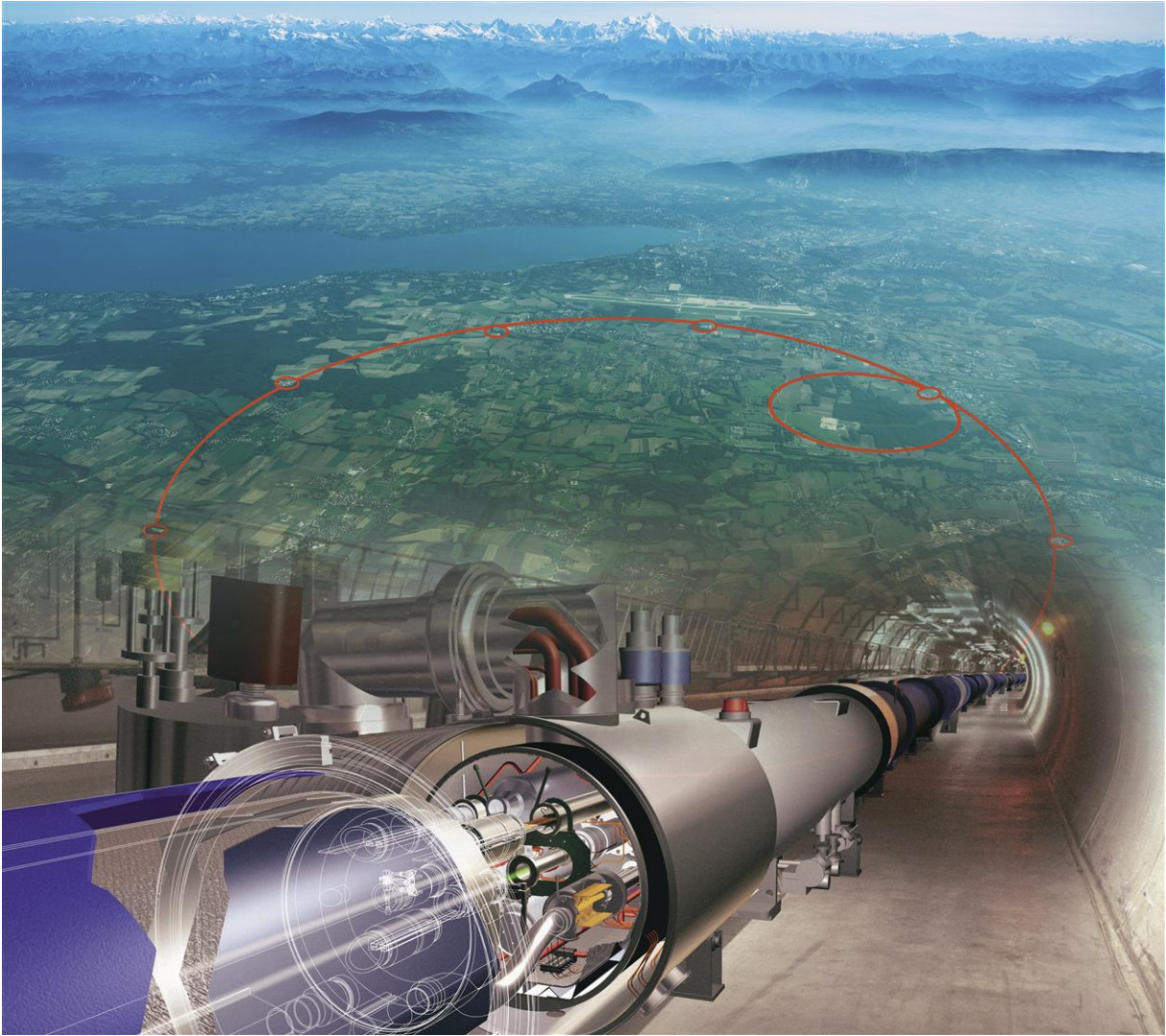


Figure 2.5: Illustration of the LHC dipole magnets and the geographical location of the 27 km LHC ring situated 100 m below ground between France and Switzerland (source CERN)

Calibration of Rotating Coils

Before looking into the analysis of the calibration process and its automation, it is useful to understand how calibrations are done and why they are important. This chapter aims at explaining the technical details of Rotating Coil sensors. An overview of the theory of magnetic measurements can be found in Appendix B, and the following calculations will be based on concepts introduced there.

3.1 Rotating Coils

One of the most used sensors for doing magnetic measurements at CERN are called Rotating Coils (Figure 3.1). These are a combination of several induction coils into segments by three or five, which are in turn combined to form a shaft. This shaft is then rotated within the accelerator magnet in order to measure the magnetic field based on the concept of magnetic induction. A detailed explanation of how these coils work can be found in Appendix B about the theory of magnetic measurements and can be useful to understand the following calculations.

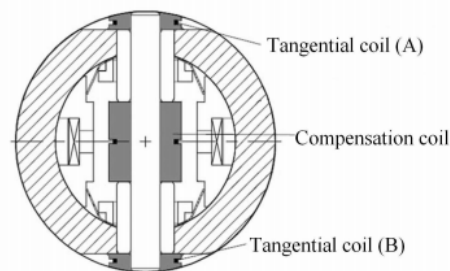


Figure 3.1: Cross section of a tangential rotating coil shaft with sensing coils A, B and a compensation coil [Petrone, 2013]

3.2 Calibration theory

Let's consider the calibration of a rotating coil that is fully immersed in a magnetic field. We will consider all parameters averaged along the coil and ignore fluctuations. The goal is to find for every segment the actual values of the coil surface, the coils misalignment, and the coil radii. This information will then be used to calculate the sensitivity factors K_n , describing the geometry of each coil. These are essential for the computation of the field characteristics in the right units as described in the last chapter. The following calculations are based on [Buzio, 2009] and personal communication with Stephan Russenchuck, along with calculations done by myself with the help from my supervisor Carlo Petrone.

3.2.1 Surface

The procedure for calibrating a coil's surface takes place in a reference dipole field (Figure 3.3). This technique resembles that of a standard rotating-coil measurement, only with two integration points instead of a continuous one. The integral with respect to time is automatically transformed into an integral with respect to the angular position as the measurement is done between two points 180 degrees apart. This makes the result insensitive to speed, which makes the manipulation easier. Starting with a tangential coil in the position $\varphi_0 = \frac{\pi}{2}$ in a normal dipole magnet, the rotation gives the following flux which, combined with the average dipole field strength seen by the coil, can be used to deduce the magnetic surface:

$$- \int_{t_0(\varphi_0)}^{t_1(\varphi_1)} U_{AB} dt = \Delta\Phi = \Phi(\varphi_1) - \Phi(\varphi_0) = 2\Phi(\varphi_1) = 2\mathcal{A}B_1 \quad (3.1)$$

where $\varphi_1 = \varphi_0 + \pi$ is the final position of the rotation, and $\mathcal{A} = K_1^{\text{tan}} = 2N_c \sin(\frac{\delta}{2})$ is the magnetic surface for all turns of the coil. B_1 is the dipole component of the magnetic field, $\Delta\Phi$ is the measured flux when doing the 180 degree rotation, K_1^{tan} is the dipole sensitivity factor for a tangential coil, N_c is the number of windings of the coil, and δ is the opening angle as defined in Appendix B. In practice, the dipole component intercepted is the average dipole component over the surface of the magnet. Positioning the coil in a way that the field can be considered as uniform along the coil's width, a map has been produced over the length of the magnet using Nuclear Magnetic Resonance (NMR) sensor. The magnetic field at a given point is measured with the use of the NMR, and the average field over the length of the coil is computed. The flux is measured using a digital integrator [Petrone, 2013]. With this knowledge, we can compute the surface using the equation

$$\mathcal{A} = \frac{\Delta\Phi}{2B_1} \quad (3.2)$$

Since the attenuation of the voltage when connecting the coil to the integrator is non-negligible, it needs to be compensated by multiplying the measured voltage with $(1 - \frac{R}{R+R_i})$, the

where R is the resistance of the coil and R_i is the input resistance of the integrator. This has not been done previously, but was implemented through my work.

In practice, this 180-degree flip is done 6 times with alternating rotation directions. This gives us an average computed surface from the measurements as well as a possibility to assess the stability of the measurement using the standard deviation. A large part of the integrator drift during the measurement is also canceled out through flipping the coils in alternating directions.

3.2.2 Parallelism

In most cases, the measurement includes several sensing coils to increase the sensitivity to higher-order harmonics. In the case of an induction coil for measuring dipoles, there are two sensing coils diametrically opposed at a certain radius from the center of the shaft, and a compensation coil at the center (Figure 3.1). The compensation coil is used to filter out the strong contribution from the main field analogically. The two sensing coils are mounted with opposite polarity in order to further increase the sensitivity to higher order harmonics. It is essential that the effective surface of the different coils are as close as possible to each other and that they are in parallel to compensate the main dipole field correctly [Petrone, 2013].

These coils are supposed to have identical surface and orientation. Any parallelism error between these coils can greatly depreciate the accuracy of measurement, and therefore needs to be handled. The following process aims to measure the misalignment angle relative to a coil. In this process, the coil is again flipped, but this time with a coil starting position of $\varphi_0 = 0$ to the field.

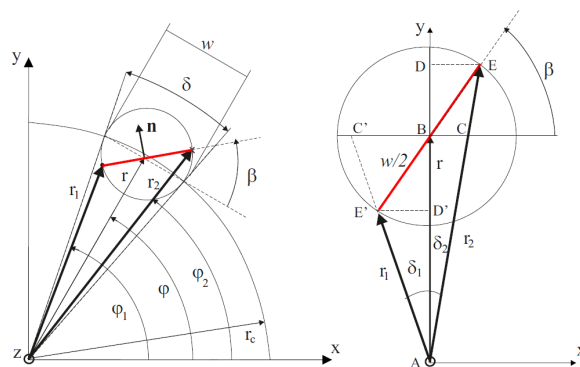


Figure 3.2: Naming conventions for angles and radii (personal communication, Stephan Russenchuck)

Let us consider the case of a tangential coil in position $\varphi_0 = 0$ that has a misalignment angle β in a normal dipole magnet according to Figure (3.2). This configuration gives results in the highest possible sensitivity for the β misalignment in a dipole field, according to personal communication with my section leader, Stephan Russenchuck. This misalignment is considered to be with respect to the middle coil of the segment, which we take as a reference point. We can now recalculate the dipole sensitivity factor as follows

$$K_1 = N\ell w \sin \beta = \mathcal{A} \sin \beta \quad (3.3)$$

where $\mathcal{A}$ is the magnetic surface of the coil, and β is the misalignment angle. The coil can then be flipped 180 degrees around, and when considering a pure dipole field with $\varphi = 0$, the induced flux $\Delta\Phi$ becomes

$$\Delta\Phi = 2Re \left\{ \sum_{n=1}^{\infty} \frac{1}{r_0^{n-1}} C_n K_n e^{in\varphi} \right\} = Re \{ C_1 K_1 e^{in\varphi} \} = B_1 \mathcal{A} \sin \beta \quad (3.4)$$

Assuming that the middle coil has a misalignment of β_0 and the outer coil has a misalignment of β_1 , the flux difference between the two coils can be expressed as:

$$\Delta\Phi_1 - \Delta\Phi_0 = B_1 \mathcal{A}_1 \sin \beta_1 - B_1 \mathcal{A}_0 \sin \beta_0 \quad (3.5)$$

Considering that $\beta_1 = \beta$ is small and defining $\beta_0 := 0$, we can say that

$$\Delta\Phi_1 - \Delta\Phi_0 = B_1 \mathcal{A}_1 \beta \quad (3.6)$$

Like in the case of the surface calibration, the dipole component of the magnetic field has to be considered as the average field over the used length of the magnet. This is acquired with the same mapping procedure as earlier. This gives the relation

$$\beta = \frac{\Delta\Phi_1 - \Delta\Phi_0}{\mathcal{A}_1 B_1} \quad (3.7)$$

If the β angle is larger than a certain tolerance (usually a few milliradian), the support needs to be modified to align one of the coils with another one serving as a point of reference. As for the surface measurements, compensation for the loss of voltage when connecting to the integrator has to be taken into account by multiplying the flux with the compensation factor.

3.2.3 Rotation radius

The rotation radius r is necessary for the measurement of all harmonics above dipole magnets. The calibration of this factor necessitates the use of a radially dependent field such as a reference quadrupole magnet (Figure 3.3).

To compute the normal gradient strength of this magnet, we will introduce a Δx displacement within a quadrupole and consider the coil to be radial. Knowing the coil surface $\mathcal{A}$ from the previous calibration step and that there is a horizontal offset x_0 between the rotation axis and the magnetic center, we can write the normal quadrupole coefficient as follows

$$B_2 = r_0 \frac{\Phi(0, x_0 + \Delta x) - \Phi(0, x_0)}{\mathcal{A} \Delta x} = r_0 g_{\text{meas}} \quad (3.8)$$

The flux difference between the initial point x_0 and $x_0 + \Delta x$ as well as the displacement Δx are measured respectively using a voltage integrator and a linear encoder while translating the coils within the magnet. This results in the measured gradient factor g_{meas} . Assuming that the quadrupole is pure, no higher order multipoles will be present, and the flux seen by the coil as a function of the rotation angle φ can be described as

$$\Phi(\varphi) = \text{Re}\left(\sum_{n=1}^{\infty} \frac{1}{r_0^{n-1}} C_n K_n e^{in\varphi}\right) = K_1 B'_1 \cos \varphi + \frac{1}{r_0} K_2 B_2 \cos 2\varphi \quad (3.9)$$

where B'_1 is the dipole term generated by *feed-down*¹ of the quadrupole. It is defined as $B'_n = \frac{n}{r_0}(B_{n+1}x_0 - A_{n+1}y_0)$ [Russenschuck, 2010], where B_{n+1} and B_n are normal field coefficients and A_{n+1} is a skew field coefficient as described in Appendix B. Here, x_0 is the horizontal and y_0 is the vertical displacement, and are terms which are generated by the misalignment between the rotation axis of the coil and the magnetic center of the quadrupole. Using this knowledge along with the fact that the coil is radial, the solution reads

$$\Phi(\varphi) = \frac{\mathcal{A}B_2}{2r_0} r \cos 2\varphi + \frac{\mathcal{A}B_2}{r_0} x_0 \cos \varphi - \frac{\mathcal{A}A_2}{r_0} y_0 \cos \varphi \quad (3.10)$$

The flux of the coil can now be considered at positions $\varphi = 0, \pi/2$ and π :

$$\begin{cases} \Phi(0) = \frac{\mathcal{A}B_2}{r_0} r + \frac{\mathcal{A}B_2}{r_0} x_0 - \frac{\mathcal{A}A_2}{r_0} y_0 \\ \Phi(\pi/2) = -\frac{\mathcal{A}B_2}{r_0} r \\ \Phi(\pi) = \frac{\mathcal{A}B_2}{r_0} r - \frac{\mathcal{A}B_2}{r_0} x_0 + \frac{\mathcal{A}A_2}{r_0} y_0 \end{cases} \quad (3.11)$$

Solving this set of equations for the rotation radius r results in the two following expressions:

$$\begin{cases} r = r_0 \frac{\Phi(0) - \Phi(\frac{\pi}{2}) - \frac{\mathcal{A}B_2}{r_0} x_0 + \frac{\mathcal{A}A_2}{r_0} y_0}{2\mathcal{A}B_2} \\ r = -r_0 \frac{\Phi(\frac{\pi}{2}) - \Phi(\pi) - \frac{\mathcal{A}B_2}{r_0} x_0 + \frac{\mathcal{A}A_2}{r_0} y_0}{2\mathcal{A}B_2} \end{cases} \quad (3.12)$$

Given that the flux difference generated by the rotation between 0 and $\frac{\pi}{2}$ and between $\frac{\pi}{2}$ and π should have opposite signs, and that the rotating radius will be considered as positive, the notation can be simplified by calling the first 90 degree rotation $|\Delta\Phi_1|$ and the second one $|\Delta\Phi_2|$. By taking the average of the two radii, that the feed-down terms generated by the misalignment disappear:

$$r_{\text{avg}} = \frac{r_0}{2\mathcal{A}B_2} \frac{|\Delta\Phi_1| + |\Delta\Phi_2|}{2} \quad (3.13)$$

¹Feed-down refers to the generation of lower-order harmonics due to a misalignment of the coil in a higher-order magnet

The fluxes in the equation above are measured with a voltage integrator while rotating the coil within the magnet. Combining this with the measured normal quadrupole coefficient developed above, the rotation radius can be computed based on measurements in the quadrupole magnet:

$$r_{\text{avg}} = \frac{1}{2\mathcal{A}g_{\text{meas}}} \frac{|\Delta\Phi_1| + |\Delta\Phi_2|}{2} = \frac{\Delta\Phi_{\text{avg}}}{2\mathcal{A}g_{\text{meas}}} \quad (3.14)$$

In practice, this is done several times, with 8 rotations in total going from 0 to 2π and back with $\frac{\pi}{2}$ rotations each time. This allows us to compute the radius several times to assess the stability of measurements through the analysis of standard deviations. The act of doing the flux measurements in reverse allows us to compensate the effect of integrator drift. To improve the drift compensation, we would need to rotate using the same time lapse each time. This could be achieved by installing a robotic system to handle the rotations and translations during calibration.



Figure 3.3: Left: Dipole reference magnet. Right: Quadrupole reference magnet with installed equipment for radius calibration operated by the head of the technicians associated to the MM section.

With the technical details surrounding the calibration of Rotating Coils in place, the assessment of the problem areas and possible solutions relating to the calibration procedure can now begin. This will be the object of Chapter 4.

Assessment of problem areas in organization and operation

Participating actively in a wide range of the Magnetic Measurements (MM) section's activities and conducting a number of informal interviews with personnel allowed me to gain some insight into how the MM section operated and what potential problems it had. As a framework for this assessment, the Business Process Modelling Notation (BPMN) [OMG, 2011] was used. The goal of this was to gain an overall view of the MM section to focus my work towards solving real problems. Some of these points resulted in technical applications leveraging my engineering knowledge, and some resulted in a process modeling task leveraging my management degree as will be detailed in the next chapter. The analysis will be presented on two different levels, one looking at the MM section as a whole, and one focusing on the calibration process, which is the main focus of my work at CERN. The BPMN models were a useful tool to understand the processes of the section but were considered not to be adapted for further analysis. Some of these models can be found in Appendix D as an illustration of parts of my analytic process.

4.1 Section level

As the analysis showed, there is much information that is generated through some of the steps of the process, and that is used by others. These include the creation of work-order tickets by clients to request a measurement, the client's measurement needs, the mechanical design files for tools, the calibration data, the measurement data, and more. Today, the sharing of this information is mostly done by saving files in the MM section's shared file system, via email, or via CERN's document management system called EDMS. This requires much manual work, and files can easily be mixed up, causing false results, confusion, and delays. The fact that the information is not centralized also poses challenges in traceability, meaning that if an error is detected at a later stage of the process, it is rather difficult to trace back the source, as the evidence is scattered around different folders and emails. Another resulting issue concerns the certification of results

that are sent to the MM section's clients, as the provenance of the measurement data is hard to trace. It would, therefore, be useful to develop a system that centralizes this information and ensures the traceability of measurements to synchronize the different processes in the MM section better and improve the quality of the service. A system that is capable of giving an overview of all the activity, trace back measurements, and see the current state of work, would be a good way to achieve better coordination between the MM section's processes.

Furthermore, the different steps of the process make use of many different tools, some of which are shared between tasks. The ISO 9001 standard for quality management points out that for certain firms, it is essential to have a good traceability of measurements in order to better certify the quality of results to clients. This means that the equipment used has to be regularly calibrated against known sources as well as being identified [ISO, 2015]. The tools used today are routinely calibrated but are not traced for a particular measurement so that their usage, state, and history can be stored in one place. No database exhaustively traces all the tools, when they have been calibrated, what measurements they have been used for, etc. A system that can handle the MM section's assets in order to make the measurements traceable could, therefore, make the quality of service better.

Also, as some processes use the same tools and other assets, it creates an interdependence that can sometimes be hurtful. For instance, the reference magnets used for calibrations are used in several R&D projects by students. At multiple occasions, this has caused calibrations to be delayed due to the booking of the magnet, or because some critical assets have been damaged or moved during R&D. A strategic decoupling of essential resources could help to reduce the interdependence of time critical tasks such as calibration from more flexible tasks such as R&D. This could remove some potential delays in the MM section's operations, which would be beneficial.

Furthermore, there are some potential improvements to be made in the collaboration between the MM Section engineers and the technicians. Work requests by engineers and students in the section for tasks such as tool manufacturing, calibration, heavy lifting, work station assembly, etc. are sent to the technicians, often via email. These can in some cases be critical to measurements, or parts of student R&D projects that are less time critical, and the head technician is responsible for their prioritization. However, he does not always have the right information at hand to attribute the proper importance to different tasks. As the requests are made independently, each person expresses a sense of urgency, which further complicates the task. This biased information and lack of overview can cause some frustration for both the technicians, who are criticized when critical tasks are delayed, and for the students and engineers, who do not get their work done in time due to false expectations. The movement of prioritization from the technicians to the engineers, who have a holistic view of the MM section's activity, could, therefore, be beneficial in this case.

Finally, the documentation that is needed for the technicians to do their work correctly

is not always clearly defined. This has in some cases resulted in tasks being delayed, and misunderstandings to happen. Through my work, I experienced such a delay because some details of a technical drawing for a calibration did not contain all the necessary information to complete the calibration. Another example I experienced involved a request from a student to a technician asking for help to order material for a project. The technician agreed, but when the list of items arrived, it was not in the form he expected and required him to do much additional work. The misunderstanding leads to both the delay of the task and to a misunderstanding that left both sides disappointed in the other. The incorporation of standard procedures for handling requests in order to have clear instructions and realistic expectations could therefore potentially reduce both delays and misunderstandings within the MM section, and lead to optimal collaboration.

4.2 Calibration process level

In addition to conducting informal interviews, I participated in the calibration process to better understand it. Three main aspects emerged that may be interesting to analyze in order to achieve a higher level of efficiency and accuracy in the calibration process: the technological aspect, the manufacturing aspect, and the design aspect. The technological aspect aims at making the supporting technology such as data acquisition systems, measurement benches, etc., more efficient and accurate. The manufacturing aspect aims at redesigning the way coils are manufactured with the same goal. Lastly, the design aspect aims at creating new designs that are more reliable from a mechanical point of view. As the two latter points are less relevant to my fields, my focus was on the technological improvements.

An important technological issue today is the software that is used for Rotating Coil calibrations. It is outdated, has limited portability, and is not expandable. This means that if the computer running it today were to crash, it would be challenging to get the software up and running again. It also means that new tools and processes cannot be included in the software to optimize the process incrementally. If at some point the software stops to work, the MM section's engineers would not be able to perform calibrations in the same way as before, which could prevent or alter the measurement of magnets. Such an operational halt would take much time to fix, and the section would not be able to deliver its service for a long time. There is, therefore, a clear need for a new software framework that allows for this reliability and flexibility.

The repetitive manual tasks found in the process are also one of the most significant sources of inefficiency today. These are very time-consuming and expose the process to the inevitable human errors that occur during tasks such as copying and pasting data. Several of the steps in the calibration procedure require the operator to gather information from several different Excel files manually via copy/paste, as well as the manual entry of data from sensors with up to six decimals. The probability of something going wrong in this process is high and tracing back the source of error can often be very laborious. This can result in several hours being spent on

finding and fixing the error, slowing down the process, and sometimes requiring several people to intervene. Hence, there is a real need for a solution that reduces the number of manual tasks required by the operators.

Much in the same way as the old software causes problems due to its irreplaceability, the hardware used for calibrations is a source of risk for the magnetic measurement operations. The voltage integrators that are used to read the magnetic flux from the measurement coils were designed in-house in the 1980/90s. The person who created them retired some years ago, which resulted in a lack of expertise on the subject due to missing dedicated personnel. Consequently, if too many of the devices break, the MM section's activity could be blocked for a long time. As the expertise is limited, it would be challenging to repair them or make new ones. There is a relatively low chance of this happening, but if it happens, it would have a significant effect on the section's activity. Therefore, it would be interesting to look at possible replacements for this device to eliminate the risk of an operational halt, while keeping the same calibration quality.

Another consequence of the tasks being manual is that the knowledge transfer among technicians becomes difficult to carry out optimally. Today, only one person has the full overview of the calibration process. He is often assisted by another technician in the tasks but remains the only person to handle the complicated tasks of moving data around in Excel files and using the software. Through more than 20 years of experience in calibrations, he has built up a lot of Tacit knowledge¹ about the process that is quite difficult to transfer to someone else. The consequence of this is that the whole process rests on one asset, meaning that if he were to be absent over a prolonged period, the activity in the MM section could come to a halt. A simplified process as well as a better way to transfer tacit knowledge, perhaps by turning it into explicit knowledge as described by [Nonaka and Takeuchi, 1995], would, therefore, be interesting to look into to make the process more rigid.

The mechanical setups on the calibration benches are different from those used in the actual measurements. The calibration benches are equipped with more basic setups that require much manual work, while the measurement benches have robotic solutions that precisely move the coils automatically. This means that the calibrations can be slightly off due to different setups. To make the setups for calibrations and measurement more alike would, therefore, increase the quality of the measurements as the calibrations would be more accurate. The use of the same software framework in both cases could further improve the accuracy with the same logic. Furthermore, the use of a robotic solution means that the calibration process could be made even more automated, freeing up the technicians to concentrate on more demanding tasks as well as limiting the chances of human error.

