CATÓLICA
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PORTO

DEVELOPMENT OF METHODOLOGIES FOR VALIDATING THE QUALITY OF A NOVEL FLUID FLOW SENSOR

Mariana Sanches Ambrósio

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Training Placement Report presented to Escola Superior de Biotecnologia of the Universidade Católica Portuguesa to fulfil the requirements of Master of Science degree in Biomedical Engineering

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November 2022

Resumo

Durante o estágio do Mestrado em Engenharia Biomédica, realizado na Riedel Communications, foi desenvolvida uma revisão sistemática da literatura a fim de se obter uma maior compreensão dos métodos de validação da qualidade de sensores, sendo que a calibração foi o foco principal. Num segundo trabalho, procedeu-se exatamente à calibração do sensor de fluxo desenvolvido pela Riedel. Ao longo deste relatório, será descrito o trabalho realizado durante o estágio, bem como os seus objetivos.

A Riedel Communications está a desenvolver um sistema cientificamente preciso e de alta qualidade para a aquisição de dados de navegação 3D. A ideia nasceu da necessidade de obter dados analíticos que reflitam melhor o movimento de um surfista em relação à água. Um sensor de fluxo de fluido (FFS) está integrado no sistema, e a sua implementação em ambientes hostis e medição sem interferir com o desempenho de um atleta são os maiores desafios. A fim de assegurar a consistência e reduzir erros, todos os instrumentos devem ser calibrados para garantir que o seu desempenho está de acordo com as normas conhecidas.

Com base na elevada consistência e repetibilidade dos resultados das experiências efetuadas, pode-se dizer que o sensor de fluxo de fluido apresentou um desempenho de alta qualidade. Portanto, o estágio foi um sucesso pois serviu como um recurso valioso para o trabalho da empresa, e todas as atividades foram concluídas com sucesso.

Palavras-chave: sensor de fluxo de fluido, calibração, qualidade, desempenho

Abstract

During the internship required for the Master's degree in Biomedical Engineering, conducted at Riedel Communications, a systematic review of the literature was developed in order to gain a greater understanding of methods for validating the quality of sensors, with a main focus on calibrations. A second assignment involved calibrating the fluid flow sensor (FFS) developed by Riedel. Throughout this dissertation, the work carried out during the internship will be described, as well as its background and objectives.

Riedel Communications is developing a scientifically precise and high-quality system for acquiring 3D navigation data. The idea was born out of the need to obtain analytical data that better reflects the movement of a surfer relative to the water. A fluid flow sensor (FFS) is integrated into the system, and its implementation in hostile environments and measurement without interfering with an athlete's performance are the biggest challenges. In order to ensure consistency and reduce errors, all instruments should be calibrated to ensure they are performing in accordance with known standards.

Based on the high consistency and repeatability of the experimental results, the fluid flow sensor displayed a high-quality performance. Therefore, the internship was a success because it served as a valuable resource for the company's work, and all activities were successfully completed.

Keywords: fluid flow sensor, calibration, quality, performance

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1. Introduction

1.1. Context and Motivations

Nowadays, sports at a competitive level require reliable quantitative judgments. As a result, technology has become an integral part of today's elite sports, due to its ability to improve performance and reduce the risk of injury. These days, wearable technology, big data analytics, and sensor technology are changing the way sports are played and analysed. Thus, with all the resources available, athletes can gain greater insight into their performance, improve training methods, and develop skills through various modern advancements (Mali & Kumar Dey, 2020). Despite the improvements in many sports, including football, tennis and many others, most water sports judgments are still empirical.

In the current state of the market, devices do not allow obtaining data on the actual effort made by athletes in water sports. Additionally, they are usually placed in areas with high turbulence, which are common in aquatic environments, making it difficult to collect reliable data without interfering with the performance of the athletes. Consequently, the devices currently available on the market do not correlate the positioning information of the athletes with the displacement of the water, resulting in measurement errors (Borgonovo-Santos, 2018).

Conventional devices such as ultrasonic Doppler displacement sensors, acoustic transducers or others that measure gliding velocity only allow for unidirectional measurement, which means they do not cover the entire range of applications. This lack or limitation of the available equipment, regarding the other movement axes, interferes with a dynamic and efficient estimation of an object real displacement in an aquatic environment. Although, gliding objects in liquid environments can be accurately measured with minimum interference, by using the biaxial flow sensor discussed in this thesis.

In addition to measuring the flow with a minimum amount of interference, RIEDEL Communications is developing the Fluid Flow Sensor (FFS) to accurately describe performance of athletes in different sports, mainly nautical. Even though, surfing played a pioneering role in the development of this technology, as a doctoral thesis was devoted to the characterization of its biomechanical and bioenergetic aspects. Surfing athletes can benefit from the application of this technology in training and coaching, for a better performance (Borgonovo-Santos, 2018). Therefore, the FFS stands out from many competitive flow sensors because it measures flow velocity and direction in three dimensions, as well as real efforts, eliminating empiricism from judgments (Borgonovo-Santos, 2018).