Finally, much in the same way as for the MM section as a whole, there is much information that is transferred between the different tasks in the calibration procedure. Today, these require the operator to keep track of information in emails and Excel files. With the introduction of an

¹Term made popular by Nonaka and Takeuchi [1995]

information management system such as a database, the flow of information between tasks could be made more efficient, which would further reduce human intervention and manual errors.

4.3 Solutions

Summing up from the reflections made earlier, there are a few points that need to be handled in order to maintain and improve the value-creation capacity of the MM section in the future:

- A way to centralize communication among the different activities of the section as well as their use of assets
- Reduce the asset interdependence between R&D and tasks directly linked to measurements
- Propose new prioritization structure and procedures for better coordination among technicians, engineers, and students
- Replace outdated software
- Replace outdated hardware
- Eliminate repetitive manual tasks
- Reduce differences between calibration and measurement benches
- Facilitate knowledge transfer in the calibration process

Based on this, we have found several solutions that could be implemented:

- Develop a new software program for the calibrations using the existing magnetic measurements framework
- Investigate the possibility of using a new type of hardware for the acquisition of signals from calibrations
- Incorporate an asset management system that would also serve as a database for linking different steps of the processes in the section
- Develop a new concept for training technicians in the calibration process such as videos or an interactive guide
- Invest in a second reference magnet in order to reduce the interference between R&D and calibrations
- Design new handover procedures and prioritization structures to increase coordination within the section

We would help to resolve several of the issues listed earlier by developing new software that handles the calibrations. First of all, the new software would replace the outdated one and ensure that the calibration procedure becomes more stable than before. Secondly, it would help eliminate several of the manual tasks involving copying and pasting items from different Excel sheets. This has several implications, such as the reduction of human errors that would speed up the time it takes to calibrate a coil system as well as increasing the quality of the results. The value-creation capacity of the MM section would hence be improved by increasing the quality of the service. Lastly, the development of a software in the same framework as is used for measurements, the Flexible Framework for Magnetic Measurements (FFMM), would help reduce the environmental difference between calibrations and measurements - further eliminating sources of error.

Furthermore, finding an alternative hardware solution for reading and integrating the signal coming from the measurement coils would eliminate the single point of error related to it, which could compromise the procedure. Some previous work has been done that indicates that the adapted use of an existing multimeter could be a possible solution, but this needs further investigation. If this investigation proves successful, it could possibly eliminate the risk of the hardware being permanently compromised as they come with an after sales service from the constructor as well as a calibration and accuracy certificate that ensures high-quality readings.

While doing this assessment, I noticed that there was a lack of overview of all the sub-processes in the MM section and its organization. A model holistically describing the section could help new and existing employees to get a sense of how their work is linked to other people in the section. Furthermore, a better way to contextualize problems found in the section and to assess their criticality would also be a result. Finally, it could help to uncover underlying problems in the organization which could have a notable impact on the MM section's efficiency.

Based on these reflections, we decided that I had to focus my work on the following three points:

- Develop a new software program for the calibrations using the existing magnetic measurements framework
- Investigate the possibility of using a new type of hardware for the acquisition of signals from calibrations
- Build a model describing the processes of the MM section

The development of these points will be the subject of the next chapter.

Detailed analysis and implementation

As a technical student at CERN, a significant amount of time has been spent working on technical implementations. This has included the development of new software for performing rotating coil calibrations in the MM section, and researching new hardware for digital integration that could potentially be better suited for the future. This work required much knowledge from my engineering studies such as programming, communication protocols, numerical analysis, optimization, electromagnetism, signal processing, and more, as well as product development knowledge gained through previous experience as a consultant intern.

For the work related to management, the focus was on process management aspects of the MM section. I dedicated much of my time to attempt to get a good overview of the section's work processes and which problems the section encountered. This was done with the help of the MM team by conducting informal interviews, building a model describing the processes, and finding and evaluating possible solutions to these problems. As summarized in the previous chapter, much of the research and problem-finding work was done early on in the internship. Once technical improvements were attempted, the modelling was done and resulted in a model that would hopefully give a more holistic view of the MM section for all its members. It also helped to uncover additional inefficiencies in the section along with contextualizing the problems described in the last chapter.

The goal of this chapter will be to give an overview of the problem-solving process used to achieve these objectives as well as present the results.

5.1 Automation of calibration procedures

Rotating Coils are produced in three parts. First, single coils are made in large numbers before having their surface calibrated. These have to be manufactured, assembled and calibrated. Then, these coils are sorted according to surface values, and mounted accordingly in groups of 3 or 5 to form segments. In this case, the surface of the coils, the parallelism between coils, and the

rotation radius of each coil have to be calibrated. Finally, different segments are put together according to final measurement needs, and are assembled and re-calibrated completely including the surface, parallelism and radius. Therefore, we need to separate the calibration into three different stages: the surface calibration, the parallelism calibration, and the radius calibration. Every calibration procedure is different and therefore requires a dedicated program to drive different devices and follow the right procedure. The software must also guide the operator precisely through every step of the process to ensure the quality of the measurement.

The following part of the report outlines the process that was undertaken to develop the new software, before analyzing the added value its development brought to the MM section. Large parts of this work are my own contributions, with support from my supervisor and other engineers when it was needed. Close collaboration with the technicians helped finalizing the software. Flow-chart descriptions of the developed calibration algorithms can be found in Appendix E, and are based on the calibration procedures outlined in Chapter 3.

5.1.1 Surface calibration program

Driver development

The surface calibration process requires the reading of several values through the use of different sensors and acquisition systems. These include a Portable Digital Integrator (PDI) [Galbraith, 1993] to measure the magnetic flux and a Nuclear Magnetic Resonance (NMR) sensor for measuring the dipole magnetic field (Figure 5.1). The PDI and the NMR both use the General Purpose Interface Bus (GPIB) protocol for communicating with the computer. To automate the data acquisition, these need to be integrated into the software. Low-level drivers for the GPIB protocol had already been incorporated into the C++ based software framework we use, which is called the Flexible Framework for Magnetic Measurements (FFMM), as well as a dedicated driver using the NMR directly. This meant that a new dedicated driver allowing the main application to communicate with the PDI in C++ had to be developed before the main application could be created.

The PDI, developed at CERN by the MM section more than 20 years ago, is currently being used in all three stages of the calibration process for Rotating Coils. It reads the output voltage of the coils to be calibrated and integrates the signal using a voltage to frequency converter and a digital counter. This method gives an excellent measurement quality in terms of accuracy. As up to 5 coils need to be measured simultaneously in a shaft, five PDIs are required in total (Figure 5.1).

The PDI uses the GPIB protocol, which also goes by the name of IEEE-488. It was first developed by Hewlett-Packard in 1965 and has been widely used to interface instruments ever since. Still today, many instruments make use of this protocol [Limburg, 2000] [NI, 2008].

As a first step of the work, understanding how the integrator worked was important, and,

due to some lack of documentation, it took some time to investigate all its features. However, a binder with documents produced during the development of the integrator in the 1980/90s was useful as a reference. This documentation contained electronic schemes, mechanical drawings, a non-exhaustive functional documentation, and source code written in Pascal and Assembly language. After some analysis and testing, I was able to understand better how the device worked and could continue with the development.

To communicate with the PDI, the National Instruments Measurement & Automation Explorer (NI-MAX) software was used on a Windows workstation dedicated to calibrations. This tool allowed the testing of different GPIB commands to understand to what extent the PDI could be controlled remotely. When this was well understood, the development of a driver class in C++ for the integrator could start. After some initial protocol level issues, commands could be sent to the integrator through the FFMM code. A graphical user interface (GUI) was also written in FFMM using a subset of an external C++ framework called Qt.



Figure 5.1: Left: Portable Digital Integrators (PDI) in their rack. Right: Nuclear Magnetic Resonance (NMR) device

The program could now send commands to the integrator, but making it read data remained an unsolved issue due to limited knowledge about some details of the GPIB protocol. A few days of testing and research resulted in a better understanding of the protocol which allowed data from the PDI to be read correctly by the software. More precisely, I understood that the integrator had different types of commands for asking for data called *triggers*. The Group Execute Trigger (GET) allows data to be read simultaneously from several devices by broadcasting a command on the GPIB bus. The External Trigger allowed each device to be triggered by an electronic input signal, and the Internal Trigger used the internal time-base of the integrator to trigger with a given frequency. The GET trigger was best adapted to the project's needs. Sending this command over the bus required some research, as it was not implemented in the existing GPIB

driver in FFMM. After some investigation, the relevant low-level functions were found deep in the framework, and new functions were implemented to extend the existing GPIB driver to allow for control over the trigger.

Once the protocol understood on a lower level, additional functionality was implemented to the driver. As an example, status polling allows the programmer to test whether the integrator has rebooted correctly or there is a saturation of the integrator during the measurement. This happened to be very useful in the development of the final program as it allowed the automated quality check of the data being read, a new feature not implemented before.

I then carried out a complete campaign for testing and debugging the developed driver. For this purpose, I developed a suitable GUI for analyzing various acquired signals in real time. These tests confirmed that the acquisition was made correctly, and the development of the main program could proceed.

Application development

In order to develop the final application, a long study was necessary to fully understand the calibration procedure. Tight collaboration with the technicians operating the calibrations was planned, and several iterations were necessary to fully and deeply understand the procedure. This allowed for a deep understanding of the practical aspects of the process, which made the application development easier. Starting from the first version, the developed software was tested rigorously, and much of the feedback received from the operators was implemented. This allowed us to be certain the acquisition was done correctly, and gave indications on how to make the software user-friendly by for instance using the same exact output formats as the previous program.

Before being able to release the program to operators, a test was performed to check the validity of the data acquisition and calculations within the program. We performed these tests on a set of coils that were under development for the High-Luminosity LHC upgrade, and they proved successful. At one of the weekly Monday morning technician meetings, we discussed the final requirements of the software with both engineers and technicians and devised a plan. First of all, I had to find and implement an open-source library for creating and editing Excel files in C++, and use this to store the output data of the calibration in the same type of document as before. The goal of this was to disrupt the existing calibration process as little as possible to ensure a smooth transition to the new program. We also decided to put in place a close collaboration with the technicians for the following weeks to tailor the program to the final user needs.

Having implemented and tested an open-source library for writing Excel files in C++, we started to do several calibrations with the software, focusing on the user experience. After several iterations, we ended up with a concept that was very intuitive, and that guided the user through

the whole process with ease (Figure 5.2 and 5.3). As suspected from the analysis, the Excel templates used for storing, analyzing, and communicating calibration results had lost their initial structure and clearness due to several copy and paste procedures done over several years. I therefor got the opportunity to improve and standardize them for use in the new program. After rigorous testing, we could conclude that the software was ready to be used in real calibrations. An additional program for calibrating single coil surfaces was also developed towards the end of the internship, and was heavily based on the one described in this part of the report.

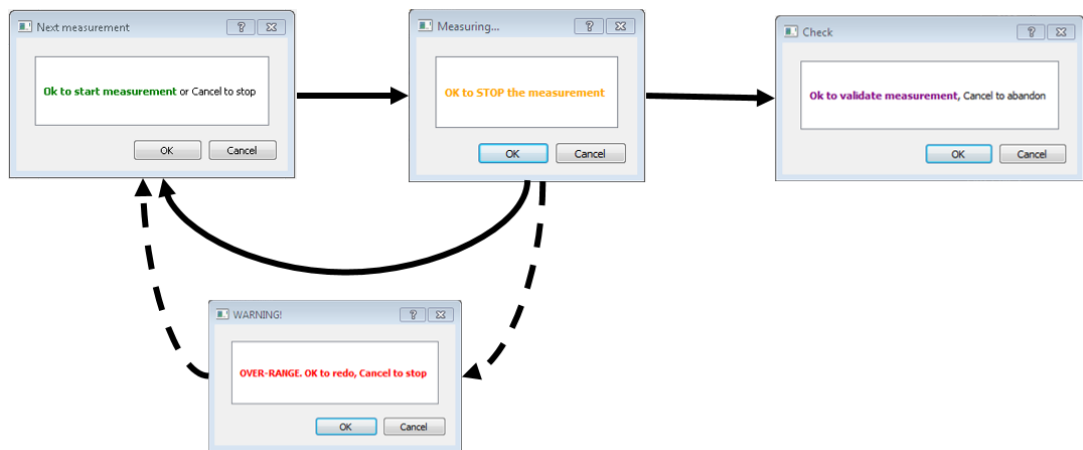


Figure 5.2: Navigation logic of the surface calibration software

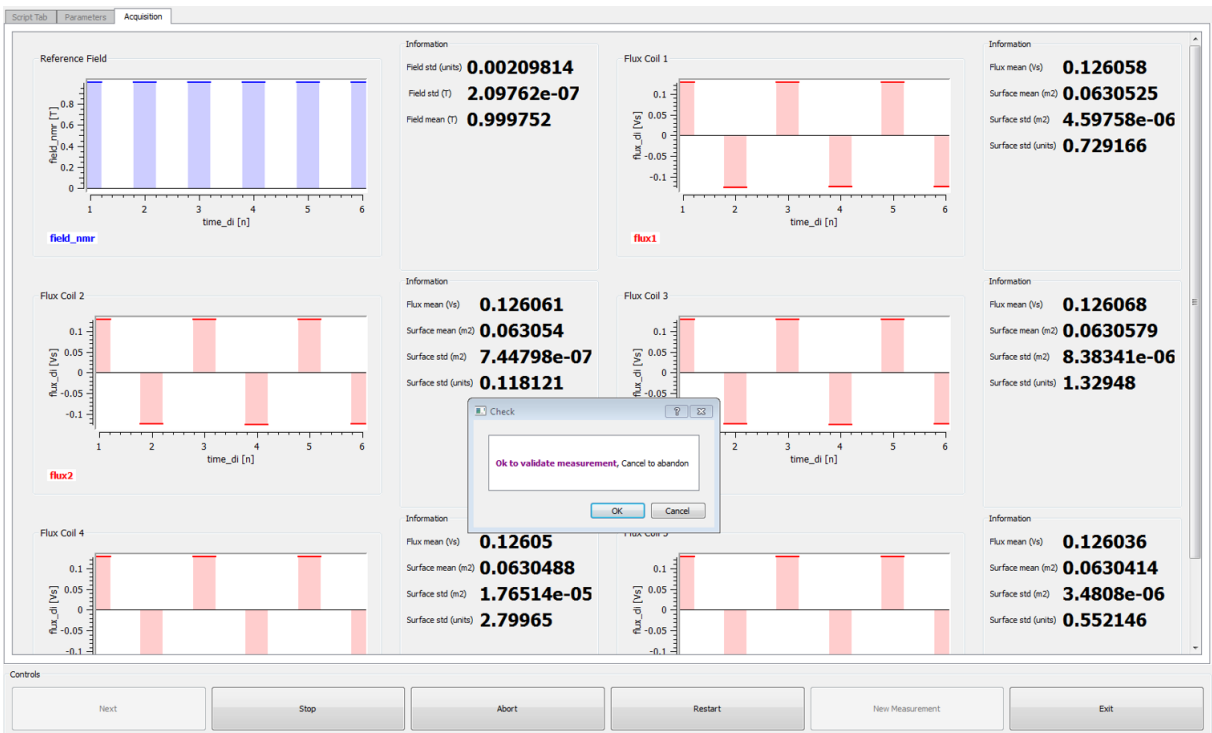


Figure 5.3: Screen shot of the surface calibration software at the final quality checking step

5.1.2 Parallelism calibration program

Application development

The development of the parallelism program went relatively smoothly after the initial development of the surface calibration program, owing to a similar implementation. After understanding the process well, a version which was tested in the same way as the surface program was implemented. Further development along with an intensive User Experience optimization period followed, and the final program was completed.

5.1.3 Radius calibration program

Driver development

The last step of the calibration process is situated within a quadrupole magnet, and aims to calibrate the rotation radius of Rotating Coils. The procedure uses the same integrators as in the two previous steps, but in addition incorporates a linear encoder by Heidenhain. This encoder used the RS-232 communication protocol and did not have an existing driver in the FFMM framework. A new driver had, therefore, to be developed.

RS-232 is a serial communication protocol. It uses 9 or 25 pins according to the implementation, where one is dedicated to the transfer of serial data, and the rest of them are dedicated to indicating the status of the data transfer. This is compatible with the serial input (USB) of most computers, and is widely used still today [Sparkfun, 2010]. Bits are transferred one by one with a given baud rate, with start and stop bits, and with or without a parity bit as described in Figure 5.4.

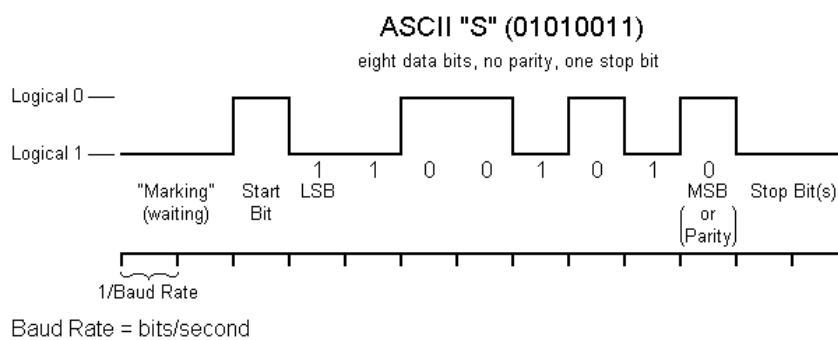


Figure 5.4: Transfer of the letter S in ASCII over RS-232 data frame [Rorvik, 2003]

To understand the protocol correctly and create the right commands for communicating with the software, NI-MAX was again used to test out commands. Once the driver for the linear encoder had been developed, a simple program for testing it was written. Once the acquisition verified, the development of the main application for the quadrupole magnet calibration could begin.

Application development

The development of the radius calibration program has been the most challenging of the programs as there are several interlinked sub-procedures. As described in Equation 3.14, the calibration of the radius of a coil requires both the quadrupole coefficient of the magnet in the form of a gradient and the integrated flux of the coil. The flux when rotating the coil is acquired in the same way as before with the integrators, but the gradient has to be measured using a combination of the integrators and the linear encoder. This requires a gradient-measurement step before doing the actual radius measurements. To reduce the uncertainty, the gradient measurement is acquired twice with different displacements of 10 mm and 20 mm, causing the resulting gradients to be averaged out for the use in the computation of the radius.

An initial version based on the procedure documentation at hand was developed. To further understand the details of the radius calibration procedure, several calibrations were carried out. This allowed for a refinement of the software procedure that was developed, aligning it with the real procedure. Analytically, the quadrupole procedure was less trivial than the others as the cases of radially or tangentially mounted coils required different calculations. This had to be taken into account both in the software and in the Excel template files.

The completion of the software was done in the same way as for the other applications, working closely with the expert personnel in a hands-on way to intimately understand the procedure and develop a well adapted interface.

5.1.4 Added value

The development of a new software program resulted in the implementation of the basic functionality of the previous program as well as several additions that made it more user-friendly and more efficient. The primary added value to the calibration process can be summarized as follows: No manual Excel tasks, automated acquisition, status polling, input resistance compensation, automated field adjustment according to mapping, easier to learn, single entry of data, more procedure flexibility, safer framework, corrected formulae.

The fact that manual Excel manipulations are no longer necessary for the completion of a calibration, and that data acquisition is automatized for all used devices will, hopefully, reduce the number of manual errors inherent to the procedure. The incorporation of status polling of the devices, which allows the software to pre-check the quality of the measurements, and of a real-time interface to supervise the measurements, also reduces the chance of having false results. According to my perceptions and those of my subordinates, this will render the exploitation of the technician's workshop more efficient. This in turn would make the MM section as a whole more efficient in performing precise magnetic measurements and R&D.

We measured the input resistance of the integrators used for the calibration to be approximately 2 M Ω . With coil resistances ranging from a few ohm to a few kilo-ohm, the voltage drop

due to the impedance bridge generated upon connection can cause relative errors in the order of 10^{-4} . As this is the order of precision the calibration process aims for, this error is significant. In the previous software, this was not compensated for, and could, therefore, affect the calibration precision. The new software includes compensation for this effect automatically, as described in Chapter 3, which then makes it more accurate than its predecessor.

One of the most error-inducing steps of the old procedure was the adjustment of the dipole magnetic field measurement. As the reference dipole is not completely homogeneous, a complete mapping of the magnetic field over its length every 10 mm is done once every year using an NMR sensor. When a coil calibration is performed, the field is acquired at one point by an NMR sensor, and the average field over the length of the coil, given its length and position, is computed. In the old Excel-file-based procedure, an operator manually inserted a value extracted from a large matrix of numbers, and it was easy to copy the wrong one. In the new program, I implemented a functionality that allowed this calculation to be done automatically based only on the prior knowledge of the position of the NMR, the starting position of the coil, and the length of the coil. The reference file containing the mapping of the magnet can easily be updated when a new one is made, and it saves the operators time and prevents potential inherent errors.

One of the main problems outlined earlier when considering the calibration software was its complexity. The challenge to understand all the steps correctly resulted in only one person being able to operate it. This complexity introduced a single point of failure - meaning no calibrations can be done when the expert is unavailable. The new software has a much simpler interface guiding the operator through all the steps of the process. This allows more people to learn the procedure and operate the calibration whenever needed. This interface only requires manual input of data at one initial step of the process. This allows more people to operate the process after the initial data about coil dimensions and other system details had been entered.

With the new software implemented in C++ into the FFMM framework, there is now a potential for the software to be further extended to use other devices already incorporated into FFMM. This will, for example, allow developers to include a database to strip the program of manual tasks further and a control of motors to allow the mechanical tasks of translating and rotating the coils to be automated by robotics. The problem of the previous program only running on a particular version of Windows is also removed by implementing it into the safer and more flexible and operating system-independent FFMM framework. FFMM is distributed in a shared repository (SVN), further enforcing its protection against loss and version changes.

Finally, having worked through the mathematical theory behind the calibration of rotating coils, some errors were detected. The most important one concerned the parallelism calibration. In contrast to the correct Equation 3.7, the division by twice the magnetic dipole component was not included in the previous calculation of misalignment angle β . Although β was used only for a minimization procedure where the coil's support was filed and adapted to minimize the angle as much as possible, the whole procedure is now more coherent mathematically and

metrologically.

5.2 Investigation of a new integrator

The in-house-made integrators used today for calibrations (PDI) are quite outdated, and expertise about their calibration and maintenance is no longer available in the MM section. This means that there is no one to repair them if they were to fail. The Fast Digital Integrator (FDI), another integrator used specifically for magnetic measurements, was developed in-house mainly for doing fast measurements. It is not the best option to use for calibrations, yet remains a possible candidate. Having an off-the-shelf product suitable for integrating the signal with the same precision as the PDI and more suited to calibration than the FDI is the solution considered. In addition, we could use the guaranteed accuracy provided by the constructor as a base for ensuring the calibration results, and take advantage of the customer service in the case of failure.

This triggered the interest in performing a feasibility study of a high-quality Multimeter such as the HP3458A from Keysight to do the integration [Keysight, 2001]. This Multimeter uses an internal dual-slope integration procedure to do the Analog-Digital conversion, which has an excellent accuracy as well as quality filters to pre-process the signal. If we could use the data acquired by these integrators directly, we would be able to reconstruct a highly accurate version of the integrated signal. The problem might come from a possible discharge time after each integration cycle which would affect the results in a negative way. Wanting to use the instrument in a different way than intended, the documentation did not provide the complete information needed. It was, therefore, my job to perform a feasibility study.

5.2.1 Driver and test program development

To be able to automatize the measurement procedure and analyze the data acquired by the Multimeter appropriately, a new driver and test script had to be developed in FFMM. Starting from a very basic Multimeter class kernel, I expanded and refined the driver to make it easy to test several different configurations using the RS-232 protocol. Next, I developed a test script that would allow us to compare the Multimeter's data with data from the FDI and PDI in parallel. This required the use of an existing FDI driver in FFMM, which demanded a significant amount of work to understand. As this study was very important for the future of the calibration process, a complex high-quality data acquisition system called DAQmx was used. This allowed the synchronized triggering and acquisition of several devices at the same time with high precision. A very accurate (16 bit resolution with 2.8 MS/s update rate) signal generator from National Instruments called PXI-6289 was also used to generate different signals to be integrated, and was piloted through a dedicated software. After having developed and tested the required software for the study, I could start investigating characteristics of the Multimeter.

5.2.2 Initial analysis and sampling method comparison

As a first step of the feasibility study, an experiment was carried out to check the approximate exactitude of the integral measured by the Multimeter. To do this, I generated constant, ramped, and sinusoidal signals with the signal generator, and acquired the data with the test script. Analyzing accurately the first results, the constant and ramp signals gave very satisfactory results, while the sine wave gave a slight error. The error was small, however, and was initially attributed to the signal generator and the Multimeter being unsynchronized.

This experiment triggered a deeper examination of the Analog-to-Digital Converter (ADC) system of the Multimeter. In addition to the classic lock-and-hold direct sampling (DSDC) of the signal, the integrator included several other options. We ended up trying to use the DCV option, which uses an internal integrator to integrate the signal over small periods of time to create samples. This seemed most relevant to our application. In this mode, the sampling and aperture time configuration became important. Sampling time is the time interval between each output sample, while the aperture time is the integration period used in the underlying acquisition process.

To test the accuracy of DCV against DSDC sampling, we compared the Multimeter acquisition with that of the FDI for the same input signals. Several different signals were acquired using different sampling and aperture times, and their difference was assessed using their normalized root mean squared deviation (NRMSD). An initial test resulted in the following results (Table 5.1), which shows that the DCV method is closer to the FDI with a factor two of difference in the NRMSD. We therefore decided to continue with that sampling method.

Measurement	NRMSD
DCV with 1.4us aperture	0.006542614
DCV with 100us aperture	0.005071625
DSDC with 1.4us aperture	0.012481043
DSDC with 100us aperture	0.013450978

Table 5.1: DCV/DSDC comparison for a 1 V amplitude and 1 Hz frequency sinusoidal signal sampled at 100 Hz.

5.2.3 Multimeter/FDI comparison

After much investigation of the Multimeter and FDI signals by tweaking several parameters and comparing data sets, the error between devices observed in the first experiment persisted. By plotting the difference between the two devices, it became apparent that the error was due to the drift of the integrator in the Multimeter as well as an error that was proportional to the amplitude of the signals. These errors can be decomposed into a linear and a proportional component and plotted in Figure 5.5.

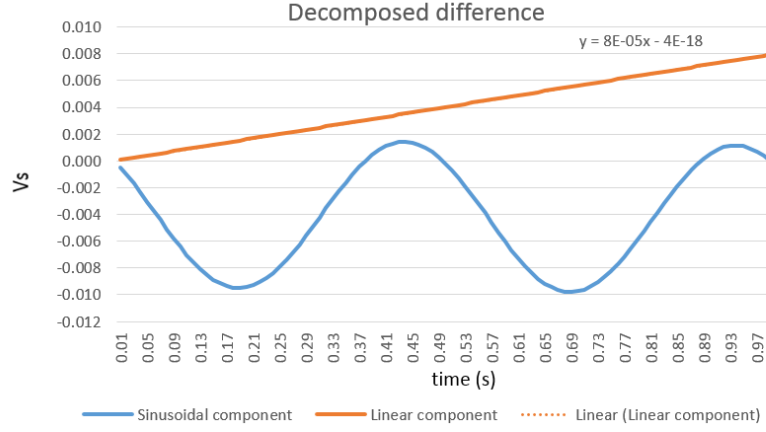


Figure 5.5: Decomposition of error between FDI and Multimeter into slope and residue. 2 Hz sinusoidal signal sampled with 100 μ s period.

The linear component was easily compensated via extrapolation, but the source of the proportional one distorting the signal had to be found. I therefore performed a test to check which of the FDI and Multimeter signals mostly resembled a pure sinusoidal signal. To make this comparison, the Least Squares (LSQ) regression method was used to fit a sine function to the data. The goal of the method was to minimize an optimization problem, giving us the value of the gain, frequency, phase, and offset that best fit the sine function. To solve the optimization problem, the Excel Solver using the Generalized Reduced Gradient (GRG) algorithm was used. The optimization problem can be formulated as follows

$$\text{Min}_{A,f,\phi,\delta} \left(\sum_{n=0}^N r_n^2(A, f, \phi, \delta) \right) \quad (5.1)$$

where $r_n = f_n(A, f, \phi, \delta) - x_n$ is the residue, and $f_n = A \sin(2\pi f n + \phi) + \delta$ is the fitting function. Also, x_n is a sampled value, ϕ is the phase, f is the frequency, and δ is the offset. The results strongly suggested that the error came from the Multimeter, as the FDI's data resulted in a much more accurate fitting with the optimization converging at $3 * 10^{-11}$ against $4 * 10^{-7}$ for the Multimeter. This suggested that there was some distortion in the data acquired from the Multimeter. The analysis of the error between the two signals further enforced this point as they had similar characteristics.

The distortion required further investigation, and we suspected the problem might be due to the sampling method of the Multimeter. We wanted to test how well synchronized the underlying integrations were with the samples. To test this, I applied a 500 Hz sinusoidal signal that was sampled at the same frequency of 500 Hz using both devices. If the resulting signal was a constant, it would mean that the sampling was well synchronized, and the opposite if it was sinusoidal. This test showed encouraging results for the Multimeter, as its signal was significantly closer to a constant value than for the FDI. As this possibly could be due to a filter in the Multimeter that filters out all high-frequency noise, we tested this same case but

with a slightly different sampling frequency, which gave the same encouraging result for the Multimeter.

A new hypothesis now emerged suggesting that one source of error could be the fact that the internal clock driving the integration was out of sync with the external triggering signal. I, therefore, reconfigured the Multimeter to use the internal clock for acquisition instead of the external trigger. By fitting a sine wave by regression in the same way as earlier, the results clearly favored the Multimeter. The FDI's LSQ minimization converged at $3 * 10^{-9}$ while the Multimeter converged at $7 * 10^{-15}$ - a clear difference compared to the use of the external trigger, and a positive result for the Multimeter.

5.2.4 Optimization of reading rate

As the use of the internal clock gave better results for the Multimeter than the FDI, we continued the investigation in this direction and tried to optimize the reading rate which was theoretically bounded at 100 kHz. Through detailed configuration, we managed to achieve this rate using a single integer data format and 50 kHz at double integer format. This optimization was a very challenging task, and required a lot of testing and documentation searching. For example, it required the manual decoding of bit arrays into ASCII code using the coding principle outlined by Figure 5.4. However, we discovered that the internal memory of the Multimeter was of only 167 kB, meaning that we could not save more than 38000 samples simultaneously. We therefore had to abandon the idea of doing high-frequency acquisitions, as we would not be able to integrate for long enough. I also tried using internal math functions of the Multimeter to pre-process the data, allowing us to read the mean value and number of samples directly. This would allow us for a more efficient reading, but the small memory still remained a problem.

As a result of the reading rate optimization, I discovered that the time gap needed between the sampling time and the aperture time due to discharging capacitors and data writing had strongly diminished. This difference was of $5 \mu s$ at 50 kHz sampling frequency and grew proportionally with the sampling period, due to the higher sampling resolution associated with a longer integration period up to $25 \mu s$ where it reached its maximum value. This implied that we could use a very long integration period allowing us to take advantage of the accuracy of the analog integration within the Multimeter as originally planned. At a maximum aperture time of 1 second, we were able to integrate 99.9975% of the signal very accurately. This would give us a potential accuracy of close to 10^{-5} , assuming that the integration error is negligible, leading to an increase of the measurement accuracy compared to the PDI.

5.2.5 Final test

As a final validation test, a calibration was undertaken using both the Multimeter and PDI to compare results. A consistent loss of signal was observed in the Multimeter, and a preliminary

negative conclusion concerning the use of the Multimeter as an integrator was reached.

I decided to contact the technical support at Keithley to look for possible solutions, and it turned out to be an interesting exchange of information. A new path for the investigation was discovered which would entail the use of a sampling method specialized for analog signals called ACDCV. As my stay at CERN came to an end, this investigation will be undertaken by someone else. Nevertheless, this experience gave me the possibility to go deep into an electronic investigation, and taught me a lot of useful knowledge about electronics debugging.

5.3 Process modeling

I noticed early on that there was no single framework for explaining the organization and processes of the MM section. This could be a very useful tool to get new employees up to speed on the section's organization, especially considering the high turn-over rate due to short student contracts. Therefore, a model was developed in part on the basis of knowledge acquired through the analysis described in Chapter 4.

5.3.1 Value Chain analysis

The MM section's primary activity is to provide a measurement service for clients at CERN, but also externally. However, there are several other ongoing performed activities. To get a better understanding of the core business of the MM section and its structure it would be interesting to model it to uncover its underlying value-creating processes. This could, in turn, be a helpful tool for discovering inefficiencies, finding solutions, and assessing the efficiency of measures taken. It also serves as a good way to gain a holistic view of the section's activity, with the goal to improve communication and collaboration between the section members. This has been done in part by Limniati [2015] as part of a masters thesis, with the goal of defining the needs for a Management Information System (MIS) that is currently being developed. The *Value Chain* framework [Porter, 1985] was used.

The Value Chain framework was first introduced by Michael Porter in 1985 and has since been the reference on which value-creation analysis has been conducted. The idea of this framework is to disaggregate the different activities of the organization to get a better understanding of the process that drives value [Stabell and Fjeldstad, 1998]. The main activity of the firm is then viewed as a collection of subsystems forming a chain that transforms inputs into profits, hence the name of Value Chain.

Porter argues that the primary activities of any firm can be entered into five generic categories: inbound logistics, operations, outbound logistics, marketing and sales, and service. Inbound logistics include receiving, storing and disseminating inputs to the product. Operations transform inputs into the final product. Outbound logistics collect, store and physically distribute the

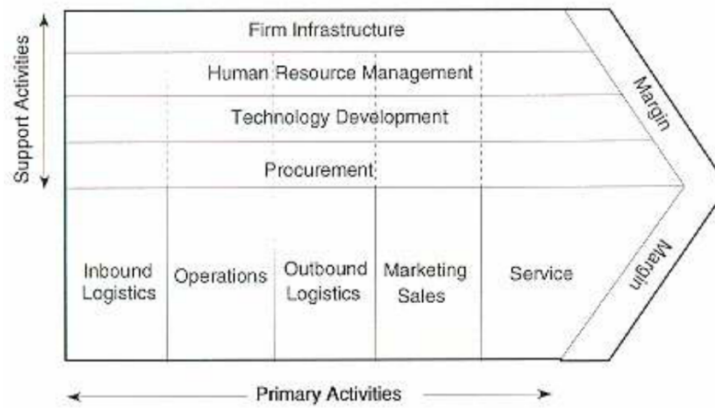


Figure 5.6: Value chain model from Porter (1985)

product to buyers. Marketing and sales provide a means by which customers can purchase the product and induce them to do so. Lastly, service aims to help enhancing or maintaining the value of the product after it has been sold.

Also, Porter points out four supporting activities that are not uniquely linked to the value-creation logic of the Value Chain, but still have a critical role in the firm: Procurement, technology development, human resource management, and firm infrastructure. Procurement has the goal of purchasing the inputs of the Value Chain, while technology development engulfs the efforts to improve the product or process. Human resource management includes recruiting, hiring, training, developing and compensating personnel, and firm infrastructure includes general management, planning, finance, accounting, legal and government affairs, and quality management [Porter, 1985].

These activities can all be modeled as in Figure 5.6, which illustrates the whole activity. Primary activities are put one after the other to show the sequential nature of the value-creating process, while the layered character of the support activities illustrate the fact that they are performed in parallel with the main activities.

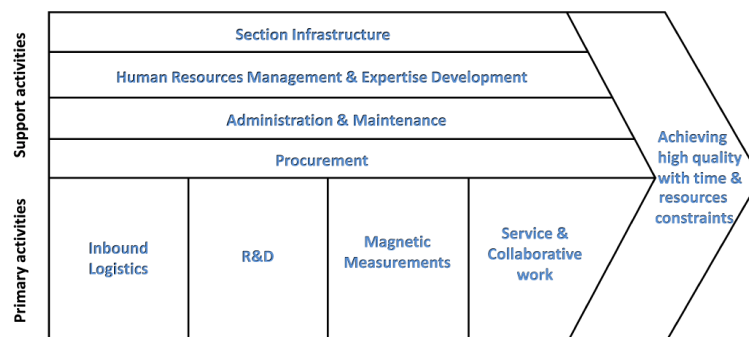


Figure 5.7: Value chain model of MM section from Limniati (2015)

Using a model adapted to a research environment, Limniati [2015] proposed a Value Chain model of the MM section. This model serves well its purpose as a tool to get an overview of

the activity of the section, but arguably misses the real logic of value-creation in this particular case. The primary purpose, and therefore the main business of the MM section, is to provide magnetic measurements. Activities such as R&D are critical for this to be possible but should be viewed as supporting activities as they are not directly linked to the performance of a particular measurement. The misalignment between the model and the reality stems mainly from the nature of the model, which was developed with traditional manufacturing in mind [Stabell and Fjeldstad, 1998]. In the existing model (Figure 5.7), we can see that the magnetic measurement process is represented in such a chain of activities. A more suited model for this type of organization could be the Value Shop analysis.

5.3.2 Value Shop analysis

The standard for quality management systems, ISO 9001:2015, issued by the International Standardization Organization in 2015 [ISO, 2015], recommends that firms use a process approach to ensure a good quality management system, and puts a lot of weight on understanding the processes correctly. While the Value Chain approach is interesting to get a sense of the main functionality of the MM section, it does not explain how the processes of the section work together to create value for its customers. It would, therefore, be interesting to have a detailed model that explains how the section creates value to have a process management approach to the optimization of the section's activity. This will allow the use of a structured approach to analyze and diagnose the MM section to propose practical solutions. The goal of the rest of this part of the report is to suggest such a new model of the MM section.

Value shops and intensive technologies

In 1998, two researchers from the Norwegian School of Business (BI) published a paper proposing a broader way to model the value-creating logic of firms [Stabell and Fjeldstad, 1998]. Instead of only considering Value Chains, they introduce the concepts of Value Shops and Value Networks as alternative ways to model a company's value configuration.

Their paper is built on the typology of long-linked, intensive, and mediating technologies introduced by Thompson [1967]. A long-linked technology is a production process that focuses on standardized outputs using standardized inputs with a fixed sequence of steps. Classic examples of this are steel plants or other traditional manufacturing companies. A mediating technology is characterized by unique products developed via standardized processes. This is typical of banks, insurance companies, and brokerage firms. Lastly, an intensive technology is defined by non-standardized processes and unique inputs/outputs. The focus is on using experts to solve problems in unique ways. Typical examples are hospital emergency rooms, R&D laboratories, and activities organized in projects.

While Porter's Value Chain is well adapted to long-linked technologies, modeling firms based

on intensive or mediating technologies with the same method can cause much of the critical value-creating logic to be ignored [Thompson, 1967]. To respond to this problem, [Stabell and Fjeldstad, 1998] proposed two new models to handle the remaining technologies: Value Shops for intensive technologies and Value Networks for mediating technologies. This section will argue that the MM section's value configuration closely resembles that of an intensive technology, and should, therefore, be modeled using the Value Shop rather than the Value Chain.

As opposed to long-linked technologies, who use standard processes to produce standard outcomes, firms who rely on intensive technologies aim to solve individual problems for their clients using an adapted application of resources for the problem at hand. The word 'shop' is meant to reference a mechanic's car repair workshop. This translates the fact that the company is built to solve a particular class of problems for their customers [Stabell and Fjeldstad, 1998]. In the case of the MM section, that is certifying the characteristics of accelerator magnets. To reduce costs and increase performance, shops also often incorporate the object that is worked on [Stabell and Fjeldstad, 1998]. In the case of mechanics, that could be the car, in the case of a hospital emergency room, that would be the patient, and in the case of the MM section, that is the magnet that is to be characterized.

Furthermore, [Stabell and Fjeldstad, 1998] go on to illustrate a set of distinctive characteristics of value-creation at firms with intensive technologies, which will be outlined next. These can be strongly related to activities at the MM section as will be seen next.

First of all, firms leveraging intensive technologies operate with a large information asymmetry between the company and its clients. This is an essential attribute and is the reason why the customer needs the firm with its capacity to figure something out that they themselves cannot. In the case of the MM section, the client lacks the ability to certify its magnets according to requirements. The section can, therefore, provide a diagnosis service where new information about the state of the magnet is transferred to the client.

Value shops are also configured to deal with unique cases. Client's problems are solvable with standard solutions most of the time, but the firm needs to be ready to deal with individual cases. This means that less experienced personnel can handle the activity most of the time, but experts are required to address special cases [Abbott, 1988]. In the MM section, this is very much the case, as most measurements are done on LHC magnets which require well-known technology and measurement systems. However, new magnets arrive that require a new measurement system or the adaptation of an existing one, such as different radius, length, etc. in the case of Rotating Coils. This is, for example, the case for the new magnets that are being developed for the High-Luminosity LHC upgrade. These new magnets require an expert engineer to take responsibility, while measurements can be executed by technicians if the procedure is standard. Even more critical is the use of experts in the data analysis phase to verify the results and reduce possible errors. This is especially important in measurements associated with prototyping, as the information will be used for design decisions in the next iteration of magnet building.

Furthermore, the activities in a Value Shop can be described as cyclical, iterative and interruptable. The iterative nature means that tasks have to be performed one after the other. In magnetic measurements, for example, one first has to describe the measurement needs, find a fitting solution, execute the measurement, and control the quality of the measurement. The cyclical attribute means that these sequences of iterative tasks can be repeated several times in the context of one activity set. In magnetic measurements, this would illustrate the fact that measurements sometimes have to be performed several times if something goes wrong or there is a need to investigate a point further. Finally, the activity is interruptible, meaning that the activity can be stopped if no solution can be found. This can be the case if the results largely deviate from the requirements, potentially causing a major perturbation the performance of the accelerator as a whole. In this case, it has to be sent back to the manufacturer to be rebuilt, and a new measurement request has to be sent after the fact.

The paper also points out that such firms can have multiple disciplines and specialties in spiraling activity cycles. In the MM section, there is the primary activity of measuring magnets and a strongly linked activity where tools for the measurements are developed. When tools for a particular measurement are not available, they need to be designed by a team of engineers. Then, these models need to be manufactured and calibrated to be used for measurements. We, therefore, have two main activities in the section. It all starts with the core activity of measurement and spirals out to the system development activity. This will be further illustrated in the graphic model described below in Figure 5.9.

Moreover, there is a significant sequential and reciprocal interdependence between steps of the Value Shop process. This demands a high level of coordination across activities and is usually solved by assigning a single person to one problem who is responsible for everything from the definition to the solution. In the MM section, a magnetic measurements engineer (MM Engineer) is in charge of each measurement project, supervises the entire procedure, and makes sure the different tasks required are well coordinated. He also has the responsibility of finding a technical solution to the measurement need, carrying out the measurement, checking it, and delivering it to the client. He, therefore, has a holistic view of the measurement project, much in the same way as a project manager has of any given project [PMI, 2004].

Finally, Stabell and Fjeldstad point out a few other characteristics of the value-creation logic related to intensive technologies, such as the use of problem-independent information acquisition systems, to do quick diagnostics of problems in a generic way to give initial indications. The fact that support activities are often done by professionals as a part of their day-to-day activities, the use of experts to solve problems and mentor the junior workforce, and the fact that referrals are often based on reputation and relationships are also mentioned. These points all apply to the MM section, and we can conclude that the categorization of the section's value-creating logic as an intensive technology seems logical. We will, as a result, proceed to the development of the Value Shop model itself.

Value Shop model representation

The Value Shop model has a different description of the primary activities than the Value Chain but keeps the same supporting activities, the first being *infrastructure*. Often, this activity includes general management, planning, financing, accounting, legal and government affairs, and quality management. This is the case in the MM section, and the section leader mainly performs the tasks. Some staff members also carry out some tasks such as customer relations management.

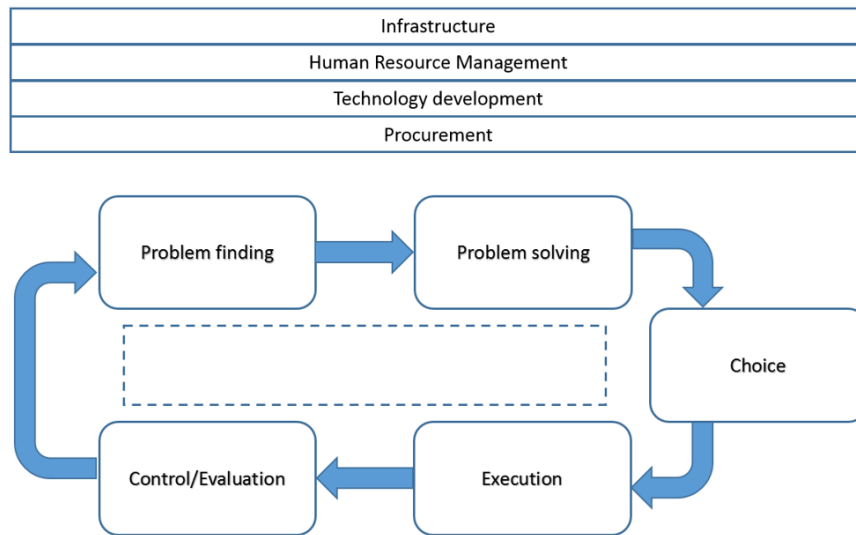


Figure 5.8: Value shop model as proposed by Fjeldstad & Stabell (1998)

The human resources management (HR) is done partly by the staff and section leader, and partly by the centralized human resources department at CERN. The MM section chooses potential candidates, but all applications must pass through the centralized HR department. In addition to this, many of these tasks involve following up the students and fellows as supervisors, defining duties and responsibilities, training, etc. This task is done by most of the staff members as well as the section leader. Each student has one supervisor who is responsible for their development and work.

The technology development activities are essential within the MM section, as new tools have to be developed all the time to satisfy future needs and be in sync with the newest technologies. We will split the technology development in the MM section into two distinct parts. One is the development of tools for immediate needs strongly linked to specific measurements. This will be considered as one of the main activities as we will see later. The second type of technology development is the ongoing more long-term R&D that is done with a longer time frame with future needs of the section in sight. This includes the development of new measurement systems, the analysis, and optimization of existing systems and processes, the incorporation of new information management systems, etc. Students mostly carry out these tasks as part of the research for their degrees. This is also the activity in which I am engaged through my internship. The technicians from the workshop as well as external partners such as technical drawers, 3D

printing services, etc. are strongly involved in this activity. This is a critical function in the section, as it allows it to continuously improve its technology, optimize processes and anticipate future needs. The problem-solving logic here is the same as the one we will see in the main activities but are ignored here as they are not directly linked with specific measurements.

Finally, the task of procurement is one that is distributed among most members of the MM section. This is done via a service at CERN called the Internal Purchase Requisition or DAI (Demande d'Achat Interne). There is a standardized process that allows authorized personnel to purchase items or services outside CERN. All needs for raw materials and equipment in the section are therefore submitted through DAI by the section, and the responsible person does the delivery and follow-up of these in the section.

The primary activities are modeled as a cyclical process with steps that closely resemble those used in project management [PMI, 2004]. The steps of the Value Shop are problem-finding and acquisition, problem-solving, choice, execution and control/evaluation. These will be applied to the core activity of the MM section, namely measurements, before including the other primary activity of system development.

The first thing that happens in a measurement cycle is that the section receives a measurement request through a "ticket" submitted through Infor EAM, an Enterprise Asset Management system adapted for this purpose, where the magnet is linked to the Engineering Equipment Data Management Service (EDMS) at CERN and a database called NORMA. EDMS allows to store, manage, organize and distribute large amounts of engineering information, and was built to facilitate the management of data in the LHC project in the 90s [CERN, 2017a]. Requests come mostly internally from CERN as part of the magnet life-cycle described earlier (Figure 2.4), but can also come from outside labs such as CEA, MedAustron, and INFN. This is handled by a staff member responsible for client relations. He reviews the request and affects a responsible *Magnetic Measurement Engineer (MM Engineer)* that effectively becomes the project manager of that measurement. This MM Engineer has the responsibility for planning, executing, documenting and delivering the measurement. This affection is often done through the Measurement Coordination Meeting (MeCoM), organized every two weeks. The engineer might arrange a meeting with the client to discuss the request and adapt it if necessary. This meeting might be joined by an expert like a physicist from an experiment or accelerator that is linked to the magnet. A document with the final measurement terms is then made, and the next step of the process can begin. In the Value Shop model, this is the *problem finding and acquisition* activity.

When the measurement needs have been established, the MM Engineer has the task of finding an adapted measurement solution for the particular case. This would be the *problem solving* step of the Value Shop model. This activity involves considering several technical possibilities such as the use of a current system, the adaptation or re-calibration of an existing system, or the development of a new one. Aspects such as time, costs and resource allocation have to be taken into account to optimize the choice. This forces the engineer to make a detailed plan of the

measurement. The measurement benches and other resources are also used by other projects, which means that the engineer has to make sure they are available, plan accordingly, and book them when necessary through an internal system.

When several options have been considered, the MM Engineer has to make a *choice*. This is a very short but critical task in the measurement process. After this work, the measurements can begin. However, if the choice requires the design of a new tool or the adaptation of an existing one, the measurement engineer requests it from the responsible for the design at the MeCoM. The proposed measurement tool can also be discussed with other experts through this meeting. If there is a need for a calibration of an existing device, the measurement engineer has to reach out to the person responsible for manufacturing and calibration. After these external tasks have been completed, the measurement process continues. We will come back to the details of these tasks in the next sub-section of this chapter.

The next step of the process is the *execution* of the measurement itself. The MM Engineer does this with assistance from technicians who help set up the measurement benches and magnets. Some of the magnets weigh several tons and therefore need to be handled with massive cranes that only can be used by certified people. Measurements can last between just a few hours and several days or weeks depending on the magnet and type of measurement. Before executing the measurement, the engineer needs to compute the Sensitivity factors of the measurement tool. This is done based on the information that comes from calibrations. These factors allow the MM Engineer to transform the measured data into magnet characteristics. After the measurements have been completed, the engineer has to analyze the data via post-processing to deeply understand its behaviour and characteristics. This can take weeks, but will indicate whether or not the magnet is within requirements.

Rigorous quality control of the measurements to ensure their correctness and consistency are finally very important and are done in the *quality check* step. The client is often involved in this step to make sure that the results are reaching expectations. If any issues are detected through post-processing or discussions with the client, several scenarios are possible. If there is a doubt about the correctness of the measurement, a new cycle of measurement can be started. The cycle will then be repeated with adaptations in order to make sure error sources are canceled out. New equipment or re-calibrations might be necessary in this case. If the errors are unacceptable and are found to stem from the magnets themselves, these can be sent to be repaired or replaced. If it is fixed, the measurement will continue automatically with new cycles through the measurement loop. However, should the magnet be changed, this would cause the interruption of the measurement, requiring the client to make a new request later. The errors found are sometimes judged to be acceptable, in which case the measurement is validated. Documentation is then created by the MM Engineer, which is handed over to the client and archived in a document management system.

In the Value Shop model (Figure 5.8), the cyclical nature of the main activities is captured

by a circular layout. It is also pointed out by [Stabell and Fjeldstad, 1998] that the value to the client is estimated by the success ratio of the mission, as well as by its convenience to the client. This means that the value is in part a function of the number of cycles through the problem-solving loop as well as their duration, which gives a good indication as to how to optimize the value-creation in the MM section.