Taking into consideration the advances in technology, water sports are not the only application for this type of sensor. Furthermore, there are numerous applications to which this type of sensor can be adapted. For example, scientific studies (Dang, 2019) have discovered an increasing number of applications for underwater robots, such as environmental monitoring, search and rescue, and many more because of their agility and long-range operation. According to an article by Li et al. (2019) one possible application is the integration of force sensors in medical applications, such as the development of a multiple-point force-sensitive catheter for real-time non-invasive intraluminal intervention. Another example is drones with flow sensors, which monitor the airflow (Śniatała, Iyengar, & Kontowicz, 2021).

The report was developed during an internship at RIEDEL Communications' R&D hub in Porto. Since the internship was in an area of interest and the project sounded very appealing, it would be a great opportunity to apply knowledge and acquire new skills. Additionally, since the idea behind it was a result of the efforts led by universities and innovative young people, it would be a great place for an internship, as it would be a collaborative environment promoting constant learning and innovation.

Founded in 1987 in Wuppertal, Germany, Riedel Communications designs, manufactures, and distributes real-time networks for video, audio, data, and communications applications for broadcast, pro-audio, events, sports, theatre, and security applications worldwide, including the Winter Olympics and Commonwealth Games (2014), Red Bull Stratos (2012), Eurovision Song Contest (2011), etc. The R&D hub in Porto is tasked with providing pioneering innovations centred around nautical technology with an emphasis on water sports, so their focus is on developing tools for performance analysis on the water and providing technology that allows the nautical sports community to watch live broadcasts and interact with performance data in real-time. The staff of the department is formed by a team leader, Márcio Borgonovo-Santos, who was also my coordinator, and a team of engineers, Damián Pérez and João Almeida, and Daniela Lopes, the office manager.

1.2. Objectives

When developing the sensor, it is essential to perform mechanical, thermal, and fluid flow calibrations, since the FFS is a temperature-sensitive sensor that measures the intensity and direction of the flow mainly, but not exclusively, in water.

Searching about calibrations through a systematic review can be an example of a search strategy, since it is a methodology that seeks to locate and synthesize certain existing studies in order to determine what is known in a given field, so it is a type of research study that seeks to answer a derived research question in an organized and systematic manner.

In summary, the report is divided into two main sections: the systematic review and the practical activities, which include calibrations and data processing and analysis. Therefore, the following objectives drove the development of this report:

- Gather scientific knowledge about calibrations and sensors with the Systematic Review.
- Perform a load calibration process.
- Analyse and process data.

1.3. Structure

This report is organized into 5 chapters. In the first chapter, the context and motivations are presented, followed by the objectives and distribution of chapters, defining the structure of the document. In the second chapter, the systematic review methodology is described, displaying the keywords that lead to the research results, which are presented as a knowledge map. The following chapter will describe the methodology of the performed practical activities. And, finally, the last two chapters will present the final considerations and some guidelines for future work.

2. Systematic Review – Calibrations: Map of knowledge

2.1. Introduction

In this modern era of technology, to ensure safety and equipment performance it is crucial to use quality instruments for making various measurements including temperature, pressure, position, flow, force, and other variables (Cable, 2005). From weather to medicine, automotive to agriculture, accurate measurements are crucial for several industries, making calibrations more important, as it ensures that the instruments provide reliable data (Seifarth, 2001).

A performance measurement system generally involves defining indicators and decisions, since output data-driven by the process is used as input data to determine possible actions and choices (Franceschini, Galetto, & Maisano, 2018). Measuring is essential for performance control and improvement. Even though implementing a measurement method is not easy, it is vital to identify the right performance indicators, as many of them may not be accurate due to system failures or external disturbances. Therefore, it will be possible to maximize efficiency and effectiveness while minimizing expenditures (Husnain, Rehan, & Solomon, 2014).

Sensors are always part of a data acquisition system, since they measure physical quantities and convert them to signals that can be interpreted by instruments, so they can only be useful if they are interpreted, contextualized, and correlated with a defined purpose (Fraden, 2016). In addition to a sensor being used to monitor performance, it can provide feedback on how to improve the performance, and it can even be used in a variety of industries. Although the ideal sensor would comply with all applicable standards, such as the engineering and safety norms of equipment and performance (e.g. standard DIN 1319-1:1995-01), there will often be imprecision due to internal and external factors (*Measurement, Instrumentation, and Sensors Handbook*, 2014).

Since sensors are applied in a variety of conditions, from laboratories to harsh environments, when they show signs of nonconformity, dangerous situations can arise (Fraden, 2016). These nonconformities can be caused by time loading, temperature, and machine interaction effect, creep, drift, etc. (Kumar et al., 2011). In this regard, sensor calibration guarantees maximum performance of sensors, including their sensitivity, and their repeatability (Fraden, 2016).

Calibrating all instruments is essential for comparing their performance with known standards, which provides consistency and reduces error. This can be accomplished by using calibration graphs, mathematical equations and computerized calibration systems (Kumar, Kumar, & Yadav, 2011). In many instrumentation systems, the application of compensation strategy is used to increase static and dynamic performances. Compensations can be made for static characteristics using many methods, including isolation and zero environmental sensitivity, such as the temperature compensation method proposed by Gavrilenkov (2019), in which the strain and temperature distribution are calculated, and the Wheatstone bridge mathematical model is used as an input.

The purpose of this systematic review was to identify, synthesize, and report scientific evidences related to the three areas of interest in calibration: thermal, fluid flow, and load, to produce a summary of the research, in order to present a state of the art.

2.2. Methodology

Literature Search and Selection

A systematic review was performed by using four relevant engineering scientific databases: IEEE Xplore, Web of Science, PubMed, and SCOPUS.

In order to define the search expression, logical operators were combined with a set of keywords, in three sections: General, Specific, and Exclusion. The first section concatenates relevant research field terms. The second includes options for specific calibration types, and the third section was added to refine the search by excluding frequent terms from other scientific fields. The structure was based on MeSH terms in PubMed and Hofmann (2005).

The resulting expression was the following: (test AND transducer AND calibration AND (thermal OR load OR fluid) NOT (ion OR biological OR membranes OR brain OR aortic OR blood OR soil OR oil)).

Since SCOPUS contained more results from other fields of science, the expression for this database includes more terms to improve the outputs: (flow AND test AND transducer

AND calibration AND (thermal OR load OR fluid) NOT (ion OR biological OR membranes OR brain OR aortic OR blood OR soil OR oil OR molecular)).

In order to be included, the articles must be written in English and relate to the Metrology field. Additionally, following some consideration and a few attempts, a time restriction "since 2001" was added, getting a substantial number of results. All the information was exported to the reference management software EndNote X9 (Clarivate Analytics) and grouped by database. Once the software EndNote eliminated the duplicates, the references were refined by a three-step process: Title Selection, Abstract Selection, and Full-Text Selection.

Title Selection – Only approved the articles that showed keywords in the titles or indicated that the research topic was calibrations and measurements.

Abstract Selection – Established by the abstracts of the articles obtained that showed measurements determined on sensors and types of calibration and testing, served as research objects.

Full-Text Selection – Based on the full-text review, therefore, for an article to be included in the Systematic Review, it must have two primary characteristics: a) calibrations and measurements of sensors in the methodology; b) types of calibrations, more specifically, thermal, fluid flow or force.

2.3. Results

Research Outcomes

Combining keywords search with a date restriction yielded 70 results in IEEE Xplore, 32 in PubMed, 93 in Web of Science, and 144 in SCOPUS, which gives 339 outcomes in four scientific databases. Afterwards, 12 of these results were discarded due to being duplicates, and after that, 327 outcomes entered the title selection process. In the title selection, 197 articles were eliminated, leaving 130 for the next selection. Then, the analysis of the abstracts selected 70 relevant scientific articles and rejected 60 articles. Finally, 38 of the 70 articles passed the full-text selection, satisfying the criteria for this review (Figure 2.1).

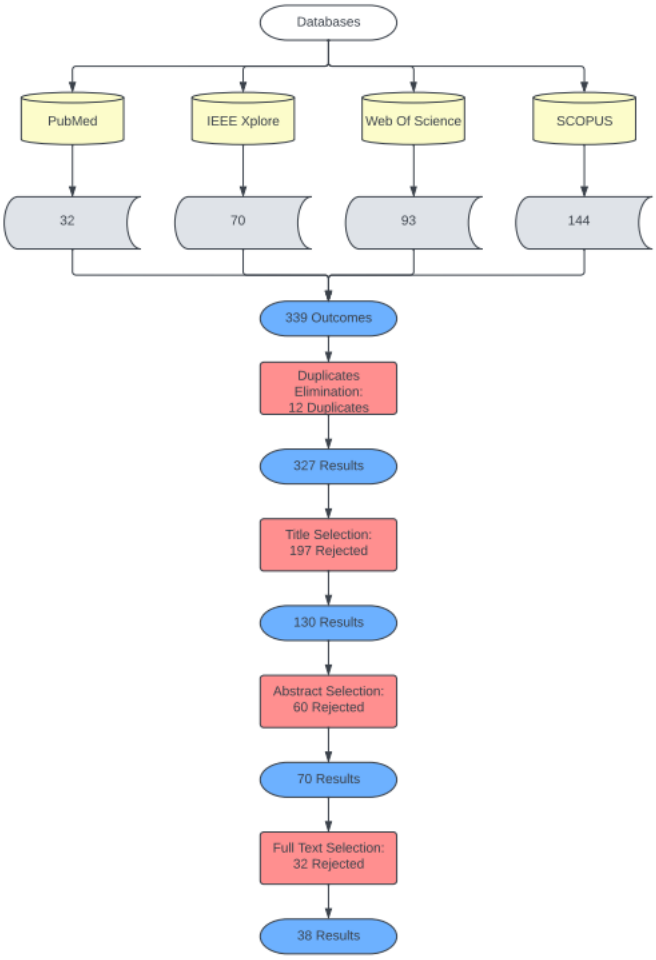

Figure 2.1 - Databases outcomes and the selection process.