Value Shop model extension

The shape of the model allows for several of these shop cycles to be put one into the other to illustrate the linkage between several sub-shops in one firm. In the case of the MM section, two separate workshops have been identified that make up its main activity. The core business is naturally the magnetic measurements described earlier. However, a sub-shop is used when a new tool has to be designed, manufactured or calibrated. This is called the *System Development Shop*. The reason for this separation in the modeling is the nature of the problem-solving logic in the two shops. In the Measurement Shop, the main goal is to provide a diagnosis about the magnet for the client. In contrast, the goal of the System Development Shop is to design and develop a quality product for its client, which could be considered to be the MM Engineer.

The core mission of the MM section remains the magnetic measurements. To illustrate this, we put the Measurement Shop at the center of our model. The System Development Shop is a blocking sub-process of the main activity, meaning that if it stops, it stops the rest of the measurement process. This is also the reason why the choice was made to render the system development explicit in the primary activities instead of the supporting ones.

Looking at the developed model (Figure 5.9 and Appendix C), we see that both shops have the same cyclical and iterative nature. However, there are also movements between shops. This is to illustrate the fact that certain steps of the process require sub-letting certain activities to other shops before the work can be resumed. This happens at the point where a measurement plan and method have been chosen, and there is a need for the development of a new system or the re-calibration of an old one. When the development has been completed, the activity of the measurements shop resumes at the execution phase. Even though it is not part of the original Value Shop model, certain supporting parties have been added on the sides to illustrate their strong link to certain steps of the process.

System Development Shop

When the MM Engineer has made the choice of a measurement method, and this requires the re-calibration of a tool or the development of a new one, we enter the System Development shop. The first step here is to define the requirements of the new system. In the case of the development of a new system, a Technical Engineer is assigned to be responsible for the new system through a MeCoM meeting. A second meeting is arranged between him and the MM Engineer to define the needs in a detailed manner. If the requirement is simply to adapt or re-calibrate an existing

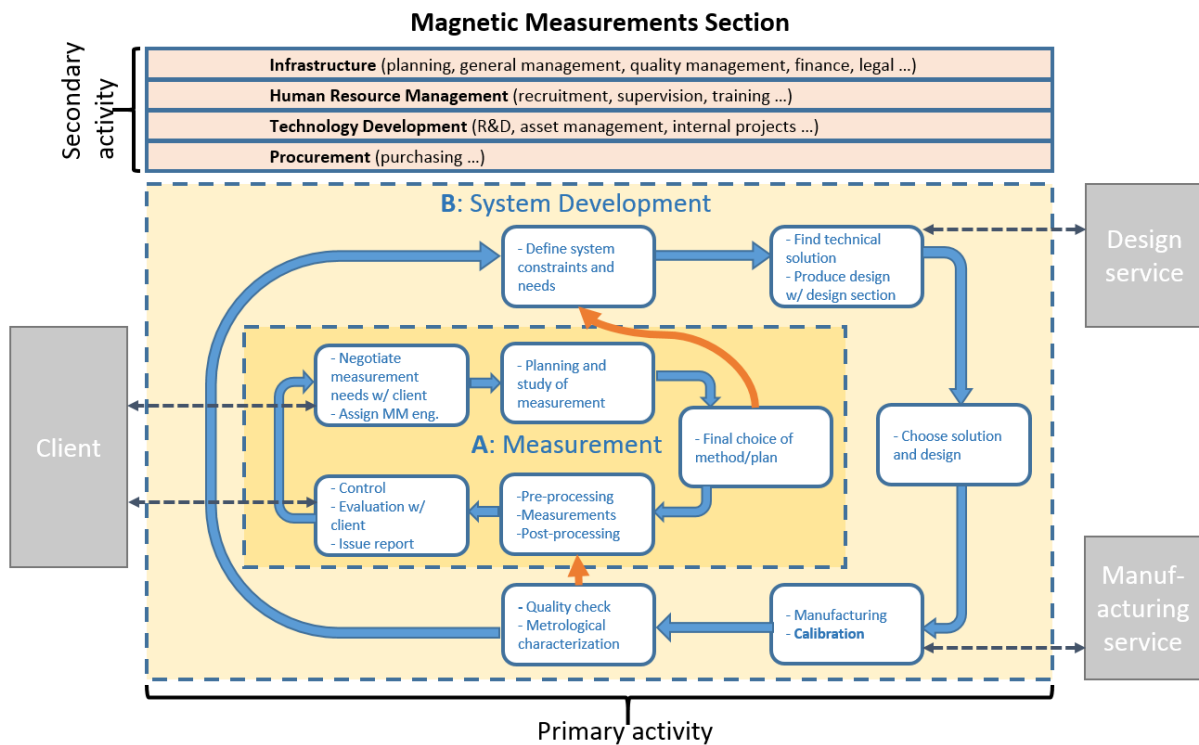


Figure 5.9: Value shop model of the MM section. Full page version can be found in Appendix Figure C.1

tool, the Head Technician responsible for the manufacturing workshop and the Measurement Engineer directly interact to define the needs.

Next, a search for the best adapted technical solution begins. For the development of new tools, this means looking for possible system designs that could be best adapted to the needs. When a good solution has been found, another section at CERN is contacted to produce the actual design in the form of technical drawings. The Head Technician responsible for manufacturing and calibration is ideally also included in this step as an expert on mechanics and manufacturing to make sure the designs are realistic. With a satisfactory design at hand, the choice is made, and the manufacturing can begin. In the case of an adjustment, this step is much quicker, and different solutions for mechanical changes are then considered. For a re-calibration, this step is used to define the technique and tools needed for the calibration.

In the execution phase of the System Development shop, the tool is manufactured and calibrated. We consider the output of this step to be a tool ready to be validated, so both the manufacturing and calibration is necessary. This is a task where the Head Technician's workshop, a staff member, is responsible. He receives the manufacturing requests from either the Technical Engineer or the MM Engineer through a specific request form on the MM section's website. A technician is then attributed to perform the manufacturing in the workshop. Most of this work is done in the workshop, but some parts occasionally have to be outsourced to either another section at CERN such as 3D printing or complex manufacturing, or to an external company. In the case of external outsourcing, the work is possibly submitted to tender in all CERN member states.

When there are several incoming calibration and manufacturing requests, the Head Technician has to manage the prioritization between these, the allocation of workforce, and the scheduling.

When the manufacturing is completed, it is time for the calibration and initial quality tests. The tools go through mechanical and electrical tests to measure some of their characteristics and check for errors such as short-circuits and mechanical weaknesses. After that, the tools undergo a calibration procedure in which their geometric characteristics are precisely determined. This is a very important step as it links the output signal of the tool to real physical units. Some of the most used measurement tools are called Rotating Coils, which are long shafts which are rotated within a magnet to determine its characteristics. These shafts are made out of several segments, which in turn are made of several coils. The System Development loop has to be applied to each of these parts and, therefore, has to be passed through several times for the development of a single finished Rotating Coil.

Once the final product manufactured, checked, and calibrated, the tool is sent back to the MM Engineer to perform a final quality check and metrological characterizations before starting the measurements. However, in the case of a technical problem with the calibration or manufacturing, this has to be fixed with a new cycle around the development cycle to diagnose the problem and solve it. If the problem is with the calibration or the manufacturing, this is handled by the technicians in the workshop. If it seems to have something to do with the design, the Technical Engineer responsible for the tool is called, potentially along with someone from the design section, to adapt the design. If the problem remains, the MM Engineer investigates the problem further, and can potentially result in a change of measurement requirements or an alternative measurement technique.

5.3.3 Problem analysis

If we now re-examine the issues we highlighted in Chapter 4, we can put them into context with the new model to get a better sense of their impact.

Several of the issues we discussed affected the calibration step of the procedure in different ways. The manual tasks can result in the entry of wrong information into one of the many data entry points. This can sometimes cause significant delays, as debugging is very difficult. I witnessed these types of errors on multiple occasions, which resulted in several days of accumulated delays. An error can cause a single step to take much longer time to complete, but can also cause problems in subsequent steps of the process. This can cause several new iterations around both the Measurement Shop and the System Development Shop. As was established earlier in this chapter (Section 5.3.2), the value-creation efficiency of a Value Shop is directly linked to the time each step takes and to the number of cycles necessary to deliver the final product. The errors caused by manual tasks therefore directly impact the efficiency of the MM section, and their elimination through a new software was, therefore, an important step.

Furthermore, the resource interdependence between calibration and specific R&D projects can have a similar impact. If someone uses a tool needed for the calibration such as an aluminum tube or an instrument, their settings can sometimes be changed or even be damaged. This can cause a lot of delays and errors that go undetected for a while in a similar way to the manual tasks. Acting on these points would, therefore, increase the value-creating efficiency of the section.

Furthermore, risks related to the integrators, the old software, or the lack of knowledge transfer to operate calibrations, generate single points of failure with clear impact on the Value Shop. If any of these failures were to happen, calibrations would stop - heavily impacting measurements. The steps are all interdependent and sequential in the sense that the previous one is needed to perform the next one. Therefore, if one task is compromised, so is the rest of the process. Prevention measures should be taken to reduce the impact of these events, as described in Sections 5.1 (calibration software and knowledge transfer) and 5.2 (integrator).

Finally, the efficiency of information transition between different tasks is also closely related to the time required to cycle through the problem-solving loop of the Value Shop. The development and deployment of an Asset Management System that would take care of all the information needed by the different steps centrally, avoiding manual or email handovers, would further increase the value-creating efficiency of the MM section.

5.4 Summary

This chapter detailed the work done on three tasks that were my main contribution to the MM section through my internship: The development of a new calibration software, the feasibility study of a potential new integrator, and the development of a process management model. Although the feasibility study did not lead to a final positive solution, the work resulted in two products that were ready to use - the Value Shop model and the calibration software. Still, all three tasks gave a good basis for further development.

As an attempt to make the knowledge transfer between calibration operators easier by transforming tacit knowledge into explicit knowledge via video was achieved at the end of my internship. Due to the fact that video production is a long process, and to the limited duration of my internship, I only had the opportunity of producing some parts of it and defining other paths for further work.

The calibration software developed and the investigation of a new integrator resulted in a large quantity of C++ code, with approximately 6500 lines of code spread over 5 scripts with corresponding GUI files and 5 driver classes with corresponding header files. An overview of some of the resulting code structure as well as a code example can be found in Appendix E.

Conclusion and suggested future work

6.1 My work

Through the internship at CERN, an assessment of problem areas within the Magnetic Measurements Section, with a particular focus on the calibration process for Rotating Coil sensors, was done by interviewing people, participating in work processes, and studying and investigating documentation. This resulted in a series of potential solutions that could solve several of the problems that were detected.

Two of these solutions ended up being the focus of my engineering work. The first one was the implementation of a new and better software to operate the calibration procedure, which greatly simplified the procedure and removed many sources of error. This work resulted in a ready-to-use software that will be used by the technicians operating the calibrations from now on. It required the development of several software scripts, the development of new hardware drivers, and much iterative work. A theoretical analysis was also done to verify some of the mathematics behind the calibration procedure. The second point aimed at exploring the potential of using a commercial multimeter as a replacement of the hardware used to acquire the integrated voltage of the Rotating Coils during calibration. This would avoid several potential risks associated with the old in-house developed hardware, and make calibrations more accurate. Although many steps were done to optimize the Multimeter for the required use case, there is still a possibility of investigating some other aspects deeply to find a definitive conclusion on the feasibility. This will require further investigations beyond the scope of this internship.

A management-related task also resulted from the preliminary assessment. The goal of this task was to develop a model describing the MM section's processes clearly. No such model existed previously, so its development would make it easier for existing staff and newcomers to understand their relation to other members of the section. The goal was also to have a framework

for analyzing the problems of the sections and propose potential solutions to these. This model was presented at a MM section meeting, and was well received [Ould-Saada, 2017].

6.2 Future work

Although this internship was very productive, many potentially interesting tasks remained undone due to limited time. These could be pathways to follow for future work by other students or staff at CERN.

First, a new database that allows for the seamless communication among programs and in delivering the final results would be very valuable. Some tasks requiring the manual input of data still remain before and after the calibration, meaning that there is still some sources of error that could falsify a calibration. Integrating a database with information relating to all coils, segments, and shafts would make the calibration work much easier by only requiring the operator to enter some minor initial settings before starting the calibration. The information about dimensions could be entered in the database during the conception of the mechanical design to avoid the loss of information when communicating the details from design to manufacturing and calibration. The database would also ensure a better tractability of each system's history, which would result in less unknown factors and repeated work. Having written the new software with future implementations such as a database in mind, it is well adapted for this extension. However, designing a correct and suitable database structure that can support the MM section's needs for the foreseeable future is a critical task that will take a lot of work.

Next, the new calibration procedure still requires the operators to rotate and translate the coil systems within the reference magnets manually. This induces several sources of error, for example, because of the variable time it takes to perform a rotation. This causes the integrators to accumulate different amounts of drift for each operation, which induces an additional source of uncertainty. Furthermore, the mechanical mounts that are used today are not as rigid and accurate as they were when built because of degradation over the years. The use of a new mechanical mount which is better designed to avoid uncertainties, along with the use of robotics to automate the manual tasks, would also reduce the uncertainties of the measurements. It would also free up the technicians to focus on other aspects of their work as only one technician would be necessary to set up the procedure, and only supervision would be needed for the rest of the calibration process.

A further analysis of the possibility of using the Keithley 3458A multimeter as a signal integrator would be interesting. The existing integrators are very accurate, but have many limitations. The use of a new technology that does not have those limitations would significantly increase the accuracy of the calibration procedure, and possibly make its further automation easier. With limited time, I could not complete this study to the point of a conclusion, but a transition meeting was organized to pass on the work to a Ph.D. student.

Through the reexamination of some of the mathematical theory behind the calibration procedure, we realized that most of its sensitivity and uncertainty analysis had been lost since its creation many years ago. A full reexamination of the mathematics behind the procedure to determine where most of the uncertainties come from would be beneficial. It would allow these uncertainties to be taken into account in the future redesign of the procedure to make it as precise as possible.

In 1990, management author and former professor of computer science at MIT, Michael Hammer, published the paper "Reengineering Work: Don't Automate, Obliterate" [Hammer, 1990] in Harvard Business Review. He argued that most companies used information technology only to automate existing tasks that were not in themselves value-creating. He urged them not to automate superficial tasks, but to obliterate them, leaving room for more efficient processes and the use of human judgment [McAfee and Brynjolfsson, 2017]. This case was reinforced by the book "Reengineering the Corporation" [Hammer and Champy, 1993], urging companies to look at their work as business processes rather than different departments doing separate tasks. This could be a good lesson to have in mind for further work on the calibration process. The work I have done could be considered merely automating existing tasks. The rest of the process is still the same, and the output as well. By incorporating some of the ideas about database integration and mechanical automation mentioned above, and keeping the concepts of re-engineering in mind, the calibration process could become much more efficient. This would result in a process where the operators no longer need to spend much time doing manual and repetitive tasks to calibrate coil systems, and could rather focus on other important tasks. As there have been issues with the technicians feeling like they get more work requests than they can handle, this re-engineering could be an important step towards solving that problem. The more natural data flow between different tasks, as described by the Value Shop model in this report (Figure 5.9), would also make the calibration process a more natural part of the whole system development process rather than being a separate task. This could result in further positive effects on the section as a whole.

Finally, a detailed strategic and organizational analysis of the way work is attributed and prioritized within the MM section, resulting in new structures and procedures, would be beneficial. This would primarily be to respond to the problems I have experienced in the communication among the technicians and the engineers and students of the section. The technicians have the responsibility for prioritizing their tasks, but this has caused many problems as they do not have sufficient knowledge about the relative importance of tasks. This has caused a lot of misunderstandings and challenges, so moving the decision point from the technicians to the engineers or the section leader, who have a better holistic view of the section's activity, would be beneficial. Furthermore, standard procedures for what information needs to be communicated to the technicians when requesting different types of work would also avoid many misunderstandings.

6.3 Final reflections

The internship at CERN allowed me to explore a range of fields and was both challenging and enriching on many different levels. I was fortunate to work on tasks strongly related to the primary activity of the MM section, and some of my work will hopefully be used as part of the procedure for measuring magnets at CERN. The enhanced calibration program developed will hopefully make the calibration part of the measurement process easier to operate and contribute to the upgrade of the Large Hadron Collider, High-Luminosity LHC. I also believe that my work on process management contributed to uncover potential for further development of the section's processes, as solutions to some of the issues I have discussed have already been discussed by the section leader and staff members at a section meeting.

As an engineering student, I had to use much of my knowledge from five years of studies to complete my work. First of all, I had to recall and extend the knowledge I had about electromagnetism and Fourier analysis from my studies to understand the theory of magnetic measurements. This took a considerable amount of time but was very enriching. Furthermore, I had to use skills such as C++ programming, instrument interfacing via different communication protocols, mathematical optimization, algebra, calculus, geometry, numerical analysis, analog and digital electronics, and more. Using these tools together in the context of solving a particular engineering problem was very satisfying, and made me realize how much I have learned over the course of my engineering degree. CERN provided training that was both directly related to and exceeded my work. As I was working with very high currents (up to 400 A in the reference magnets), I had to do a safety course in electrical systems. This took three full days and taught me several concepts in the field of electrical systems. Moreover, I attended several "Academic Training Courses" provided by CERN in areas such as industrial and medical applications of particle accelerators, and in machine learning. A senior scientist from Google also gave a guest lecture in deep learning. As CERN is a major research center in particle physics, I was pushed to read up on related fields in physics. This gave me an outlook on other fields than my own, which I found very inspiring.

As a management student, I also found this internship to be very formative. Most of my experience studying management has been with for-profit organizations in focus, hence, it was very interesting to get experience at a non-profit research organization. Many concepts from courses in innovation strategy, project management, marketing, and entrepreneurship inspired my reflections around the section's process management. I also had to learn many new concepts and read a large number of papers on process management, automation, re-engineering, knowledge transfer, business modeling, organizational analysis, and more. Although not everything ended up as part of my final work, it greatly inspired me and taught me a lot about the importance of good management in research organizations.

Combining managerial and engineering aspects was very interesting as it allowed me to

get a holistic view of what it takes to optimize a company. Starting with getting the overview of the section, understanding where the problems are, analyzing different solutions to these problems, and then implementing a solution was a very satisfying way to incorporate both my fields of study into one internship. I believe it is essential to be able to see things from several perspectives, and having worked with both engineering and management aspects has allowed me to do so.

As a final professional experience before entering the professional world as a graduate, this internship has been an enjoyable and formative experience. I was well received at CERN, and have had an excellent supervisor who has guided me through my work here. Working with and meeting people from all over the world, speaking different languages, and working in a range of different fields at a leading research organization has been a truly inspiring experience. Having worked closely with both my areas of study in close relation to each other made me realize the power of combining the overview gained by management analysis along with the engineering implementations to develop efficient solutions that make a difference.

Finally, my experience at CERN has made me reflect on new potential aspects of my future career. The work done in the Magnetic Measurements Section is a small step in the process of building, maintaining, and upgrading one of the most impressive instruments ever made by humankind. Although it has been awe-inspiring to work on parts of a project whose final goal is to answer deep questions such as what the universe is made of and how it started, I realized that I have a real fascination for working with technological applications that have a more immediate impact on society, as well as being more implicated with the final product. I will therefore start my career doing product development for a start-up company. Having worked in a research environment has, however, triggered my interest in potentially doing a Ph.D. later on.

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CERN and the Magnetic Measurements Section

A.1 CERN

A.1.1 History

After the Second World War, the state of science in Europe was no longer at the level it used to be with many scientists having fled to other countries, especially the US. In order to unite the European countries after years of fighting and to bring back world-class science, several scientists including Niels Bohr, Edoardo Amaldi, Raoul Dautry, Lew Kowarski and Pierre Auger started to imagine creating a European atomic physics laboratory. The first proposal to create such a lab was put forward to UNESCO by Louis de Broglie in December 1949. By the beginning of 1952, 11 countries had signed the first resolution for establishing the European Council for Nuclear Research, and the acronym CERN was born. The lab was then constructed in Geneva due to its centrality in Europe and international history. The official creation of the laboratory happened the 20th of September 1954 with 12 member states under the official name of European Organization for Nuclear Research [CERN, 2012a].

Since then, CERN has been the home of several scientific breakthroughs in the field of particle physics such as the observation and creation of antimatter, the discovery of W and Z bosons, the mediators of the weak nuclear force, and lately the discovery of the Higgs Boson in 2012 which resulted in the 2014 Nobel Prize in physics. All this in an attempt to better understand the fundamental structure of our universe. In addition, the technological development required to make these discoveries also resulted in several technical breakthroughs. CERN technologies have, among others, been used in medical and aerospace breakthrough applications. The World Wide Web's (www) basic concepts were developed at CERN by Tim Berners-Lee in 1989, and the first website and web server were run there by the end of 1990 with the address info.cern.ch. What we commonly know as the Web was hence born, and the world has never

been the same ever since [CERN, 2012a].

A.1.2 Accelerator complex

CERN has a large number of particle accelerators that work together in order to accelerate particles nearly to the speed of light (Figure A.1). In succession, these accelerators increase the energy of beams of particles before injecting them into the next one. From an initial source in the form of a hydrogen bottle, protons are extracted and injected into the Linac 2 linear accelerator. Next, the Proton Synchrotron Booster (PSB), the Proton Synchrotron, and the Super Proton Synchrotron (SPS) accelerate the protons to an energy of 450 giga-electronvolts (GeV) [CERN, 2012d].

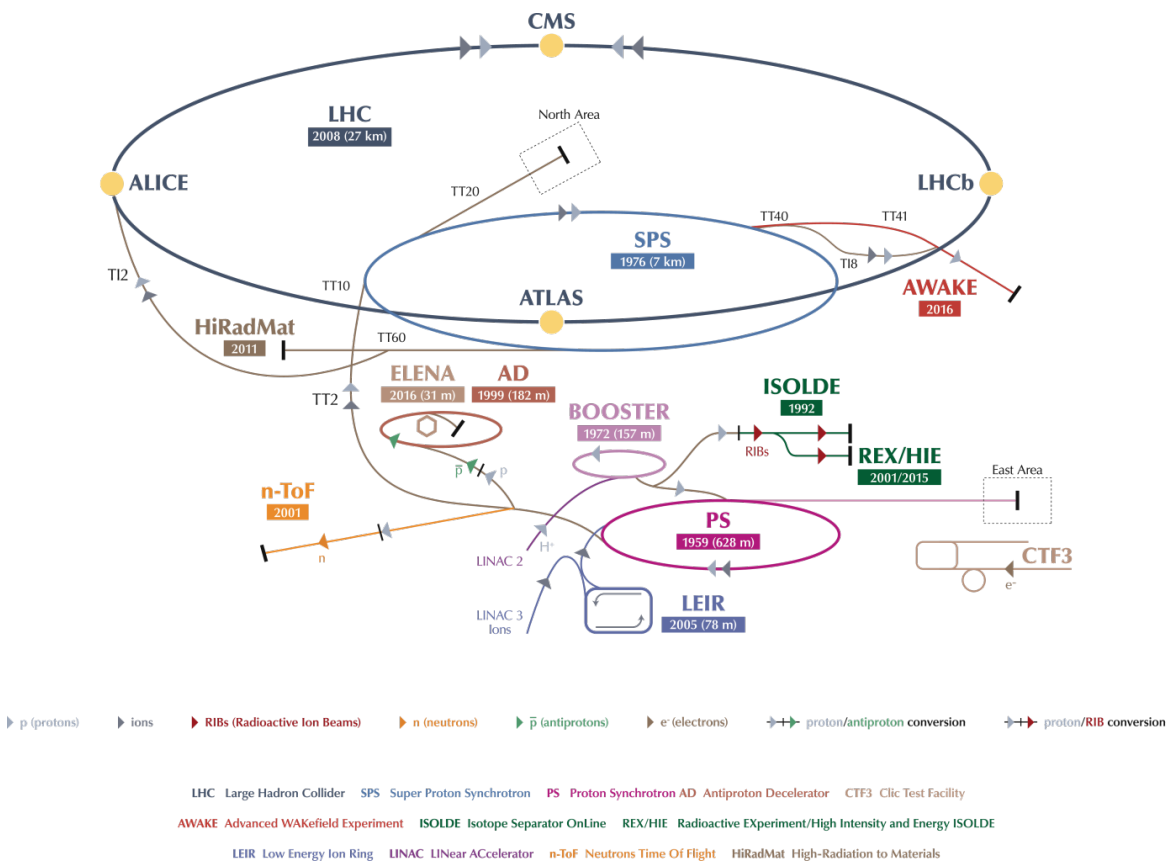


Figure A.1: CERN Accelerator Complex (source CERN)

Finally, the protons are transferred into the two beam pipes of the Large Hadron Collider (LHC). The proton beams go in opposite directions around the LHC until reaching a maximum energy of 6.5 tera-electronvolts (TeV) before being collided together. With its 27-kilometer underground ring of superconducting magnets and accelerating structures on the border between France and Switzerland, it is the world's largest and most powerful particle accelerator. Its tubes are kept at ultrahigh vacuum and at a temperature of -271.3°C or 1.85 kelvin, which is colder than in outer space. This is in order to allow the 1232 dipoles and 392 quadrupole superconducting magnets to generate a strong magnetic field of up to 8 tesla to guide the beam.

The dipole magnets are used to bend the beam in the circular form of the LHC, the quadrupole magnets are used to focus the beam, and radio-frequency cavities are used to accelerate the beam [CERN, 2017b].