To facilitate the identification of the studies, the following tables list the authors, publication year, the purpose, findings, and source for each study, along with the impact factor from 2021 of the journals. In the following tables, the journal articles are listed first (Table 2.1), followed by conference papers (Table 2.2).

Table 2.1 - List of the articles included in this review with the author/year, purpose, findings, and published journals.

Authors/Year	Purpose	Findings	Journal
Navarrini and Nesti (2021)	Vector network analyser technique used to remove the effects of the measured errors	The effects can be mitigated by using a thin sheet of lossy material inside the adapter, placed orthogonally to the work polarization, dumping down the resonances to acceptable levels for a good calibration.	Electronics Journal (Impact Factor: 2.690)
Kelemenova, Dovica, Kolarikova, Benedik, and Maxim (2021)	Calibration of load force sensor using small weights	In the indirect measurement, thanks to the use of lever transmission, it's possible to use small weights to create a load of up to 100 kg.	MM Science Journal (Impact Factor: 0.850)
Gao, Rao, Yin, Tian, and Li (2021)	Measurement of high-precision dynamic multi-component loads using an approach based on synchronizing the measuring device with the shaft rotation.	The dynamic compensation method can effectively address the existing moment of inertia problem which can benefit the measurements of highspeed rotating machinery.	IEEE Sensors Journal (Impact Factor: 4.325)
Winter et al. (2020)	Optical fiber transducer evaluation for flow monitoring in industrial environments.	The auxiliary OFs ensured the stability and support of Fiber Bragg Gratings, facilitating both static and dynamic calibration.	IEEE Sensors Journal (Impact Factor: 4.325)
Socha, Bednarz, and Zhu (2020)	Calculation of bending moment and torque in slender circular beams using a loading transducer.	The calibration factor for moment suffered deviation from the theoretical value because of manufacturing tolerances.	International Journal of Distributed Sensor Networks (Impact Factor: 1.938)
Jun, Akbar, Lei, Hua, and Danaish (2020)	Designing, analysing and calibration of a six-degree-of-freedom force/thrust measurement stand.	Providing support with the rear section at the very tail of long test objects provides more precise results.	IET Science Measurement & Technology Journal (Impact Factor: 1.517)
Goanta (2020)	Extensometer measures two mechanical strains at the same time—one from tensile load and the other from torsion load.	Considering the way, the elastic beams were made, as well the location of the strain gauges, their residual bending moments do not influence the signals acquired.	Sensors Journal (Impact Factor: 3.847)
Zheng, Zhao, Jiang, and Song (2019)	Electrostatic force used to generate dynamic force to calibrate a transducer.	The proposed calibration method could not offer a sinusoidal force signal.	IEEE Access Journal (Impact Factor: 3.476)

(To be continued)

Table 2.1 (continuation)

Zhang, Tian, Ren, Hua, and Jia (2019)	Measurement of force using a variable force ratio test system based on piezoelectric effect.	The system can be utilized for universal variable angle large force measurement (>500N) in vector control engine, friction stir welding, and large manipulator.	Advances In Mechanical Engineering Journal (Impact Factor: 1.566)
Feng, Chen, Cheng, and Zhang (2019)	Novel approach for online recalibration of wheel force transducer/sensor.	Gravity-based method takes less time because it utilizes the shape-from-motion phase to eliminate the need for data collection.	IEEE/ASME Transactions on Mechatronics Journal (Impact Factor: 5.867)
Mangini et al. (2018)	Two-phase flow analysis in a single loop pulsating heat pipe (SLPHP) filled with pure ethanol	Temperature gradients along a liquid slug could be measured with 1,5 K accuracy.	Experimental Thermal and Fluid Science Journal (Impact Factor: 3.370)
Walendziuk and Idzkowski (2017)	Presentation of a prototype version of a weight scale using a supply circuit of strain gauge load cells.	Inaccuracies in strain gauge sensor construction are the main cause of uncertainties.	Tehnicki Vjesnik-Technical Gazette Journal (Impact Factor): 0,864
Presas et al. (2017)	Determination of the frequency response function of structures	With the use of piezoelectric patches, the determination is more efficient.	Sensors Journal (Impact Factor: 3.847)
Stagonas, Marzeddu, Cobos, Conejo, and Muller (2016)	Pressure mapping system to measure wave impact-induced pressures and loads	In the strongest wave impacts, the pressure mapping system in combination with the tactile sensor used, reports shorter rise times than pressure transducers.	Coastal Engineering Journal (Impact Factor: 5.427)
Jin, Liu, Bai, Wang, and Wang (2015)	Real-time detection of liquid level by a sensor in complex environments	The system has characteristics of intrinsic safety by limiting the energy of the circuit to avoid or restrain the thermal effects and sparks.	Sensors Journal (Impact Factor: 3.847)
Hack, Lin, Patterson, and Sebastian (2015)	Reference material for establishing the minimum measurement uncertainty of optical systems for measuring 3D surface displacement fields in deforming objects.	The minimum measurement uncertainties were less than 3% for the cartesian components of displacement during static in-plane bending and less than 3 μm for out-of-plane displacements during dynamic loading.	Measurement Science and Technology Journal (Impact Factor: 2.398)