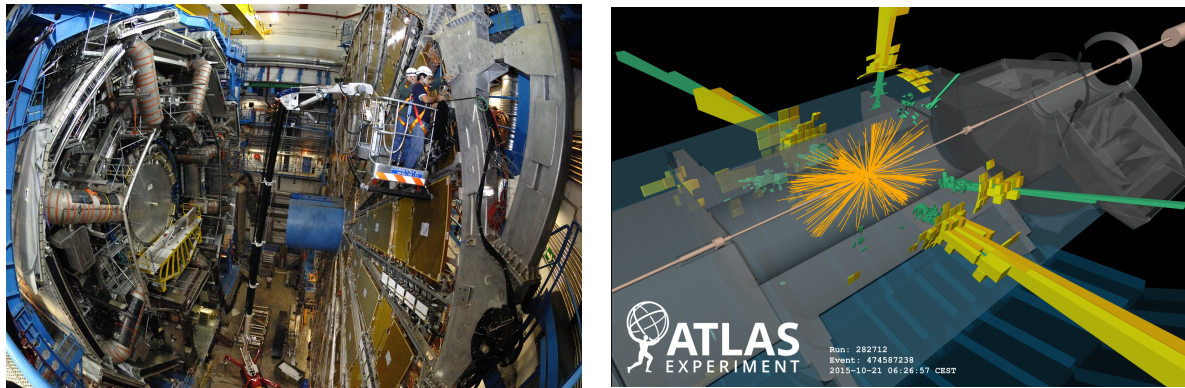


Figure A.2: Left: Construction of the Atlas detector. Right: 3D model of a particle collision in Atlas (Source CERN)

When the particles have reached their maximum energy, they are collided at four collision sites. Around each collision site, a particle detector analyses the stream of particles resulting from the collision. Each of these are run by separate experiments that have different goals. The ATLAS and CMS experiments are the largest ones, and aim at investigating a large range of physical phenomena (Figure A.2). They are based on complementary detection techniques are used to cross-check new discoveries. The ALICE (heavy ion collisions) and LHCb (Bottom quarks) experiments focus on more specialized phenomena. These detectors also use large magnets to measure the mass and charge of the generated particles [CERN, 2012c].

With approximately 600 million collisions every second, an impressive amount of data has to be acquired, stored and analyzed in order to search for new physics and rare phenomena. To analyze the data more efficiently, CERN uses the Worldwide LHC Computing Grid (WLCG), which allows computers from all around the world to collaborate in analyzing the data. This Grid builds on technology from the World Wide Web, which was invented at CERN in 1989 [CERN, 2012b], and allows a sharing of computing resources in addition to information.

In order to increase the potential for new discoveries, the LHC has planned an upgrade called the High-Luminosity LHC. This aims at augmenting the luminosity of the beam which is an important performance indicator in accelerators. This is proportional with the number of collisions taking place every second. The result of this is more data for the experiments to analyze, allowing the detailed analysis of new particles such as the Higgs Boson. The plan is for the HL-LHC to be operational by 2025. This upgrade requires the development of new magnets of up to 11 tesla, which requires innovations in magnet design, cryogenics, measurements and more [CERN, 2015]. My section at CERN is involved in this work, and so were my contributions during the internship.

A.1.3 Organization

The highest authority in the organization is the CERN council. It is made out of two representatives from each of the 22 member states. One represents the government's administration while the other represents the countries scientific interests. They are assisted by the Scientific Policy Committee and the Finance Committee. The council is charged with appointing a Director-General for periods of 5 years. This person is charged with running the CERN laboratory, and is assisted by a directorate. The CERN laboratory is then divided into 10 departments which are run by each their head [CERN, 2012e].

In the case of my internship, I have been working within the Technology (TE) department. Its mandate is to develop technologies which are specific to existing particle accelerators facilities and future projects. This responsibility includes different types of magnets like normal conducting, superconducting, fast pulsed and more, the integration and protection of these magnets, power converters, cryogenics, vacuum systems, coatings and surface treatments [CERN, 2017c].

Furthermore, my work is done within the Magnets, Superconductors and Cryostats (MSC) group of the TE department. It is responsible for the design, construction, measurement and quality control of accelerator magnets, the integration in the CERN accelerator complex, the support to operation of the accelerators for magnets, and the development of technologies for present and future accelerators.

More specifically, I have been part of the Magnetic Measurements (MM) section. This section is responsible for performing high quality magnetic tests of magnetic devices for the accelerators at CERN and other external parties. Like all sections at CERN, it has a section leader who is responsible for the overall activity as well as a team of permanent staff members that are responsible for specific activities within the section. These are mostly engineers with PhDs in electrical or mechanical engineering. In addition, the section has a large amount of temporary staff. These are mostly students pursuing BSc, MSc or PhD degrees as well as fellows, with contracts normally between 6 months and 3 years. Under supervision of the permanent staff, these students mostly work with the development of long term RD projects while the permanent staff is responsible for the more time sensitive core tasks of the section. The section has a group of technicians who are responsible for manufacturing and calibration of measurement tools as well as the execution of some measurements. They are hired from an outside company due to CERN staffing regulations, and are under the responsibility of one of the permanent staff members.

Theory of Magnetic Measurements

B.1 Accelerator basics

Particle accelerators were first invented in the 1930s to make advancements in nuclear physics. They are now an important tool in particle physics research, as well as in medicine, manufacturing, and other fields. Either in the form of a ring or a linear structure, particle accelerators accelerate and guide a beam of particles in order to perform a specific task. At CERN, a sequence of linear and circular accelerators are used, some of which provide a pre-accelerated particle beam to the LHC, which itself is a circular accelerator. When the particles achieve high enough energy with two beams turning in opposite directions, they are collided against each other. The resulting stream of particles is then analyzed by large particle detectors with the goal of understanding the underlying physics, and solve some of the mysteries in the universe [Golluccio, 2012] [CERN, 2017b].

Common for all types of accelerators is the central role of electromagnetism. Radio-frequency cavities are used to accelerate particles with an electric field, and magnets are used to guide or focus the beam with magnetic fields. Central to this dynamics is the Lorentz equation:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (\text{B.1})$$

This equation describes the electromagnetic force $\mathbf{F}$ exerted on a particle of charge q by the electric field $\mathbf{E}$ and the magnetic field $\mathbf{B}$ while travelling at speed $\mathbf{v}$.

An electric field can therefore be used to accelerate particles. In order to maintain a focused beam, a series of quadrupole magnets with alternating polarity are used to compress the beam axis by axis. Dipole magnets are then used to curve the beam around the circular accelerator.

B.2 Field harmonics

The description of accelerator magnet quality is often based on its so called field harmonics or multipole coefficients. These are found through the Fourier coefficients of the magnetic field [Petrone, 2013]. When these harmonic factors are calculated, the quality of the field can be determined by computing the harmonic distortion factor. In this section, I will describe the theory behind the measurement of field harmonics. The calculations will be based on the book "Field Computation for Accelerator Magnets" by Russenschuck [2010].

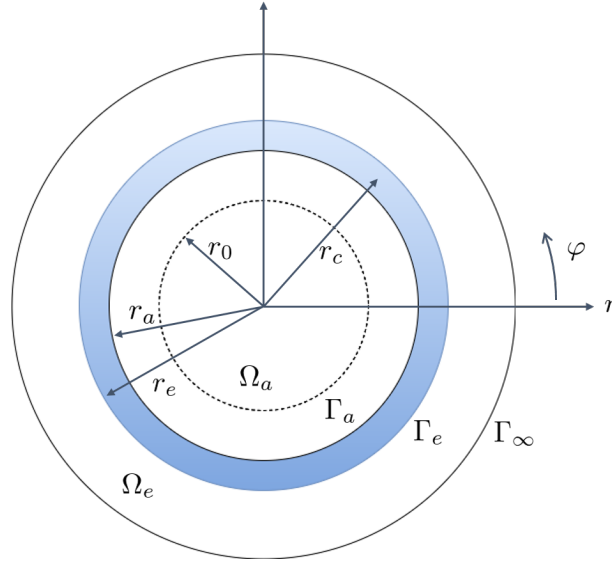


Figure B.1: 2D circular coordinate system describing the magnet aperture and used for solving the boundary value problem. Based on Russenschuck [2010]

We start by solving the Laplace equation for the vector potential A_z in a 2D circular coordinate system described in Figure (B.1). This coordinate system is well adapted to describe the aperture of an accelerator magnet. By using the separation of variables method to integrate the Laplace equation, $\nabla^2 A_z = 0$, and comparing it to the boundary values of our problem domain Ω_a , we can obtain the general solution

$$A_z(r, \varphi) = \sum_{n=1}^{\infty} r^n (\mathcal{A}_n \sin n\varphi + \mathcal{B}_n \cos n\varphi) \quad (\text{B.2})$$

The field components can then be expressed as

$$B_r(r, \varphi) = \frac{1}{r} \frac{\partial A_z}{\partial \varphi} = \sum_{n=1}^{\infty} n r^{n-1} (\mathcal{A}_n \cos n\varphi - \mathcal{B}_n \sin n\varphi) \quad (\text{B.3})$$

$$B_\varphi(r, \varphi) = -\frac{\partial A_z}{\partial r} = -\sum_{n=1}^{\infty} n r^{n-1} (\mathcal{A}_n \sin n\varphi + \mathcal{B}_n \cos n\varphi) \quad (\text{B.4})$$

The components $\mathcal{A}_n$ and $\mathcal{B}_n$ of the expressed field are known as *multipole coefficients* or *field harmonics*. These are undetermined at this stage. We can however see that each of the integer values n of the solution of the Laplace equation correspond to a specific flux distribution generated by ideal magnet geometries. The value $n=1$ corresponds to the dipole, $n=2$ to the quadrupole, and $n=3$ to the sextupole flux density distributions. This will be very relevant in the characterization of magnets as they describe different types of magnets used in accelerators and their geometrical purity.

If we now consider the magnetic flux density measured at a reference radius $r = r_0$ as a function of the angular position φ , we can obtain the Fourier series expansion of the field components as follows

$$B_r(r_0, \varphi) = \sum_{n=1}^{\infty} (B_n(r_0) \sin n\varphi + A_n(r_0) \cos n\varphi), \quad (\text{B.5})$$

$$B_\varphi(r_0, \varphi) = \sum_{n=1}^{\infty} (B_n(r_0) \cos n\varphi + A_n(r_0) \sin n\varphi), \quad (\text{B.6})$$

where

$$A_n(r_0) = \frac{1}{\pi} \int_0^{2\pi} B_r(r_0, \varphi) \cos n\varphi d\varphi, n = 1, 2, 3, \dots, \quad (\text{B.7})$$

$$B_n(r_0) = \frac{1}{\pi} \int_0^{2\pi} B_r(r_0, \varphi) \sin n\varphi d\varphi, n = 1, 2, 3, \dots \quad (\text{B.8})$$

$A_0 = 0$ as a result of the lack of divergence in magnetic flux density.

The B_r field components are in practice numerically calculated with N discrete points k in the interval $[0, 2\pi)$

$$\varphi_k = \frac{2\pi k}{N}, k = 0, 1, 2, \dots, N-1 \quad (\text{B.9})$$

We can hence calculate the two times N Fourier coefficients by the *Discrete Fourier Transform* (DFT):

$$A_n(r_0) \approx \frac{2}{N} \sum_{k=0}^{N-1} B_r(r_0, \varphi_k) \cos n\varphi_k, \quad (\text{B.10})$$

$$B_n(r_0) \approx \frac{2}{N} \sum_{k=0}^{N-1} B_r(r_0, \varphi_k) \sin n\varphi_k. \quad (\text{B.11})$$

This establishes a relation between field components and the multipole coefficients $A_n(r_0)$ and $B_n(r_0)$ at the reference radius r_0 . The components $B_n(r_0)$ and $A_n(r_0)$ are called normal and skew multipole coefficients of the field, given in units of tesla.

Field components at any radius r are then given by

$$B_r(r, \varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^{n-1} (B_n(r_0) \sin n\varphi + A_n(r_0) \cos n\varphi), \quad (\text{B.12})$$

$$B_\varphi(r, \varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^{n-1} (B_n(r_0) \cos n\varphi - A_n(r_0) \sin n\varphi). \quad (\text{B.13})$$

where $B_r(r, \varphi)$ and $B_\varphi(r, \varphi)$ are the radial and tangential field components.

It is common practice to normalize the multipole coefficients with respect to the main field component¹ $B_N(r_0)$. The lowercase notation $b_n(r_0)$ and $a_n(r_0)$ describe these components relatively to the main field, and are therefore dimensionless. In case of the radial field component, this gives

$$B_r(r, \varphi) = B_N \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^{n-N} (b_n(r_0) \sin n\varphi + a_n(r_0) \cos n\varphi). \quad (\text{B.14})$$

Applying the trigonometric $(\cos \varphi + i \sin \varphi)^n = (e^{i\varphi})^n = e^{in\varphi} = \cos n\varphi + i \sin n\varphi$, $n \in \mathbb{Z}$, the magnetic field can, in Cartesian coordinates components, be expressed as:

$$B_x(r, \varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^{n-1} (B_n(r_0) \sin(n-1)\varphi + A_n(r_0) \cos(n-1)\varphi) \quad (\text{B.15})$$

$$B_y(r, \varphi) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0} \right)^{n-1} (B_n(r_0) \cos(n-1)\varphi - A_n(r_0) \sin(n-1)\varphi) \quad (\text{B.16})$$

The multipole coefficients are often combined in the complex notation $C_n(r_0) = B_n(r_0) + i A_n(r_0)$.

In accelerator magnets, the normal components indicate a vertical field in the horizontal plane while the skew terms indicate a horizontal field. In Fig. B.2, the field lines for normal and skew dipoles (B_1, A_1) and quadrupoles (B_2, A_2) are shown.

Field errors are given by the relative errors with respect to the main field component B_M at the reference radius r_0

By choosing a complex plane (x, y) , the harmonic can be expressed in terms of the complex variable $z = x + iy$

$$B(z) = B_y(z) + iB_x(z) = \sum_{n=1}^{\infty} C_n(z) \left(\frac{z}{r_0} \right)^{n-1}. \quad (\text{B.17})$$

The field quality, described as relative errors with respect to the main field component B_M at the reference radius r_0 , is given by

$$c_n = b_n + ia_n = \frac{C_n}{B_M}. \quad (\text{B.18})$$

¹This is B_1 for the dipole, B_2 for the quadrupole, and so on.

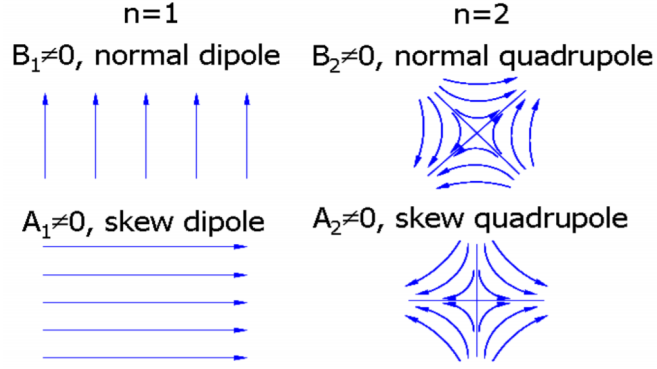


Figure B.2: Field lines of normal and skew dipole and quadrupole magnets: (above-left): normal dipole field lines; (below-left): skew dipole field lines; (above-right): normal quadrupole field lines; and (below-right): skew quadrupole field lines [Petrone, 2013].

This is perfectly in accordance with the magnetic measurement method using Rotating Coils, which will be described next.

B.3 Rotating Coil sensors

At CERN, and specifically for the LHC accelerator, the sensors used for measuring magnets are called Rotating Coils. These allow for measurement of magnetic field harmonic coefficients A_n and B_n by measuring the magnetic flux linked to the angular movement of the coil [Bottura, 1997]. According to the working definitions, we will call a single coil an induction coil. These induction coils are put together to build an array, which can be put into cylindrical form to form what we call a segment. One or several segments are then assembled to form a shaft, which is used for magnetic measurements [Russenschuck, 2010].

This measurement is based on Lenz's law, which dictates that when a conductor loop moves with respect to a magnetic field, a voltage is induced as a result of the flux variation. This flux variation can be a result of either the movement of the coil within the magnetic field, or by changing the field.

By Faraday's law, the change of flux induces a voltage U on the terminals of the coil:

$$U = -\frac{d\phi}{dt} \quad (\text{B.19})$$

In order to measure the magnetic flux, we therefore need to integrate the voltage induced

$$\Phi = -\int_{t_1}^{t_2} U dt \quad (\text{B.20})$$

We can then proceed to calculate the flux $\phi(\varphi)$ linked to the angular position of the coil φ . Assuming that the field is uniform in the z-direction, and that the coil has N turns around the

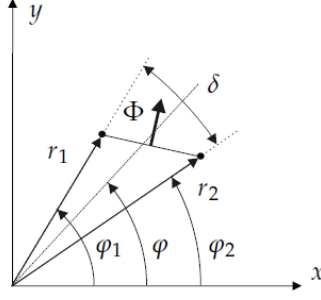


Figure B.3: Naming conventions for reference system)source personal communication with Stephan Russenschuck)

area $\mathcal{A}$

$$\Phi(\varphi) = N \int_{\mathcal{A}} \mathbf{B} \cdot d\mathbf{a} \quad (\text{B.21})$$

where $\mathbf{B}$ is the magnetic field and $d\mathbf{a}$ is the surface element vector. If we assume that the coil is perfectly centered in the aperture of the magnet, and that it rotates around its axis at velocity ω , we can say that the angular position is expressed by $\varphi = \omega t + \Theta$. Θ describes the angle at time $t = 0$.

We can express the flux linkage $\Phi(\varphi)$ by using the radial field described earlier (B.12)

$$\Phi(\varphi) = N\ell \int_{r_1}^{r_2} B_r(r, \varphi) dr \quad (\text{B.22})$$

If we now express this as a series expansion of the radial field, we have:

$$\begin{aligned} \Phi(\varphi) = N\ell \bigg[& \sum_{n=1}^{\infty} \frac{r_0}{n} \left(\frac{r_2}{r_0}\right)^n (\mathcal{B}_n(r_0) \cos n\varphi_2 + \mathcal{A}_n(r_0) \sin n\varphi_2) \\ & - \sum_{n=1}^{\infty} \frac{r_0}{n} \left(\frac{r_1}{r_0}\right)^n (\mathcal{B}_n(r_0) \cos n\varphi_1 + \mathcal{A}_n(r_0) \sin n\varphi_1) \bigg] \quad (\text{B.23}) \end{aligned}$$

We now have a link between the flux that will be measured by the rotating coil and the field harmonics. These harmonics can now be deduced based on the knowledge of the mean radius and the mean surface. This is what we will be looking for in the calibration process, which will be the focus of my work. In order to express this in an easier way, we can rewrite the flux as follows, using the coil-sensitivity factors K_n^{rad} and K_n^{tan} :

$$\Phi(\varphi) = \sum_{n=1}^{\infty} \frac{1}{r_0^{n-1}} [K_n^{\text{rad}} (\mathcal{B}_n(r_0) \cos n\varphi + \mathcal{A}_n(r_0) \sin n\varphi) - K_n^{\text{tan}} (\mathcal{B}_n(r_0) \cos n\varphi + \mathcal{A}_n(r_0) \sin n\varphi)] \quad (\text{B.24})$$

where the radial and tangential coil-sensitivity factors are defined as follows:

$$K_n^{\text{rad}} = \frac{N\ell}{n} [r_2^n \cos n(\varphi_2 - \varphi) - r_1^n \cos n(\varphi_1 - \varphi)] \quad (\text{B.25})$$

$$K_n^{\text{tan}} = -\frac{N\ell}{n} [r_2^n \sin n(\varphi_2 - \varphi) - r_1^n \sin n(\varphi_1 - \varphi)] \quad (\text{B.26})$$

There are two categories of rotating coils that have to be differentiated at this point - tangential and radial coils. If we first consider that we have a tangential coil, we get that $r_1 = r_2 = r_c$, $\varphi_1 = \varphi + \delta/2$, $\varphi_2 = \varphi - \delta/2$. Therefore we have:

$$K_n^{\text{tan}} = \frac{2N\ell}{n} r_c^n \sin\left(\frac{n\delta}{2}\right) \quad (\text{B.27})$$

$$K_n^{\text{rad}} = 0 \quad (\text{B.28})$$

where If we consider a radial coil, we have $\varphi_1 = \varphi_2 = \varphi$, inner radius r_1 and outer radius r_2 and $K_n^{\text{tan}} = 0$. We therefore get:

$$K_n^{\text{rad}} = \frac{N\ell}{n} (r_2^n - r_1^n) \quad (\text{B.29})$$

We will from now on refer only to K_n when talking about the sensitivity factor, assuming that the coil is either purely tangential or radial.

By using the equations (B.17) and (B.22), we can then express the flux linkage as follows:

$$\Phi(\varphi) = Re \left\{ \sum_{n=1}^{\infty} \frac{1}{r_0^{n-1}} C_n K_n e^{in\varphi} \right\} \quad (\text{B.30})$$

where $C_n := B_n + iA_n$ and the complex sensitivity factor is given by

$$K_n = K_n^{\text{rad}} - iK_n^{\text{tan}} = \frac{N\ell}{n} (r_2^n e^{in(\varphi_2 - \varphi)} - r_1^n e^{in(\varphi_1 - \varphi)}) \quad (\text{B.31})$$

The calibration process consists of finding the corresponding K_n values that describe the coil. We have multiple possibilities for doing so. We could do a geometrical measurement of the coil in theory, but that would not yield an acceptable precision (around $10^{-3} - 10^{-4}$) [Buzio, 2009]. At CERN, the measurement of a reference magnet for which the harmonic coefficients are known is used to compute the surface, width and radius of the coil using the measurement and a few known factors. A dipole magnet is used in order to obtain the coil surface and misalignment, and a quadrupole magnet in order to obtain the rotation radius.

Full page Value Shop

This appendix shows a full page version of the Value Shop model developed in this report, see Section 5.3.2 for closer inspection.

Magnetic Measurements Section

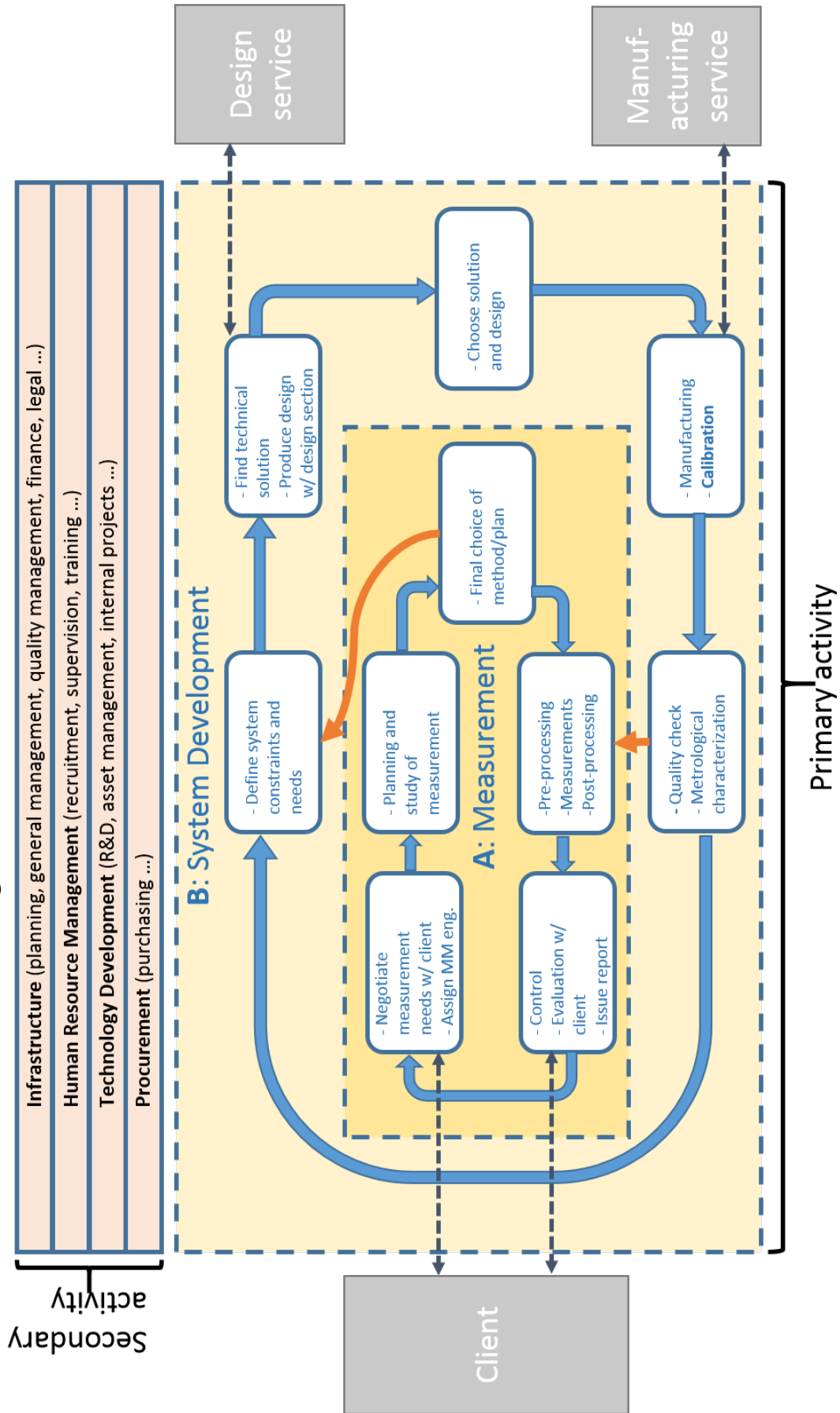


Figure C.1: Value shop model of the MM section

Business Process Modeling Notation

This appendix shows some of the models based on the Business Process Modeling Notation (BPMN) that were generated through my analysis of the Magnetic Measurements Section. They are meant to be illustrative for my analysis process, and not as tools for understanding the section by themselves as they are not readable in this format.