(To be continued)

Table 2.1 (continuation)

Nilsson and Rosdahl (2014)	Development and validation of portable force-measurement devices for recording forces applied by each foot to the foot bar of a kayak and the horizontal force at the seat.	A strong linearity was found between transducer output signal and load force in the push and pull directions for both foot-bar transducers perpendicular to the foot plate and the seat-force-measuring device.	Int J Sports Physiol Perform Journal (Impact Factor: 4.211)
Marcillo, Johnson, and Hart (2012)	The implementation, characterization, and evaluation of a low-cost infrasound sensor.	The low-cost sensor with low noise and high dynamic range is appropriate for infrasonic studies that may encounter high levels of background infrasound noisy and/or near-source environments.	Journal of Atmospheric and Oceanic Technology (Impact Factor: 2.531)
Macione, Nesbitt, Pandit, and Kotha (2012)	Construction of a loading machine for performing in vivo dynamic mechanical loading.	The linear amplifier improves resolution at the expense of having a shorter working range (due to saturation).	Review of Scientific Instruments (Impact Factor: 1.843)
Kumar et al. (2011)	Improved performance of force transducers with the automation of 50 kN dead weight force machine and the calibration system.	The uncertainties caused by the operator are usually dominant and must be evaluated for the given operator, although this task is very difficult.	Measurement Science Review (Impact Factor: 1.697)
Moeller and Polzin (2010)	Variation of a hanging pendulum thrust stand capable of measuring the performance of an electric thruster operating in the vertical orientation.	The error on the slope of each calibration curve represents only the error on the curve fit of the data, which in the past has been the dominant source of error in the calibration data.	Review of Scientific Instruments (Impact Factor: 1.843)
Kang, Baer, Rudert, Pedersen, and Brown (2010)	New approach to array-based contact stress sensor calibration, using a novel wringer-like calibration device.	Utilizing a traveling wave of contact load for purposes of calibrating a grid-array contact stress sensor is applicable to a wide range of specific sensor designs and transduction modalities.	Journal of Biomechanics (Impact Factor: 2.789)
Chen et al. (2005)	Underwater evaluation of the dynamic response of the fibre optic sensor.	The small profile and resistance to hydrostatic artifacts make the fibre optic pressure sensor an attractive tool for in vivo experiments.	Physiol Meas Journal (Impact Factor: 2.688)

Table 2.2 - List of the articles included in this review with the author/year, purpose, findings, and the source conference.

Authors/Year	Purpose	Findings	Conference
Zhao, Xu, Chai, Hao, and Iop (2020)	Development of a portable on-site torque wrench calibration device	The electric loading system helps operator load torque quickly, which save time and labour.	2020 4TH International Conference on Electrical, Automation and Mechanical Engineering
Karaböce, Özdingiş, Durmuş, and Çetin (2019)	Calibration of portable ultrasonic probes using a load cell-based wattmeter.	The power of the ultrasonic probes was measured in the range of 15 W - 150 W, but after using more sensitive load cells, the powers below 1 W can also be measured.	2019 IEEE International Symposium on Medical Measurements and Applications
Kang et al. (2019)	New mathematical model covering the influence of the flow velocity	The temperature of the air flowing through the flowmeter does not change during the tests.	2019 IEEE International Ultrasonics Symposium
Prilepko, Lysenko, and Iop (2018)	Creating a new high-precision calibration method of dynamic forces transducers.	Uncertainties are reduced thanks to the inertialess principle of dynamic forces excitation through a piezoactuator.	Metrology, Standardization, Quality: Theory and Practice, (Msq-2017)
Lidtke, Giorgio-Serchi, Lisle, and Weymouth (2018)	Design, calibration, and testing of an experimental rig for measuring unsteady loads underwater	The calibration protocol for the linear force and moments guarantees an optimal error constraint in steady and dynamic test cases.	2018 IEEE International Conference on Soft Robotics
Hujer and Muller (2018)	Influence of layer thickness on the calibration sensitivity of film sensors	The thickness of the protective layer defines the possible duration of the measurement.	Conference - Experimental Fluid Mechanics 2017
Foyer and Kahmann (2018)	Requirements of a force lever system to be used in nacelle test benches	A force transducer and a small change of the effective lever length are required to achieve a measurement uncertainty smaller than 1 %.	Sensors and Measuring Systems; 19th ITG/GMA-Symposium
Longo et al. (2017)	The development of an electrical and optical sensor with simultaneous measurement	Fiber Bragg Gratings sensors can be applied in severe environmental conditions.	2017 2nd International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT)
Deshpande, Jawale, and Thorat (2016)	Design, development, calibration, and testing of a cantilever beam transducer to measure three forces ignoring moments.	The variation between the results comes from strain gauge bridges that give a lot of fluctuations even after real-time averaging, the noise in the circuit cannot be fully filtered and manufacturing tolerances and misalignment of axes.	2016 7th International Conference on Mechanical and Aerospace Engineering

(To be continued)

Table 2.2 (continuation)

Weidong, Hao, and Jisheng (2013)	Review of methods for evaluating the dynamic response of force transducers against typical varying forces, and proposition of a new method for calibrating force transducers based on direct sine force load.	An analysis of the different influences on measurement uncertainty of the method indicated that the highest contribution was on the order of 1%.	2013 IEEE 11th International Conference on Electronic Measurement & Instruments
Kuells, Dessonet, Bohland, Nau, and Thoma (2013)	Proposition of a calibration method that evaluates and compares all points of the measured pulse.	Optimizing the mounting conditions can reduce the high deviations from trial to trial for the same accelerometer, and this can be helpful if a sensor's sensitivity changes from repeated loading or over time.	2013 Transducers & Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems
Alves, Dias, Cabral, Gaspar, and Rocha (2013)	Proposition of a high-resolution inclinometer.	Due to the actuation voltage resolution of 300V, the system resolution is set at 0.01˚, above the theoretical limit of 0.001˚.	2013 Transducers & Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems
Ogushi, Nishino, Maeda, and Ueda (2011)	Proposition of a calibration method of torque wrench testers (TWT) using reference torque wrenches.	The calibrated TWT was found to have the capability of a reference standard for testing commercial hand torque wrenches according to JIS B4652 requirements.	SICE Annual Conference 2011
Muftah and Haris (2010)	Modification of the torque sensor for the measurement of dynamic load during rotation.	Although the chosen strain gauges are better contact materials, a certain amount of variation of the contact resistance (contact noise) is unavoidable with slip ring transmitters.	2010 4th International Conference on Application of Information and Communication Technologies

The following graphs were created to illustrate the number of journal articles and the number of conference papers (Figure 2.2) from a time-based perspective.

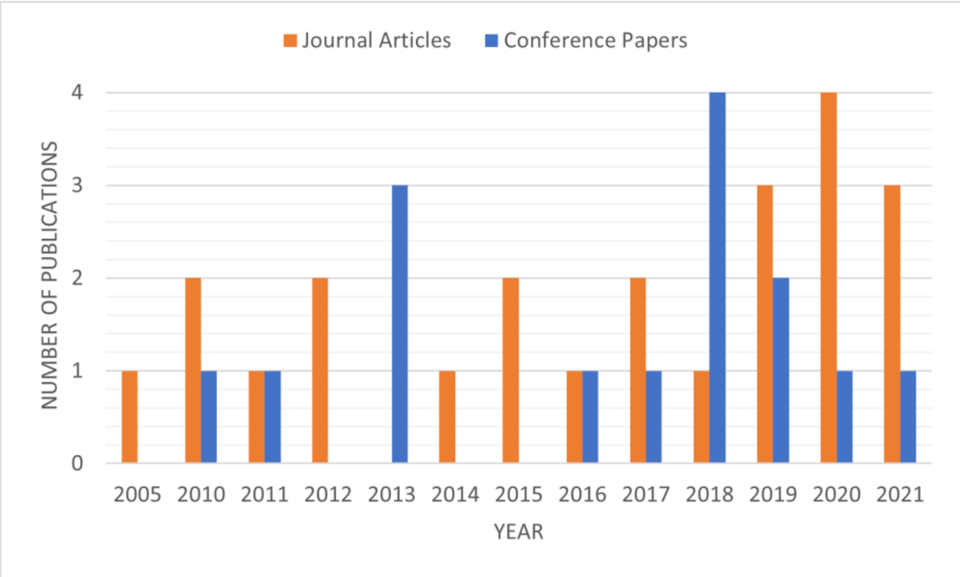

Figure 2.2 - Number of journal articles and conference papers over the years.

This research unraveled what influences and characterizes the various calibration types and methods, as well as how to apply calibration to various sensors. In addition, research findings, analyses of trends, and an overview of research fields were also presented. This systematic review culminates in the presentation of the map of scientific knowledge shown below (Figure 2.3), whose branches are discussed after.