The first model (Figure D.1) describes the work processes associated with a magnetic measurement. Each horizontal box describes different actors within the MM section, and the tasks they have inside them are executed by that person or group. The second model (Figure D.2) describes a part of the calibration procedure in the same way, and the final model (Figure D.3) describes the detailed process of a surface calibration.

These models were very useful to get a schematic overview of different tasks, and as a basis for discussion in the context of informal interviews conducted. Printing them out in large format also allowed me to use them as a framework to reason using a pen to take notes on it.

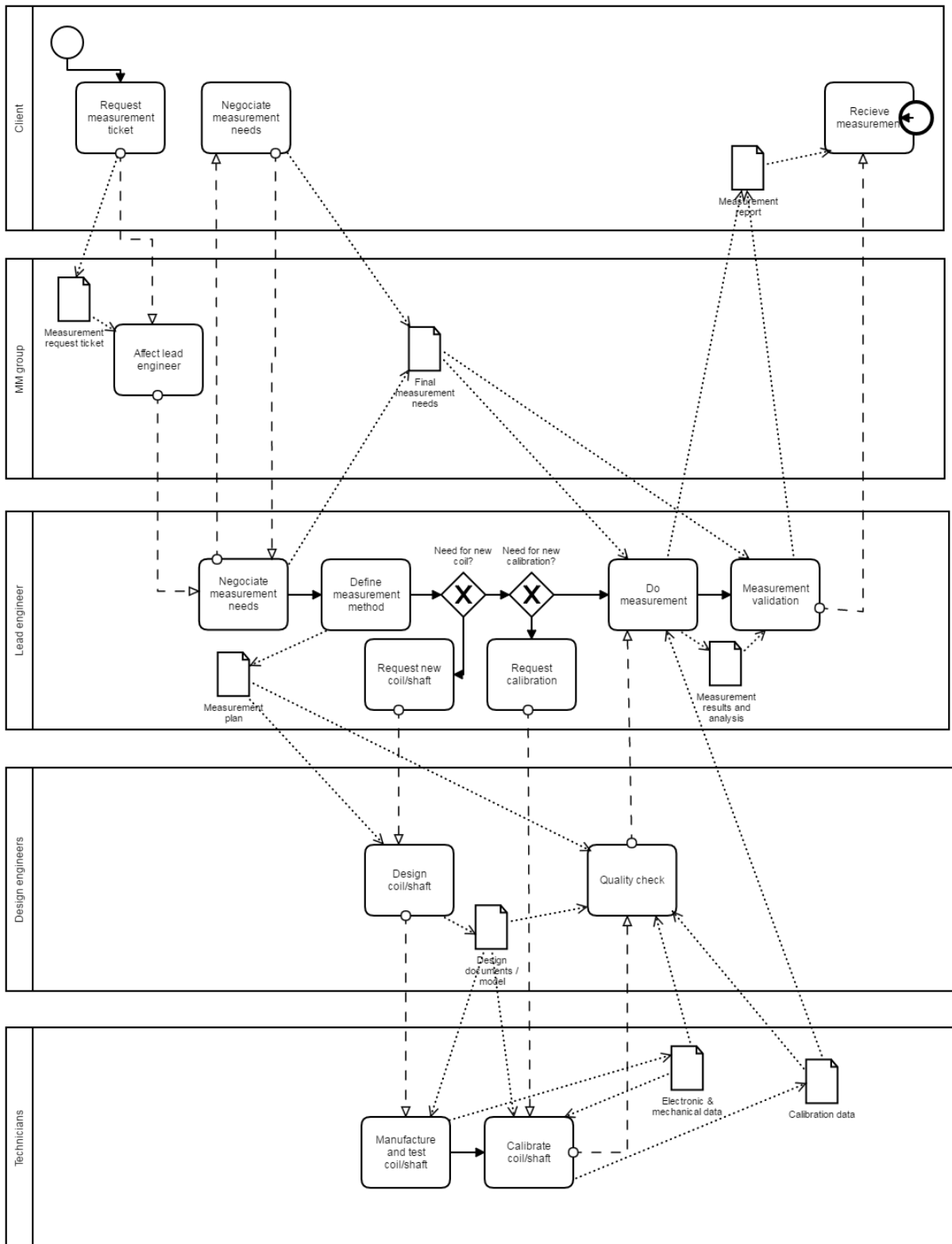


Figure D.1: BPMN model of the measurement process at the section level.

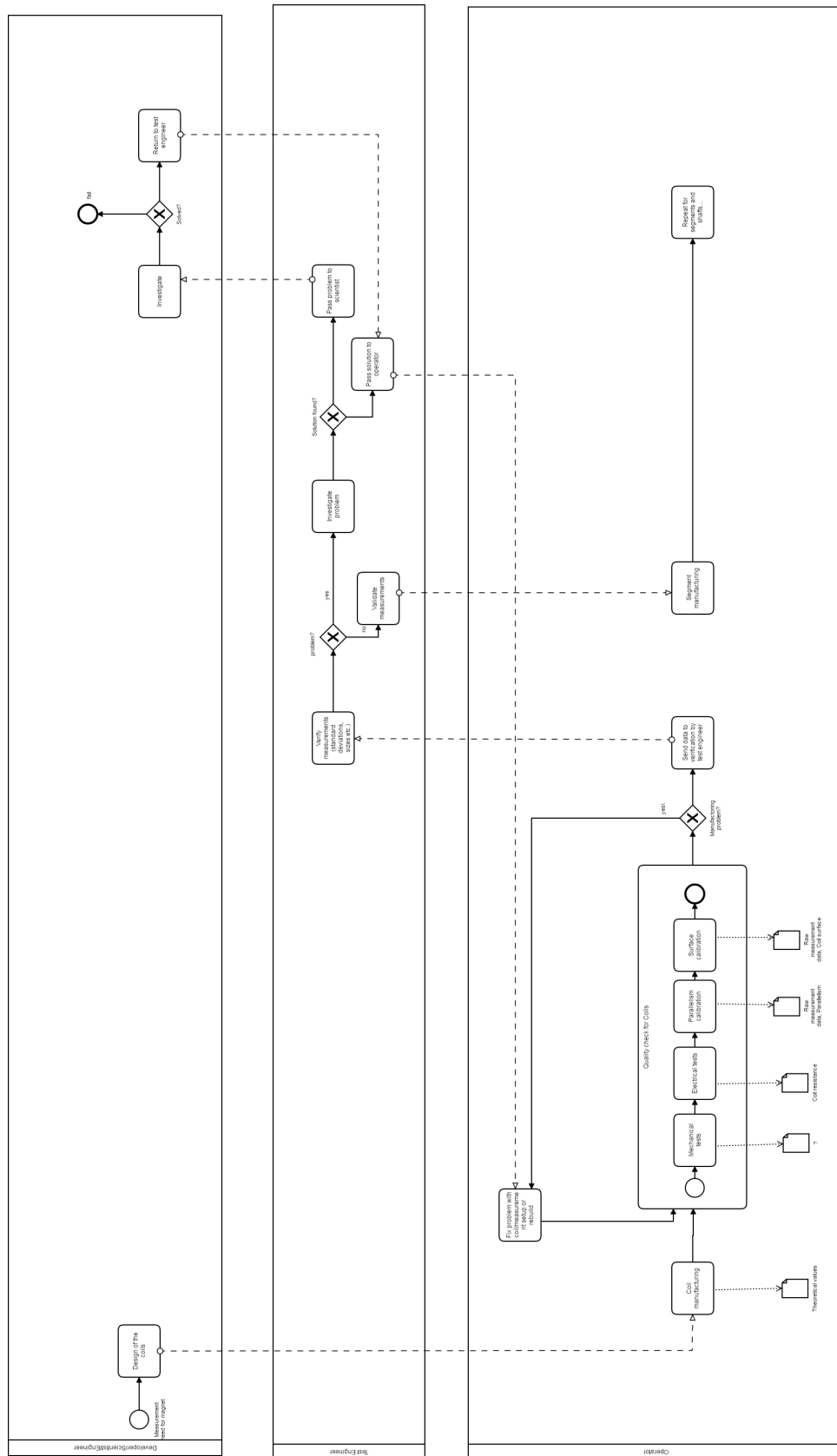


Figure D.2: BPMN model of a part of the calibration procedure

Code details

This appendix shows a series of flow-charts describing the algorithms that were implemented in FFMM with C++ in order to automate the calibration procedure. It is not exhaustive, but is meant to represent the general logic of the program. This can be a useful document for future technical students that will continue work on my programs in order to understand the code more quickly. A diagram illustrating the implemented code structure in FFMM along with an example code is also included to illustrate some of the work that was done.

E.1 Algorithms

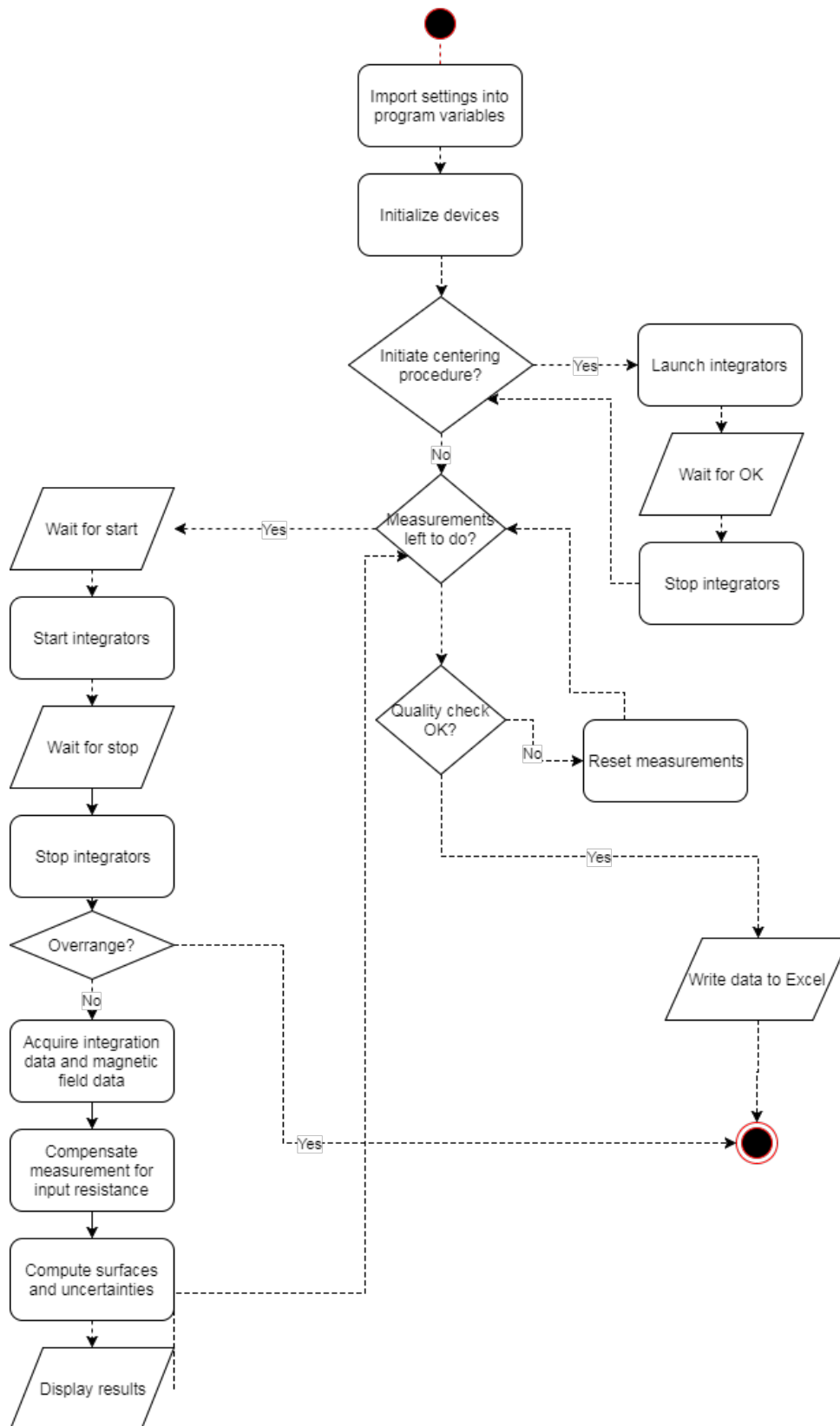


Figure E.1: Logic of the software script for surface calibrations

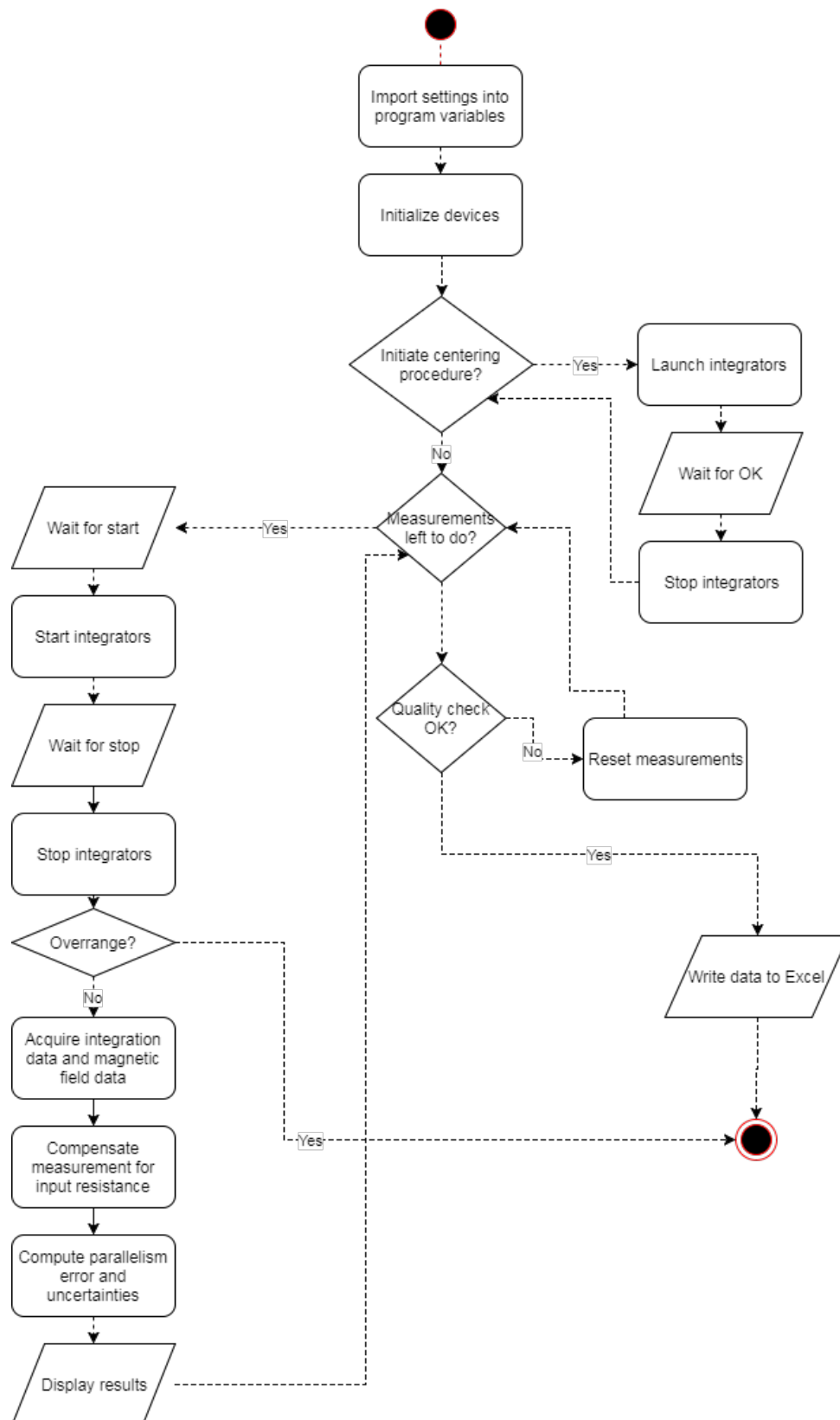
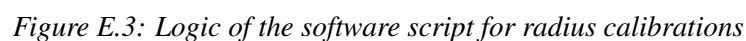


Figure E.2: Logic of the software script for parallelism calibrations



E.2 Software structure

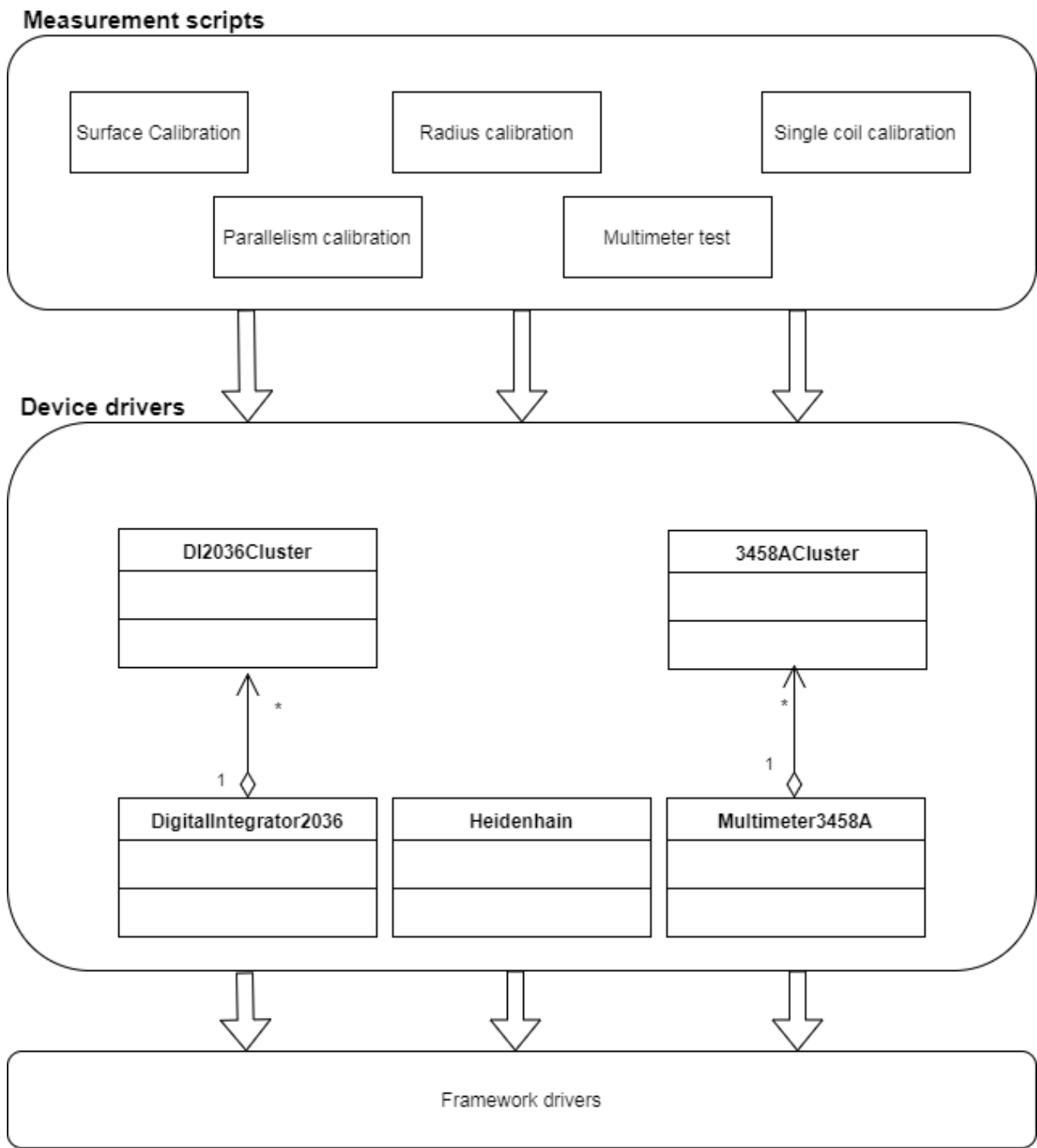


Figure E.4: Structure of the software developed through the internship within FFMM

E.3 Sample code: PDI driver

E.3.1 Header file

```
1  #ifndef DI2036
2  #define DI2036
3
4  #include "core/devices/Digital_Integrator.h"
5
6  #include "base/communication/FactoryBus.h"
7  #include "base/communication/IBusConfigurator.h"
8  #include "base/communication/GPIBConfigurator.h"
9  #include "base/communication/GPIB.h"
10
11 #include <stdio.h>
12 #include <iostream>
13 #include <fstream>
14 #include <math.h>
15
16 namespace fmm {
17     namespace core {
18         namespace devices {
19             /** \addtogroup deviceL */
20             //@{
21
22             class DigitalIntegrator2036 : public Digital_Integrator {
23             public:
24                 typedef Poco::SharedPtr<DigitalIntegrator2036> Ptr;
25
26             private:
27                 DigitalIntegrator2036( std::string name);
28                 DigitalIntegrator2036( std::string name, std::string mod, std::string ser_num, std::string man );
29
30                 //! binary file to store measurement data.
31                 std::ofstream* data_file;
32
33                 //! Used to identify a fatal fault event.
34                 int fatal_fault;
35                 std::string fileName;
36                 int Total_Number_data;
37                 int samples_read;
38
39                 //! to hold on the first occurrence of over range fault.
40                 int n_over_range;
41
42                 //! for configuring communication
43                 int _interfacenum;
44                 int _devaddr;
45                 int n_conf_f;
46
47                 int m_gain;
48                 int m_timeout;
```

```

49     int m_blockmode;
50     std::string m_trigger;
51     int m_sensitivity;
52     std::string m_units;
53     int m_pointsBlockmode;
54     std::string m_devicename;
55
56     Poco::SharedPtr<GPIB> gpibbus;
57     Poco::SharedPtr<GPIBConfigurator> conf;
58
59     /*! \brief Info used to hold information about a fault
60
61         The following three keys are used (mandatory for a right Fault↔
62         Detector reaction ):\n
63         - key ("SENDER_METHOD"): type string , name of the method where a↔
64           fault happened;\n
65         - key ("STATUS"): type string , identifies the machine status;\n
66         - key ("ERROR"): type string , if an error occurs that holds the ↔
67           type of error otherwise the string "NO_ERROR"
68     */
69     Event_info fault_info;
70
71     static const int MAXREAD_DI = 100;
72
73     void DigitalIntegrator2036::sendStr(char* str);
74
75     static const short DATA_READY = 1;
76     static const short OVER_RANGE = 2;
77     static const short NO_OF_POINTS_REACHED = 4;
78     static const short BUFFER_FULL = 8;
79     static const short LAST_VALUE = 16;
80     static const short READY_FOR_TRIGGERS = 32;
81     static const short SRQ = 64;
82     static const short RESETING = 128;
83
84 public:
85     ~DigitalIntegrator2036( );
86
87     /*! This method is used to create the device */
88     static DigitalIntegrator2036* createDevice(std::string name);
89
90     /*! This method is used to create the device*/
91     static DigitalIntegrator2036* createDevice( std::string name, std↔
92       ::string mod, std::string ser_num, std::string man );
93
94     /*!
95     \BRIEF This method is used to retrieve a pointer to the object ↔
96       named std::string name
97     \pre The object with name std::string name has to be already ↔
98       created
99     \post An exception is thrown if the device with name is not ↔
100       available (TO-DO substitue exception with fatal fault)
101     */
102     static DigitalIntegrator2036* getDeviceInstance(std::string name);
103
104     /*!

```

```

98 \brief This method is used to configure and open the communication↵
    between the device and the PC.
99 \param interfacenum it's the number of GPIB.
100 \param devaddr device address
101 \param timeout the timeout in milliseconds of GPIB bus
102 \post if the communication cannot be opened a configuration ↵
    fault is thrown and the method onConfigurationFault is ↵
    called.

103 */
104 void configure( int interfacenum, int devaddr, int timeout );
105
106 //! This method is used to release the device
107 static void deleteDevice(std::string name);
108
109 //Returns the identification string of the integrator
110 void readID (std::string* ID);
111
112 //Selects the ending of character string sent by integrator. ↵
    Arguments: {0,1,2}
113 //0: Terminates with EOI (End Or Identify). Default.
114 //1: Terminates with Carriage Return + EOI
115 //2: Terminates with Carriage Return Line Feed + EOI
116 int setEnding(int opt = 0);
117
118 //! \brief Selects gain of the preamplifier. Arguments {1,4,16,64}
119 // 1: Gain: 1, Range: 5V. —DEFAULT
120 // 4: Gain: 4, Range: 1.25V.
121 // 16: Gain: 16, Range: 0.3125V.
122 // 64: Gain: 64, Range: 0.078125V.
123 int Set_Gain (double gain = 1);
124
125 //! \brief method for reading board gain
126 int Read_Gain (double*) ;
127
128 //! \brief method for setting the type of trigger to be used.
129 // GET: GPIB Group Execute Trigger (GET). DEFAULT
130 // EXTERNAL: Integrator external trigger
131 // TIME_BASE: One second time base trigger
132 int Set_Trigger (std::string);
133
134 //! \brief method for setting the sensibility of the analog output↵
    Arguments {1,2,...,7}
135 // 1: Analog output = 10uVs, 10uT, 0.01G/volt DEFAULT
136 // 2: Analog output = 100uVs, 100uT, 0.1G/volt
137 // ...
138 // 7: Analog output = 10Vs, 10u\T, 10000G/volt
139 int Set_Output_Sensitivity(int sens = 1);
140
141 //! \brief method for reading the actual analog output sensitivity↵
    {1,2,...,7}
142 // 1: Analog output = 10uVs, 10uT, 0.01G/volt DEFAULT
143 // 2: Analog output = 100uVs, 100uT, 0.1G/volt
144 // ...
145 // 7: Analog output = 10Vs, 10u\T, 10000G/volt
146 int Get_Output_Sensitivity(int *);
147

```

```

148      /// \brief method for setting the units of the integrator values
149      //  VS DEFAULT
150      //  VOLTS
151      //  GAUSS
152      //  TESLA
153      int Set_Units(std::string unit = "VS");
154
155      /// \brief method for reading the units of the integrator values
156      //  0: VS DEFAULT
157      //  1: VOLTS
158      //  2: GAUSS
159      //  3: TESLA
160      int Get_Units(std::string *);
161
162      /// \brief method for starting the integration
163      int Start (void);
164
165      /// \brief method for stopping the integration
166      int Stop (void);
167
168      /// \brief method for resetting the integrator
169      int Reset (void);
170
171      /// \brief method for enabeling the display on the front panel. (↔
172      //      Default on)
173      int Enable_Display(void);
174
175      /// \brief method for disabeling the display on the front panel
176      int Disable_Display(void);
177
178      /// \brief method for setting the integrator mode {0,1}
179      //  0: IMMEDIATE: Integrator values are sent to the GPIB after each↔
180      //      trigger. DEFAULT
181      //  1: BLOCK: Integrator values are stored in memory after each ↔
182      //      trigger, (1000 max) and are sent to the GPIB afterwards
183      int Set_Mode(int);
184
185      /// \brief method for setting the number of measurements to be ↔
186      //      done when in BLOCK mode. {0,1,...,1000}
187      int Set_No_Of_Points_Block(int);
188
189      /// \brief method for reading the data from the integrator. ↔
190      //      Returns -1 if Over-Range has been detected.
191      int Read(std::string *data);
192
193      /// \brief method for resetting the pointer
194      int Reset_Pointer();
195
196      /// \brief method for checking if there is an over-range error on ↔
197      //      the integrator when reading data
198      bool isOverRange();
199
200      /// \brief method for checking if the device is in resetting mode ↔
201      //      after power-on
202      bool isResetting();

```

```

197      //!< \brief method for setting of rate the Analog to Digital ↵
          conversion
198      int Set_ADC_Rate(double);
199
200      //!< \brief method for reading the A/D rate from board
201      int Read_ADC_Rate (double*);
202
203      //!< \brief method for setting the motor turn number in harmonic ↵
          coil measurements
204      int Set_Number_of_Turns (int) ;
205
206      //!< \brief method for reading the motor turn number in harmonic ↵
          coil measurements
207      int Read_Number_of_Turns (int*);
208
209      //!< \brief method for setting the number of triggers to be ↵
          acquired
210      int Set_Number_of_Trigger_per_Turn(int);
211
212      //!< \brief method for reading the number of triggers to be ↵
          acquired
213      int Read_Number_of_Trigger_per_Turn(int*);
214
215      //!< \brief method for setting the size of board output buffer size
216      int Set_Buffer_Acquisition_Size (int);
217
218      //!< \brief method for reading the size of board output buffer size
219      int Read_Buffer_Acquisition_Size (int*);
220
221      //!< \brief method for reading the state of the board
222      int Read_State (int*);
223
224      //!< \brief method for carrying out the board calibration
225      int Calibrate(void);
226
227      Event_info getEvent_info(){return fault_info;}
228
229      int ReadData(float * pData);
230  };
231  //@}
232  } // devices
233  } // core
234  } // fmm
235  #endif

```

E.3.2 Main file

```
1  #include <string>
2  #include <stdio.h>
3  #include <iostream>
4  #include <iterator>
5  #include <vector>
6  #include <algorithm>
7
8  #include "core/devices/DigitalIntegrator2036.h"
9  #include "core/utils/DynamicParameter.h"
10
11 using namespace fmm::core::devices;
12 using namespace std;
13
14 //-----Constructors and desctructors-----
15 DigitalIntegrator2036::DigitalIntegrator2036( std::string name ) : ←
    Digital_Integrator( name ) {
16     setEnvironment();
17     // fault_info.insert("DEV_TYPE","FDI");
18     configuration_f;
19     local_f;
20     warning_f;
21     n_over_range=0;
22     m_gain = 1;
23     m_blockmode = 0;
24     m_trigger = "GET";
25     m_sensitivity = 1;
26     m_units = "VS";
27     m_pointsBlockmode = 100;
28     m_devicename = name;
29
30 #ifdef WIN32
31     fileName="c:\\";
32 #else
33     fileName="/tmp/";
34 #endif
35     fatal_fault=0;
36     data_file = new ofstream( );
37     samples_read=0;
38 }
39
40 DigitalIntegrator2036::DigitalIntegrator2036( std::string name, std::string mod, ←
    std::string ser_num, std::string man ) : Digital_Integrator( name, mod, ser_num←
    , man ){
41     setEnvironment();
42     // fault_info.insert("DEV_TYPE","FDI");
43     configuration_f;
44     local_f;
45     warning_f;
46     n_over_range=0;
47 #ifdef WIN32
48     fileName="c:\\";
```

```

49 #else
50     fileName="/tmp/";
51 #endif
52     fatal_fault=0;
53     data_file = new ofstream( );
54     samples_read=0;
55 }
56
57 DigitalIntegrator2036::~DigitalIntegrator2036( ) {
58     if(sysLogChanged)
59         delete (DigitalIntegrator2036::p_env->systemLog);
60     if(dataLogChanged)
61         delete (DigitalIntegrator2036::p_env->dataLog);
62 }
63
64 //-----Device creation and delete-----
65 DigitalIntegrator2036* DigitalIntegrator2036::createDevice( std::string name ){
66
67     // put the device named "name" into hashmap if it isn't already
68     // and return a pointer to it.
69     // if the device is already in hashmap return the pointer.
70
71     if (!isRegistered(name)) {
72         DigitalIntegrator2036* dev = new DigitalIntegrator2036( name );
73         registerDevice(dev);
74         return dev;
75     }
76     DigitalIntegrator2036* digint = dynamic_cast<DigitalIntegrator2036*>(getDevice(
77         name));
78     if (digint == NULL) throw DeviceTypeNotCorrectException();
79     else return digint;
80 }
81 DigitalIntegrator2036* DigitalIntegrator2036::createDevice( std::string name, std::
82     ::string mod, std::string ser_num, std::string man ){
83
84     // put the device named "name" into hashmap if it isn't already
85     // and return a pointer to it.
86     // if the device is already in hashmap return the pointer.
87
88     if (!isRegistered(name)) {
89         DigitalIntegrator2036* dev = new DigitalIntegrator2036( name, mod, ser_num,
90             , man );
91         registerDevice(dev);
92         return dev;
93     }
94     DigitalIntegrator2036* digint = dynamic_cast<DigitalIntegrator2036*>(getDevice(
95         name));
96     if (digint == NULL) throw DeviceTypeNotCorrectException();
97     else return digint;
98 }
99
100 DigitalIntegrator2036* DigitalIntegrator2036::getDeviceIstance(std::string name){
101     DigitalIntegrator2036* digi = dynamic_cast<DigitalIntegrator2036*>(getDevice(
102         name));

```

```

99         return digi;
100     }
101
102     void DigitalIntegrator2036::deleteDevice( std::string name ){
103
104         Virtual_Device* dev;
105         try {
106             dev = getDevice(name);
107             DigitalIntegrator2036* _DigitalIntegrator2036 = dynamic_cast<<
                DigitalIntegrator2036*>(dev);
108             if (_DigitalIntegrator2036 == NULL) throw DeviceTypeNotCorrectException();
109             unregisterDevice(_DigitalIntegrator2036);
110             delete _DigitalIntegrator2036;
111         } catch (DeviceNotFoundException e){
112             e;
113             std::string s1="WARNING: Device "+name+" not registered , nothing removed<←
                ... ";
114             (s_env->systemLog)->logMessage("warning",s1);
115             (s_env->console)->writeln(s1);
116         }
117     }
118
119     //-----Configure <←
        communication-----
120     void DigitalIntegrator2036::configure(int interfacenum, int devaddr, int timeout){
121         conf = new GPIBConfigurator();
122         _interfacenum=interfacenum;
123         _devaddr=devaddr;
124         n_conf_f=1;
125         m_timeout = timeout;
126         conf->setTimeout(timeout);
127         int right_setting=0;
128         Event_info inf;
129         while (!right_setting){
130             conf->setInterfaceNum(_interfacenum);    // GPIB0
131             conf->setDevAddr(_devaddr);              // Digital Integrator's default <←
                address (??)
132             gpibbus = new GPIB(conf);
133             inf=gpibbus->openConnection();
134             if (inf.get_int("Open_Connection_Code")){
135                 (p_env->console)->writeln(inf.get_string("msg"));
136                 right_setting=1;
137             } else {
138                 configuration_f.notify(this ,inf);
139             }
140         }
141     }
142
143     //-----GPIB Commands<←
        -----
144
145     void DigitalIntegrator2036::readID (std::string* ID) {
146         char readBuffer[MAXREAD_DI];
147         string output = "";
148         string sendString = "IDENTIFY!";
149         gpibbus->write(0,(void *)sendString.c_str() ,(int)strlen(sendString.c_str()));

```

```

150     delay(2000);
151     gpibbus->read(0,readBuffer,MAXREAD_DI);
152
153     int i = 0;
154     //TODO: Make this more viable
155     while ((readBuffer[i]!='\0') && (i<= strlen(readBuffer))){
156         output = output + readBuffer[i];           // convert the char array buffer ←
157             into string format
158         //readBuffer[i] = '\0';
159         i++;
160     }
161     (*ID) = string(output);
162 }
163
164 int DigitalIntegrator2036::setEnding(int opt){
165     char sendString[MAXREAD_DI];
166     stringstream temp;
167     int err = 0;
168
169     temp << "ENDING: ";
170     switch(opt) {
171         case 0:
172             temp << "EOI!";
173         case 1:
174             temp << "CR!";
175         case 2:
176             temp << "CRLF!";
177         default:
178             //Argument error!
179             fault_info.erase_insert("SENDER_METHOD","setEnding");
180             fault_info.erase_insert("STATUS","ERR_FUNC");
181             fault_info.erase_insert("ERROR","Function is not valid");
182             DigitalIntegrator2036::warning_f.notify(this,fault_info);
183             err = 1;
184             break;
185     }
186
187     if (!err) {
188         strcpy(sendString, temp.str().c_str());
189         gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
190         return 0;
191     }
192
193     return -1;
194 }
195
196 int DigitalIntegrator2036::Set_Gain (double gain) {
197     char sendString[MAXREAD_DI];
198     stringstream temp;
199     m_gain = gain;
200
201     if (gain == 1 || gain == 4 || gain == 16 || gain == 64) { //Check if argument ←
202         is in the allowed argument space
203         temp << "GAIN:" << gain << "!";
204         strcpy(sendString, temp.str().c_str());

```

```

204         gpibbus->write(0, (void *)sendString, (int)strlen(sendString));
205         return 0;
206     } else {
207         //Argument error!
208         fault_info.erase_insert("SENDER_METHOD", "Set_Gain");
209         fault_info.erase_insert("STATUS", "ERR_FUNC");
210         fault_info.erase_insert("ERROR", "Function is not valid");
211         DigitalIntegrator2036::warning_f.notify(this, fault_info);
212         return -1;
213     }
214 }
215 }
216
217 int DigitalIntegrator2036::Read_Gain (double* gain) {
218     char readBuffer[MAXREAD_DI];
219     stringstream temp;
220     double readGain;
221
222     string output = "";
223     string sendString = "GAIN!";
224     gpibbus->write(0, (void *)sendString.c_str(), (int)strlen(sendString.c_str()));
225
226     delay(1000);
227
228     gpibbus->read(0, readBuffer, MAXREAD_DI);
229     temp.str("");
230     temp << readBuffer;
231     temp >> readGain;
232
233     (*gain) = readGain;
234
235     return 0;
236 }
237
238 int DigitalIntegrator2036::Set_Trigger (string opt) {
239     char sendString[MAXREAD_DI];
240     stringstream temp;
241     m_trigger = opt;
242
243     if (opt.compare("GET") || opt.compare("EXTERNAL") || opt.compare("TIME_BASE") <= 0) {
244         temp << "TRIGGER:" << opt << "!";
245         strcpy(sendString, temp.str().c_str());
246         gpibbus->write(0, (void *)sendString, (int)strlen(sendString));
247         return 0;
248     } else {
249         //Argument error
250         fault_info.erase_insert("SENDER_METHOD", "Set_Trigger");
251         fault_info.erase_insert("STATUS", "ERR_FUNC");
252         fault_info.erase_insert("ERROR", "Function is not valid");
253         DigitalIntegrator2036::warning_f.notify(this, fault_info);
254         return -1;
255     }
256 }
257 }
258

```

```

259 int DigitalIntegrator2036::Set_Output_Sensitivity(int sens) {
260     char sendString[MAXREAD_DI];
261     stringstream temp;
262     m_sensitivity = sens;
263
264     if ((sens >= 1)&&(sens <= 7)) { //Check if argument is in the allowed argument←
        space
265         temp << "ANALOG_OUTPUT:" << sens << "!";
266         strcpy(sendString, temp.str().c_str());
267         gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
268         return 0;
269     } else {
270         //Argument error!
271         fault_info.erase_insert("SENDER_METHOD","Set_Output_Sensitivity");
272         fault_info.erase_insert("STATUS","ERR_FUNC");
273         fault_info.erase_insert("ERROR","Function is not valid");
274         DigitalIntegrator2036::warning_f.notify(this,fault_info);
275         return -1;
276     }
277
278 }
279
280 int DigitalIntegrator2036::Get_Output_Sensitivity(int *sens) {
281     char readBuffer[MAXREAD_DI];
282     stringstream temp;
283     double readSens;
284
285     string sendString = "ANALOG_OUTPUT!";
286     gpibbus->write(0,(void *)sendString.c_str(),(int)strlen(sendString.c_str()));
287
288     delay(1000);
289
290     gpibbus->read(0,readBuffer,MAXREAD_DI);
291     temp.str("");
292     temp << readBuffer;
293     temp >> readSens;
294
295     (*sens) = readSens;
296
297     return 0;
298 }
299
300 int DigitalIntegrator2036::Set_Units(string unit) {
301     char sendString[MAXREAD_DI];
302     stringstream temp;
303     m_units = unit;
304
305     if (unit.compare("VS") || unit.compare("VOLTS") ||unit.compare("GAUSS") ||unit←
        .compare("TESLA")) {
306         temp << "UNITS:" << unit << "!";
307         strcpy(sendString, temp.str().c_str());
308         gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
309         return 0;
310     } else {
311         //Argument error
312         fault_info.erase_insert("SENDER_METHOD","Set_Units");

```

```

313         fault_info.erase_insert("STATUS","ERR_FUNC");
314         fault_info.erase_insert("ERROR","Function is not valid");
315         DigitalIntegrator2036::warning_f.notify(this,fault_info);
316         return -1;
317     }
318 }
319
320 int DigitalIntegrator2036::Get_Units(string * unit) {
321     char readBuffer[MAXREAD_DI];
322     stringstream temp;
323     string readUnit;
324
325     string sendString = "UNITS!";
326     gpibbus->write(0,(void *)sendString.c_str(),(int)strlen(sendString.c_str()));
327
328     delay(200);
329
330     gpibbus->read(0,readBuffer,MAXREAD_DI);
331     temp.str("");
332     temp << readBuffer;
333     temp >> readUnit;
334
335     (*unit) = readUnit;
336
337     return 0;
338 }
339
340 int DigitalIntegrator2036::Start() {
341     char sendString[] = "START!";
342     gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
343     return 0;
344 }
345
346 int DigitalIntegrator2036::Stop() {
347     char sendString[] = "STOP!";
348     gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
349     return 0;
350 }
351
352 int DigitalIntegrator2036::Reset() {
353     char sendString[] = "RESET!";
354     gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
355     return 0;
356 }
357
358 int DigitalIntegrator2036::Enable_Display(void) {
359     char sendString[] = "DISPLAY:ON!";
360     gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
361     return 0;
362 }
363
364 int DigitalIntegrator2036::Disable_Display(void) {
365     char sendString[] = "DISPLAY:OFF!";
366     gpibbus->write(0,(void *)sendString,(int)strlen(sendString));
367     return 0;
368 }

```

```

369
370 int DigitalIntegrator2036::Set_Mode(int mode) {
371     char sendString[MAXREAD_DI];
372     stringstream temp;
373     int err = 0;
374     m_blockmode = mode;
375
376     temp << "MODE: ";
377     switch(mode) {
378         case 0:
379             temp << "IMMEDIATE!";
380             break;
381         case 1:
382             temp << "BLOCK!";
383             break;
384         default:
385             //Argument error!
386             fault_info.erase_insert("SENDER_METHOD", "Set_Trigger");
387             fault_info.erase_insert("STATUS", "ERR_FUNC");
388             fault_info.erase_insert("ERROR", "Function is not valid");
389             DigitalIntegrator2036::warning_f.notify(this, fault_info);
390             err = 1;
391             break;
392     }
393
394     if (!err) {
395         strcpy(sendString, temp.str().c_str());
396         gpibbus->write(0, (void *)sendString, (int)strlen(sendString));
397         return 0;
398     }
399
400     return -1;
401 }
402
403 int DigitalIntegrator2036::Set_No_Of_Points_Block(int points) {
404     char sendString[MAXREAD_DI];
405     stringstream temp;
406     m_pointsBlockmode = points;
407
408     if ((points >= 0) && (points <= 1000)) {
409         temp << "NO_OF_POINTS: " << points << "!";
410         strcpy(sendString, temp.str().c_str());
411         gpibbus->write(0, (void *)sendString, (int)strlen(sendString));
412         return 0;
413     } else {
414         //Argument error!
415         fault_info.erase_insert("SENDER_METHOD", "Set_No_Of_Points_Block");
416         fault_info.erase_insert("STATUS", "ERR_FUNC");
417         fault_info.erase_insert("ERROR", "Function is not valid");
418         warning_f.notify(this, fault_info);
419         return -1;
420     }
421 }
422
423 int DigitalIntegrator2036::Read(string *data){
424     char readBuffer[MAXREAD_DI];

```

```

425     bool overrange;
426     string output = "";
427     string sendString = "RESET_POINTER!";
428     // gpibbus->write(0,(void *)sendString.c_str() ,(int)strlen(sendString.c_str()))↵
429     ;
430     gpibbus->assertTrigger(0);
431     delay(200);
432     overrange = isOverRange();
433     delay(50);
434     gpibbus->read(0,readBuffer,MAXREAD_DI);
435
436     int i = 0;
437     while ((readBuffer[i]!='\0') && (i<= strlen(readBuffer))) {
438         output = output + readBuffer[i];          // convert the char array buffer ↵
439         into string format
440         readBuffer[i] = '\0';
441         i++;
442     }
443
444     (*data) = string(output);
445
446     if (overrange) return -1;
447     return 0;
448 }
449
450 int DigitalIntegrator2036::Reset_Pointer() {
451     string sendString = "RESET_POINTER!";
452     gpibbus->write(0,(void *)sendString.c_str() ,(int)strlen(sendString.c_str()));
453     return 0;
454 }
455
456 //SERIAL POLLING METHODS
457 bool DigitalIntegrator2036::isOverRange() {
458     short status;
459     gpibbus->serialPoll(_interfacenum, _devaddr, 0, &status);
460     return (status & OVER_RANGE)&&(status & DATA_READY);
461 }
462
463 bool DigitalIntegrator2036::isResetting() {
464     short status;
465     gpibbus->serialPoll(_interfacenum, _devaddr, 0, &status);
466     return (status & RESETTING);
467 }
468
469 //-----Private support functions↵
470
471 void DigitalIntegrator2036::sendStr(char* str) {
472     gpibbus->write(0,str,(int)strlen(str));
473 }
474
475 //-----Methods left from superclass. Not used↵
476
477 /// \brief method for setting of rate the Analog to Digital conversion
478 int DigitalIntegrator2036::Set_ADC_Rate(double rate){return 1;}
479 /// \brief method for reading the A/D rate from board
480 int DigitalIntegrator2036::Read_ADC_Rate (double* rate){return 1;}

```

```

477 /// \brief method for setting the motor turn number in harmonic coil measurements
478 int DigitalIntegrator2036::Set_Number_of_Turns (int turns) {return 1;}
479 /// \brief method for reading the motor turn number in harmonic coil measurements
480 int DigitalIntegrator2036::Read_Number_of_Turns (int* turns){return 1;}
481 /// \brief method for setting the number of triggers to be acquired
482 int DigitalIntegrator2036::Set_Number_of_Trigger_per_Turn(int tpt){return 1;}
483 /// \brief method for reading the number of triggers to be acquired
484 int DigitalIntegrator2036::Read_Number_of_Trigger_per_Turn(int* tpt){return 1;}
485 /// \brief method for setting the size of board output buffer size
486 int DigitalIntegrator2036::Set_Buffer_Acquisition_Size (int size){return 1;}
487 /// \brief method for reading the size of board output buffer size
488 int DigitalIntegrator2036::Read_Buffer_Acquisition_Size (int* size){return 1;}
489 /// \brief method for reading the state of the board
490 int DigitalIntegrator2036::Read_State (int* state){return 1;}
491 /// \brief method for carrying out the board calibration
492 int DigitalIntegrator2036::Calibrate() {return 1;}

```

Résumé détaillé en Français

F.1 Introduction

Dans le cadre de mes études, j'ai complété un stage de fin d'études de six mois au sein de l'Organisation Européenne pour la Recherche Nucléaire (CERN) à Genève en Suisse. Ce stage s'est déroulé dans la section de Mesures Magnétiques (MM), avec le but d'automatiser la procédure de calibration pour un système de mesures magnétiques, suivi d'une analyse managériale de l'organisation de la section.

En tant qu'étudiant ingénieur, j'ai suivi le cursus Automatique et Électronique à l'INSA (Institut National des Sciences Appliquées) de Toulouse, avec une majeure en « Innovative Smart Systems ». De plus, j'ai suivi un double cursus avec l'IAE (Institut d'Administration des Entreprises) de Toulouse en Management de l'Innovation. Le but était de combiner des connaissances d'ingénierie et de management afin de développer des technologies plus pertinentes avec un plus grand impact en vue.

Au cours de mon stage, j'ai essayé d'utiliser cette double compétence afin d'analyser des problèmes rencontrés par la section MM, pour ensuite proposer des solutions adéquates. En commençant mon stage par plusieurs discussions avec le personnel et par une recherche documentaire afin de bien comprendre l'organisation, les procédures, et la technologie de la section, j'ai pu me faire une idée globale et détaillée des points intéressants à inspecter afin d'améliorer le fonctionnement de certaines procédures. Je me suis focalisé sur la procédure de calibration d'un système de mesure magnétique appelé "bobines tournantes", et plusieurs points d'amélioration ont été mis en évidence.

Suite à cette première analyse organisationnelle et opérationnelle, j'ai principalement travaillé sur trois tâches principales. J'ai d'abord développé un logiciel permettant d'automatiser de grandes parties de la procédure de calibration existante, qui, jusque là, était basée sur plusieurs tâches manuelles, sources potentielles d'erreurs et de délais. Ensuite, j'ai inspecté la possibilité d'utiliser un nouveau système d'intégration de tension dans la procédure de calibration afin de

mettre à jour l'instrumentation actuelle et ainsi éviter des risques d'arrêt et autres discontinuités dans les procédures futures. Finalement, j'ai travaillé sur une analyse détaillée du fonctionnement de ma section au CERN en développant un modèle des procédures internes afin de donner une meilleure vue d'ensemble sur la section et de permettre une analyse managériale et procédurale plus poussée dans l'avenir.

Au cours de ce stage, j'ai donc dû utiliser de nombreuses connaissances acquises pendant mes études d'ingénieur, comme l'électromagnétisme, l'analyse numérique, le développement C++, les protocoles de communication, la transformée de Fourier, l'optimisation, et bien plus. J'ai aussi dû m'appuyer sur des concepts rencontrés lors mes études de management pour faire des analyses et mettre au point des modèles. Ajouté à cela, tout au long de ce stage, je me suis familiarisé à et ai adopté de nouveaux concepts bien utiles.

Ce sommaire en français a pour but de résumer le contenu de mon stage. Je commencerai par expliquer le cadre et les objectifs du stage. Je continuerai avec une analyse préliminaire des problèmes détectés dans la section MM, et présenterai des solutions potentielles adéquates. Ensuite, je donnerai de plus amples détails sur mon travail d'analyse, de conception et d'implémentation de solutions techniques tout au long de mon séjour. Finalement, je conclurai sur mon expérience au CERN, et proposerai des perspectives d'avenir.

F.2 Cadre et objectifs du stage

Mon stage s'est déroulé au sein du laboratoire CERN, un centre de recherche initialement nucléaire, créé en 1954 et situé à Genève. Après la deuxième guerre mondiale, il y avait peu de recherche de qualité en Europe, et le laboratoire a été établi pour donner un second souffle à la recherche fondamentale Européenne. Depuis, le CERN est devenu le plus grand centre de physique des particules du monde. Plusieurs découvertes de haut plan, un grand nombre de Prix Nobel et des innovations et retombées technologiques sont à l'actif du CERN. La récente découverte du Boson de Higgs en 2012 suivi du prix Nobel de physique de 2014, l'invention du World Wide Web en 1989 et les applications médicales, pour ne citer que quelques exemples, en font la fierté des chercheurs, ingénieurs et autres techniciens et étudiants.