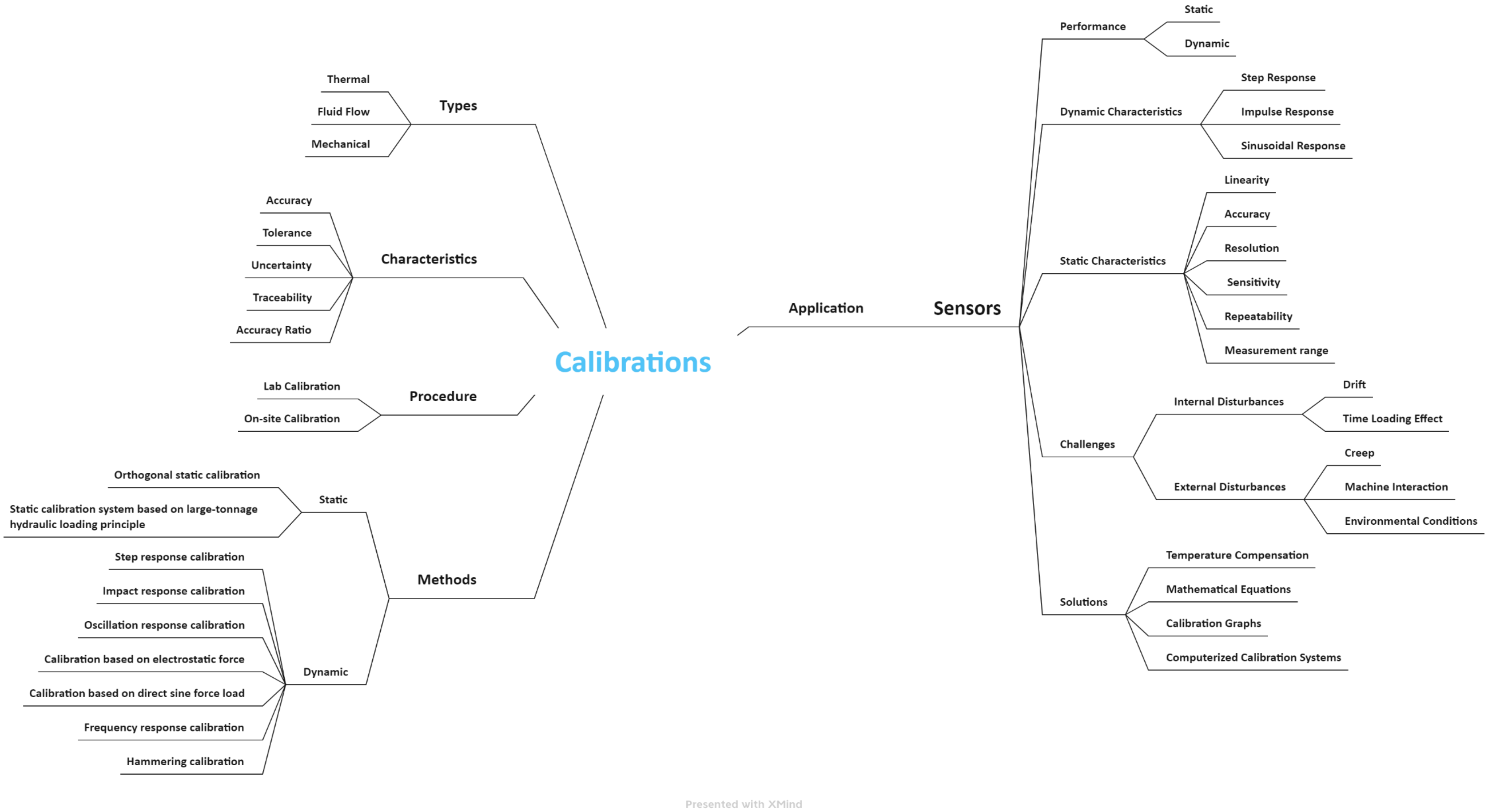

Figure 2.3 - Map of scientific knowledge of calibrations.

2.4. Discussion

In the keyword selection process, a series of experimentations led to a structure that would enable the selection of relevant publications and exclude irrelevant data. Consequently, some of the results were discarded since they were not within the scope of the research (i.e. anatomy, biology, and geology).

This systematic review used the following databases: IEEE Xplore, SCOPUS, PubMed, and Web of Science. A selection of databases was made based on the access the University provides - one focused more on engineering and the other on multidisciplinary research. For the third database, it was decided to use Pubmed since it is a free online resource for searching and retrieving biomedical literature. The search for another reliable source of results led to the selection of Web of Science, the world's most trusted global citation database.

Following the methodological structure of other studies together with the PRISMA 2020 flow diagram and checklist, the selections related to titles, abstracts, and full text were performed. The database created with the selected references underwent an in-depth reading to retrieve the words that could represent the major areas of knowledge, within the studied topic. Other researchers have employed the same methodology, for example, Borgonovo-Santos (2018) described the areas of scientific knowledge about surfing, followed by Martins (2021), which summarized information on electrical circuit sealing processes in sensors. The same methodological structure of these studies resulted in better background knowledge and decision-making concerning the experimental procedures.

In this systematic review, due to their different natures, the results were divided between conference papers and journals, differentiating the two in order to enhance the analysis. Both conference papers and journal articles require a review process before they are accepted, but journals undergo a more thorough process, whereas conference papers normally only require a general review. However, conference papers can provide valuable insights into a specific field of research such as novel approaches or methodologies.