Le CERN s'est doté d'un grand complexe d'accélérateurs de particules. Un de ce accélérateurs s'appelle le Large Hadron Collider, et est le plus grand accélérateur de particules au monde. Avec ces 27 kilomètres, il accélère des protons et autres ions lourds les dotant d'une vitesse toute proche de celle de la lumière avant de les rentrer en collision. Les débris de collisions ainsi créés sont enregistrés et étudiés par d'énormes détecteurs de particules afin d'analyser la matière dans sa forme la plus élémentaire, et ainsi tenter de donner des réponses à des mystères tels que l'origine de l'univers et la nature de la matière sombre.

Pour faire fonctionner ces accélérateurs, il faut un grand nombre d'aimants de différentes sortes, basés sur des technologies de pointe. Pour le LHC, des aimants dipôles et quadripôles sont

nécessaires. Ces aimants, qui sont supraconducteurs, nécessitent un grand nombre de mesures dans leur développement et leur opération. Ceci est la tâche principale de la section où j'ai travaillé au sein du CERN.

Après la fin de la construction du LHC, la section de mesures magnétiques devait changer de façon de travailler. Pendant la phase de construction, le travail était plus basé sur la production en série que sur la recherche et développement. Il a donc fallu changer plusieurs procédures afin de s'adapter au nouveau régime. C'est pour tenter de revisiter certaines procédures, et doté de mes connaissances d'ingénieur et de management, que j'ai été embauché pour un stage en tant que Technical Student au CERN.

F.3 Analyse opérationnelle et organisationnelle

Tout au long de mon stage, j'ai passé beaucoup de temps à parler avec différents membres de la section MM afin de bien comprendre les procédures internes, leur façon de collaborer ainsi que les problèmes rencontrés dans leur travail. Avant de commencer l'étude technique d'amélioration des procédures, j'ai fait une analyse des problèmes majeurs que j'ai découverts afin de bien construire un plan d'action pour mon stage. Cette analyse a été faite à deux niveaux différents, le premier étant au niveau de la section MM globale, et le deuxième au niveau plus spécifique de la procédure de calibration des bobines tournantes utilisées dans la mesure du champ magnétique des aimants.

F.3.1 Section

Il y a un grand nombre d'informations à transférer entre les différentes procédures internes liées aux mesures magnétiques. Ces informations sont souvent transférées par mail ou manuellement, ce qui peut causer des pertes ou changement d'information. De plus, un grand nombre d'équipements différents sont utilisés dans les mesures, et il n'y a pas de façon claire de savoir quels outils ont été utilisés pour quelle mesure. Ceci peut aussi causer des problèmes dans la certification de la qualité des mesures. Il serait donc intéressant de développer un système informatique qui permettra de mieux gérer et coordonner l'information au sein de la section.

Un premier problème est causé par le partage de ressources entre différentes procédures internes. Certaines de ces procédures, telle la calibration de capteurs, sont critiques dans la procédure de mesures, alors que d'autres telle la R&D le sont moins. Dans le cas de la calibration, il est arrivé que le travail est repoussé ou que des erreurs de mesures se sont introduites à cause d'un dérèglement ou monopole du matériel. Ceci est un problème d'organisation autant qu'un problème de ressources manquantes, mais l'achat de nouveaux équipements, pour découpler davantage les activités en terme de ressources, pourra permettre d'éviter des problèmes dans le futur.

A cela s'ajoute des problèmes de coordination entre les ingénieurs de la section et les techniciens qui sont chargés de fabrication et de calibration de systèmes de mesure, de l'opération de certaines mesures magnétiques, et de maintenance des laboratoires. Il y a d'abord un problème de planification du travail. C'est aujourd'hui la responsabilité des techniciens de donner des priorités aux différentes tâches qui leur sont attribuées afin de les finir dans des délais donnés. Le manque de vue d'ensemble de l'activité affecte le respect des priorités et délais. Une nouvelle structure de priorisation à un niveau hiérarchique plus élevé pourrait résoudre ce problème en donnant la responsabilité à une personne ayant une vue d'ensemble de l'activité de la section.

Vient finalement le problème de communication qui vient du manque de procédures standard dans l'octroi des tâches à remplir par les techniciens. Par exemple, afin de faire calibrer une canne de mesure, il manquait, dans les dessins techniques transmis, certaines informations critiques nécessaires au bon déroulement de la calibration. Les techniciens ont découvert cela après avoir passé une heure à installer le matériel mécanique, et ont dû abandonner. Un autre cas observé concerne une mésentente entre étudiant et technicien sur le format de demande d'assistance dans la demande d'achat de matériel. Ne sachant pas ce qu'attendait le technicien, l'étudiant a donné l'information nécessaire sous une forme inadéquate, rendant la tâche chronophage pour le technicien qui a mal pris la chose. Les malentendus peuvent donc causer des tensions, et il serait bien d'implémenter des procédures standard de de transmission de tâches.

F.3.2 Procédure de calibration

Dans la procédure de calibration, le problème majeur qui a été trouvé est que le logiciel utilisé est déprécié. Il tourne sur une machine Windows, et ne fonctionne que sur une version du système d'exploitation. La procédure ne peut être reproduite si changement de version il y a. De plus, ce logiciel demande beaucoup de manipulations manuelles de données, ce qui peut souvent induire des erreurs. Finalement, le code est écrit en Basic, ce qui rend la maintenance, ou toute extension avec de nouvelles fonctionnalités, très difficile. Le développement d'un nouveau logiciel indépendant du système d'exploitation ou de version donnée, automatisant les tâches de manipulation de données, et ouvert à des extensions multiples et développements ultérieurs, pourrait donc rendre la procédure de calibration beaucoup plus efficace et stable.

De plus, les intégrateurs de tension utilisés pour faire l'acquisition du signal venant des cannes de mesure ont aussi un risque associé. Ces instruments ont été développés dans la section il y a plus de vingt ans, et l'expertise requise n'est plus disponible. Cela veut dire qu'il n'y a plus personne qui connaît tous les détails de fabrication ou de réparation de ces intégrateurs. Ce point de défaillance unique ne peut être supprimé que par l'octroi d'un nouvel instrument d'une précision au moins équivalente. Il serait donc intéressant d'explorer les possibilités d'utilisation de nouveaux intégrateurs afin d'éviter ce risque.

La complexité opérative de la procédure est directement liée à un transfert du savoir difficile

à assurer. Le technicien responsable de la calibration a plus de 20 ans d'expérience et connaît la procédure intimement. Cependant, il est difficile de transmettre ce genre de connaissances tacites à cause de la complexité du traitement de données manuel. Toute absence prolongée de l'expert veut dire annulation de certaines calibrations. Il serait donc judicieux de rendre la procédure intrinsèquement plus simple et de développer un nouveau concept d'apprentissage permettant un transfert de connaissances efficaces envers une équipe d'opérateurs de calibration.

Finalement, il serait intéressant de développer un système mécanique et robotique pouvant automatiser les tâches mécaniques jusque là manuelles. Un tel système est déjà utilisé pour les ultimes mesures de champ magnétique des aimants. L'utilisation d'un système semblable pendant la calibration et la mesure pourrait aider à atteindre une meilleure précision, et permettrait aux techniciens de se concentrer sur d'autres aspects importants de leur travail.

F.4 Analyse détaillée et implémentation

F.4.1 Développement du logiciel de calibration

Les bobines tournantes, qui sont beaucoup utilisées dans les mesures magnétiques au CERN et qui sont basées sur le concept d'induction magnétique, sont produites en plusieurs étapes. Premièrement, des bobines seules sont produites en série et calibrées pour caractériser leurs surfaces magnétiques. Ensuite, ces bobines sont regroupées par ressemblance de surface et assemblées par trois ou cinq pour former des segments. Ces segments doivent être calibrés pour caractériser les surfaces des bobines après montage, leur parallélisme, et leur rayon. Plusieurs segments forment ensuite des taupes, qui sont utilisées pour les mesures finales, et qui nécessitent les mêmes calibrations que les segments. Il y avait donc trois programmes différents qui devaient être conçus afin de moderniser la procédure et répondre aux besoins explicités auparavant. Le développement de ces programmes ont aussi nécessité le développement de plusieurs interfaces spécifiques pour les outils d'acquisition de données utilisés.

Driver

La première étape de l'automatisation de la procédure de calibration était donc de développer des drivers qui allaient permettre aux programmes principaux de communiquer avec des instruments de mesure. Trois instruments différents étaient nécessaires dans la procédure de calibration: un intégrateur numérique portable (PDI), un encodeur linéaire (Heidenhain), et un capteur de champ magnétique par résonance magnétique nucléaire (NMR). Le driver du capteur NMR était déjà mis en oeuvre, mais les deux autres nécessitaient d'être développés.

Le PDI utilisait un protocole de type General Purpose Interface Bus (GPIB), et le Heidenhain un protocole de type RS-232. Des drivers spécifiques à ces protocoles étaient déjà implémentés dans la plate-forme C++ dite FFMM (Flexible Framework for Magnetic Measurements), et j'en ai fait usage afin de développer les classes C++ pour les instruments. Au cours de ce travail,

j'ai dû rentrer dans les détails pour comprendre les protocoles de communication, comment les utiliser dans le cadre d'un programme C++, et comment était structuré l'environnement de développement FFMM en général. Quand les drivers pour un des instruments étaient complétés, un nouveau driver pour synchroniser plusieurs d'entre eux était développé. Avant de conclure, chaque driver a été rigoureusement testé pour assurer son fonctionnement correct.

Application

Une fois les drivers développés et testés, il était temps de passer au développement des applications en soi. Avant de concevoir les nouvelles procédures de mesure sous forme informatique, il était important de bien comprendre les procédures actuelles. La participation à des calibrations avec les techniciens, ainsi que l'étude de la documentation des trois procédures, ont pris beaucoup de temps. Une fois la procédure comprise, le développement pouvait débuter. Hormis quelques problèmes techniques d'implémentation, le développement d'une première version fonctionnelle fût assez rapide. Cependant, l'optimisation de ce logiciel ainsi que son intégration dans la procédure actuelle ont pris beaucoup plus de temps. Ceci a nécessité plusieurs itérations avec les techniciens afin de rendre l'expérience utilisateur optimale: définition et implémentation du format de sortie sous forme de fichiers référence Excel, tests rigoureux des données en sortie, et l'intuitivité de l'interface graphique.

Valeur ajoutée

Le développement du logiciel de calibration a conduit à un produit prêt à utiliser qui va être mis en opération par les techniciens de la section dès la fin de mon stage. Ce logiciel résout plusieurs problèmes rencontrés dans la section auparavant: élimination de tâches manuelles, acquisition automatique de tous les signaux critiques, possibilité de vérifier la qualité des mesures automatiquement, compensation pour la chute de tension causée par l'impédance d'entrée de l'intégrateur, et ajustement automatique de la mesure de champ magnétique. De plus, le logiciel est plus facile à utiliser et à apprendre, est extensible et permet d'ajouter aisément de nouvelles fonctionnalités ultérieurement, est conçu sur une plateforme plus stable, et contient des formules corrigées par rapport à la version précédente. Finalement, la production d'un film d'apprentissage a été commencé afin de faciliter le transfert de savoir-faire lié à la calibration à de nouveaux opérateurs.

F.4.2 Recherche sur un nouvel intégrateur

Afin d'étudier les caractéristiques du Multimètre HP3458A de Keithley, que nous espérons implémenter en tant qu'intégrateur dans la procédure de calibration, il a d'abord fallu mettre en place un programme permettant d'expérimenter dans le cadre de la plateforme FFMM. Pour cela, un driver pour le Multimètre a été développé ainsi qu'un script permettant de comparer le Multimètre avec un autre intégrateur utilisé pour des mesures magnétiques nommé FDI (Fast Digital Integrator). Un script permettant une calibration de surface a été développé afin

de procéder à un test final. Un système d'acquisition de données baptisé DAQmx ainsi qu'un générateur de signaux nommé PXI-6289 ont aussi dû être implémentés. C'était en effet important de pouvoir procéder à un grand nombre d'expérimentations avec différentes configurations, ceci dans le but d'évaluer la performance en intégration du signal fourni par le Multimètre.

Après une analyse préliminaire utilisant les programmes FFMM développés, le choix s'est porté sur une méthode d'échantillonnage du signal nommée DCV (Direct Current Volts). Cette méthode utilise un intégrateur de signaux pour échantillonner le signal de façon beaucoup plus précise que par échantillonnage ponctuel (DSDC). Une comparaison de chacun des signaux échantillonnés des deux façons (DCV et DSDC) avec un signal référence échantillonné à haute fréquence par le FDI a confirmé la supériorité du mode DCV, que l'on a, du fait, gardé pour le restant de l'étude.

Dans le but de vérifier la précision de l'intégration par Multimètre, une comparaison plus rigoureuse a été faite avec le FDI. Après avoir comparé plusieurs ensembles de données échantillonnées de façon synchrone par les deux instruments, une erreur proportionnelle de distorsion persistait, alors que l'erreur linéaire a pu être compensée par extrapolation. Le générateur de signaux étant plus précis que l'erreur entre les deux signaux, l'erreur ne pouvait pas venir de celui-ci. Afin de trouver quel instrument était à l'origine de cette distorsion, une analyse de pureté du signal sinusoïdal acquis était mise en place. Une analyse par transformation de Fourier rapide (FFT) dans Matlab ne donnant pas une résolution suffisante, j'ai mis en place une régression multi-variable pour vérifier quel signal avait le moins de distorsion. En formulant et en résolvant un problème d'optimisation adéquat, le minimum de la fonction trouvé ainsi que les variables résultantes ont été utilisés pour juger quel signal était le plus près d'une fonction sinus pure appliquée en entrée. Le résultat indiquait clairement que l'erreur venait du Multimètre. Après plus de recherche, la source de l'erreur a été attribuée au fait que le signal pour enclencher l'échantillonnage venait de l'extérieur, et n'était pas synchronisé avec l'horloge interne du Multimètre. En utilisant l'horloge interne pour échantillonner et en refaisant l'étude de distorsion, nous avons trouvé que le Multimètre était bien plus précis que le FDI.

En optimisant la vitesse de lecture, une tâche qui a demandé beaucoup d'expérimentation et de développement, j'ai réussi à faire en sorte que le signal acquis soit le plus proche possible de la valeur réelle de l'intégrale mesurée. Théoriquement, après ce travail, on aurait dû obtenir une mesure d'intégrale précise à 10^{-5} . Cependant, lors d'un test final où le Multimètre a été utilisé pour faire une calibration de bobine tournante, il y avait toujours une erreur non-négligeable.

Après avoir discuté avec le service client de Keithley, une nouvelle piste s'est ouverte, mais je n'avais malheureusement plus de temps de la poursuivre, mon stage arrivant à échéance. La tâche va donc être transmise à une autre personne après mon stage, sachant que des bases assez solides ont été posées.

F.4.3 Modèle Value Shop

Comme détaillé dans la section F3, et afin de développer un modèle de la section, j'ai utilisé plusieurs techniques différentes. J'ai participé à plusieurs des procédures internes afin de bien les comprendre, j'ai fait des entretiens avec différentes personnes afin de comprendre leur travail, et j'ai lu beaucoup de littérature académique sur le sujet d'analyse organisationnelle. Ceci a finalement abouti à un modèle basé sur le concept de la Value Shop.

La Value Shop est un outil de modélisation de la logique de création de valeur d'entreprises à base de « technologies intenses ». Classiquement, la procédure de création de valeur d'entreprises a été faite à partir du modèle de Chaîne de Valeur proposée par Porter [1985]. Ce modèle est bien adapté pour modéliser des entreprises opérant en chaîne de production, mais moins adapté pour des entreprises qui ont une autre logique de travail comme les laboratoires de recherche et développement. Deux chercheurs ont donc proposé deux nouveaux modèles pour venir compléter la Chaîne de Valeur [Stabell and Fjeldstad, 1998].

Ces modèles se basent sur les typologies de technologies proposées par Thompson [1967], les technologies intenses, les technologies de médiation, et les technologies à longue durée de vie. Les entreprises de transformation de matière classiques comme les usines à aluminium utilisent des technologies à longue durée de vie. Les entreprises qui connectent les gens tels que les banques font usage de technologies de médiation. Finalement, les entreprises qui résolvent des problèmes à base d'expertise utilisent des technologies intenses. Stabell and Fjeldstad [1998] proposent que la Chaîne de Valeur est plus adaptée aux technologies à longue durée de vie, qu'à celles de médiation et intenses. Ils ont donc proposé la Value Shop pour les technologies intenses, et la Value Network pour les technologies de médiation. Après une analyse plus détaillée, j'ai trouvé que la section de mesures magnétiques ressemble beaucoup à une technologie intense, et le choix de la Value Shop comme outil de modélisation était approprié.

Après plusieurs itérations, je suis arrivé au modèle final visualisé dans la Figure F.1.

F.5 Conclusions et perspectives futures

Mon travail

Au cours de ce stage, j'ai pu travailler sur un grand nombre de thèmes différents allant de l'électromagnétisme, la programmation, les protocoles de communication, les mathématiques, l'analyse numérique, l'optimisation, l'électronique jusqu'à la modélisation de processus, l'analyse organisationnelle, le transfert de connaissances, la coordination de personnes et bien plus. Ceci m'a permis de développer des compétences liées à mes deux diplômes.

Après une analyse préliminaire de l'état des lieux dans la section de mesures magnétiques au CERN, mon travail s'est focalisé autour de trois thématiques principales : le développement d'un nouveau logiciel pour calibrer les bobines tournantes, une étude de faisabilité concernant

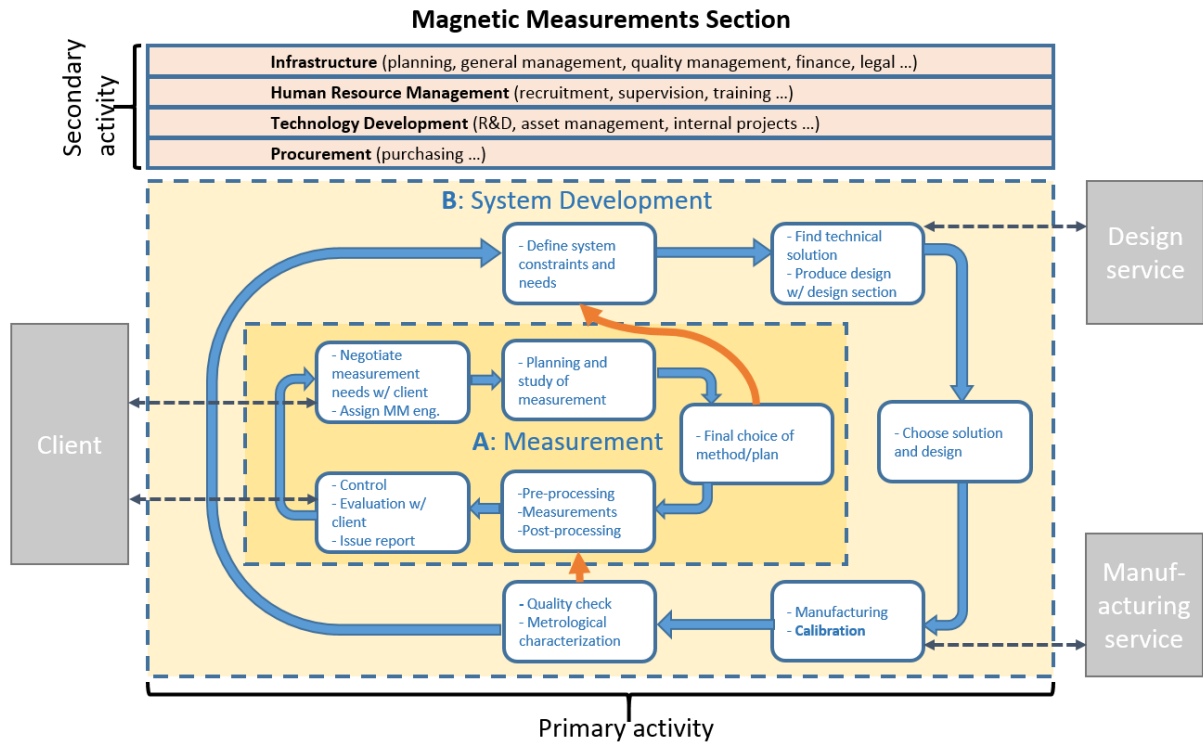


Figure F.1: Modèle Value Shop de la section MM.

l'adoption d'un nouvel instrument d'intégration de signaux, et le développement d'un modèle des processus internes de la section.

Le nouveau logiciel a permis de rendre la procédure de calibration de bobines tournantes plus facile, éliminant des sources d'erreurs existantes ainsi que des points de risque et de défaillance unique. Le but de l'étude de faisabilité concernant le Multimètre était aussi d'éliminer un point de défaillance unique dans la procédure, mais n'a pas abouti à une conclusion définitive par manque de temps. Cependant, de nouvelles pistes de recherche ont été trouvées, et un doctorant de la section va se charger de continuer l'étude sur de bases solides. Finalement, le modèle de processus a été conçu en suivant un modèle nommé Value Shop. Le but était de clarifier les relations entre différentes personnes dans la section de mesures magnétiques afin de leur permettre de mieux collaborer, ainsi que de donner un cadre structuré pour analyser les processus de la section et de proposer des solutions efficaces aux problèmes qu'ils peuvent avoir.

Le développement de programmes C++ nécessaire pour le nouveau logiciel de calibration et pour l'étude de faisabilité a résulté en approximativement 6500 lignes de code réparties sur 5 scripts avec des fichiers d'interface graphique correspondants, ainsi que 5 drivers. Un résumé de la structure du code ainsi qu'un exemple de code de driver peuvent être trouvés en Annexe E.

Perspectives futures

Pour continuer le développement technologique de la procédure de calibration, il serait intéressant d'implémenter plusieurs nouveaux concepts. Premièrement, une base de données commune à toutes les bobines, segments, et taupes de mesure pourrait faciliter l'entrée et sortie

d'information dans l'application que j'ai développée. Elle dépend encore de l'entrée manuelle de données, ce qui est chronophage et peut potentiellement induire des erreurs de calibration. De plus, un grand nombre de tâches manuelles mécaniques sont nécessaires pour faire les calibrations. Ces tâches consistent à tourner ou translater les systèmes de bobines tournantes dans un champ magnétique, ce qui pourrait être automatisé en programmant des systèmes de robots. Cette incorporation pourrait rendre la procédure davantage autonome, permettant ainsi d'éviter plusieurs sources d'erreur. Finalement, une nouvelle analyse de sensibilité de la théorie mathématique derrière la procédure de calibration aiderait à repérer les points critiques induisant le plus d'erreurs afin d'en tenir en compte dans les améliorations ultérieures de la procédure. Le mésalignement est un des paramètres en question. Il serait aussi intéressant de continuer le travail d'analyse que j'ai commencé concernant le nouvel intégrateur. Le travail que j'ai accompli jusque là ainsi que des suggestions ultérieures ont déjà été transmises à un doctorant auquel la tâche a été attribuée.

Finalement, il serait intéressant de faire une analyse détaillée des processus de communication liés aux interfaces entre tâches dans les procédures associées aux mesures magnétiques au sein de la section ainsi qu'une analyse organisationnelle et stratégique concernant la hiérarchisation de tâches. Des malentendus, pouvant avoir des impacts négatifs, peuvent ainsi être évités, par exemple, en introduisant une des procédures standard limitant, dans la mesure du possible, le nombre de cas de malentendus et autres.

Conclusions finales

Au cours de ce stage, j'ai pu utiliser un grand nombre de concepts appris au cours de mes études d'ingénieur et en management. Dans mon travail technique, j'ai dû faire usage de concepts comme la programmation en C++, l'interfaçage d'instruments de mesure par logiciel, plusieurs concepts mathématiques, électroniques, électromagnétiques et d'analyse de signaux. Dans les aspects managériaux, j'ai été fortement inspiré par plusieurs concepts étudiés en cours, et j'ai pu me familiariser avec beaucoup d'autres à travers d'articles académiques. De plus, le fait d'observer les processus dans la section de mesures magnétiques et d'analyser l'organisation et la communication au sein de la section, a été instrumental dans la compréhension de l'importance du management dans une organisation de recherche.

La combinaison des deux domaines couverts par mes diplômes m'ont permis d'avoir une vue d'ensemble de ce qui est nécessaire de faire pour améliorer les procédures dans une entreprise. En commençant par une analyse préliminaire, et procédant à la définition de la problématique, suivi d'une proposition de solution, menant finalement à l'implémentation des solutions, j'ai pu voir toute la logique de bout-en-bout. À travers ce processus je me suis rendu compte de l'importance de la complémentarité entre managers et ingénieurs. Ce travail a résulté en un produit fini qui va être utilisé, ce qui était aussi très satisfaisant. Mon expérience au CERN a été globalement très positive, et j'ai pu me développer dans des domaines divers et de plusieurs façons. J'ai eu la chance de travailler sous la tutelle d'un excellent directeur de stage qui m'a

guidé à travers plusieurs obstacles. J'ai pu côtoyer et travailler avec maintes personnes du monde entier, de langues et cultures différentes, travaillant dans des domaines variés. Muni de toute cette expérience, je me sens prêt à rentrer dans la vie professionnelle.

Finalement, ce stage m'a permis de réfléchir sur ma carrière future. Le travail accompli rentre dans le cadre d'un projet global de construire, maintenir, et améliorer une des machines les plus impressionnantes du monde, le LHC. Cependant, mon travail s'est focalisé sur une petite partie de ce projet. J'ai toujours été très fasciné par le développement de produits ayant un impact plus direct sur la société tout en étant proche du produit final. C'est pour cela que j'ai choisi de joindre une start-up comme première expérience professionnelle. Néanmoins, mon stage au CERN m'a ouvert les yeux sur les possibilités offertes par un doctorat.