As shown in the previous tables (Table 2.1 and Table 2.2), many different journals have been published, but "Sensors Journal" appears more often, which is excellent since it is a peer-reviewed journal with an excellent reputation. While the number of papers is much greater, the conference that was most relevant was the "Transducers & Eurosensors XXVII" that was held in 2013. Besides the source, the purposes and findings for each study are also listed in the tables.

Research purpose describes why a researcher chooses to explore a certain topic, including how it is significant and what gaps the study intends to address. In this review, the improvements and calibrations of load sensors/transducers is the most common rationale in both journals and conference papers. The findings are the outcomes that can be found during research. A major finding of this review is that thermal and fluid flow sensors are less explored compared to load sensors.

According to Figure 2.2, the number of articles published in journals has increased recently. Therefore, peer-reviewed journals are the preferred medium for presenting experiments and novel ideas. However, conference paper numbers have decreased over the past few years. The pandemic that occurred in 2020 may be one possible explanation for this occurrence.

Following the selection and reading of the articles, the most relevant topics of each article were retrieved. Based on the topics, the map (Figure 2.3) was built in order to achieve a general overview of a research topic and identify relevant concepts. However, the process can be time-consuming and can become overly complex. Next, the main branches of the map of knowledge will be discussed:

a) Calibrations Characteristics and Methods: The majority of studies focused on upgrading sensors through calibration, determining and improving accuracy, tolerance, traceability, accuracy ratio, and uncertainty values. Numerous articles provided an overview of the existing dynamic and static calibration methods, with a focus on the dynamic calibrations when it comes to improving and developing new methods.

b) Calibrations Procedures: Some papers reviewed the process of changing laboratory calibrations into intelligent on-site calibration devices, which would facilitate the process by eliminating transportation and avoiding manual operating errors.

c) Sensors Characteristics: The characteristics of the sensors were also a major topic in these papers. As observed in some articles, dynamic characteristics refer to the characteristics of the sensors output when its input changes, and are often expressed as step response, impulse response, or frequency-domain (sinusoidal) response. Static characteristics refer to the set of criteria defined for the instrument, which are used to measure quantities that slowly vary over time or mostly stay constant. Static parameters of the sensor that were discussed in the articles include linearity, sensitivity, repeatability, measurement range, accuracy, resolution, etc.

d) Sensors Challenges and Solutions: There was also a lot of discussion about problems that may arise in sensors, including either external (e.g. temperature) or internal (e.g. drift) disturbances. This can lead to changes in the zero offset, sensitivity, measurement span, etc., affecting the sensors performance. Additionally, some possible solutions are discussed in the articles that address these problems (e.g. temperature compensation and calibration systems).

2.5. Final Remarks

The variety of reports reveals the importance of calibration, as well as the wide variety of applications in sensor calibration, including offset compensation and calibration graphs. This is mainly because calibration ensures accurate measurements, which are fundamental to the quality, safety, and innovation of most products and services people use and depend on every day. Additionally, scientists may find this systematic review useful for identifying trends, strengths, and gaps in research that have yet to be fully explored, rapidly verifying the rationale and situating the findings of the reports.

3. Evaluation of the conformity between fluid flow sensors

3.1. Introduction

The world's increasing dependence on technology makes measurement science, or metrology, even more valuable. As a result, technological advancements lead to the constant requirement for even higher levels of accuracy (Nunes, 2013). Consequently, metrology and quality are two very important areas for our industry and for the society. As a result, certifications and accreditations are conducted to ensure credibility and quality assurance, as well as ensuring the effectiveness of services or products. In this process, an outside party verifies compliance with certain quality requirements by carrying out conformity assessments (Barradas & Sampaio, 2013). Thus, the performed activities in this internship contributed significantly to the hub's work with regard to future certification and accreditation.

The FFS combines a 2D flow sensor and 3D movement sensor, with a temperature monitoring system integrated; more specifically, it is a transducer that measures both direction and intensity of a flow. The device consists of a mechanical frame, with a central pin engaged on a round Maltese-cross like shaped base. Due to its perfectly orthogonal and bidirectional geometry, the mechanical frame was based on the Maltese cross, allowing to decouple the force components. With the sensor pin rising above the limit layer of water drainage, it is able to measure the relative displacement between the sliding object and the water accurately, as there are no turbulence zones present. To reduce sliding interference, the sensor must be enclosed in a casing and covered. During the activity, the central pin deflects as it resists the draining of the water (Borgonovo-Santos, 2018).

An early illustration of the FFS body with its mechanical parts can be observed in the figure 3.1. The pin (1), being more rigid than the cross, triggers an effort transference, which leads to differential deformations, depending on the direction. The deformation is measured by electronic strain gauges (4) that are strategically placed and glued on the Maltese cross (2) (Martins, 2021). Based on their purpose of use, three different sensors have been developed to meet any situation. In each of the three, the thickness of the Maltese cross varies (2, 3 or 4 mm), making it possible to use either a robust (thicker) or a more sensitive (less thick) sensor depending on the situation.

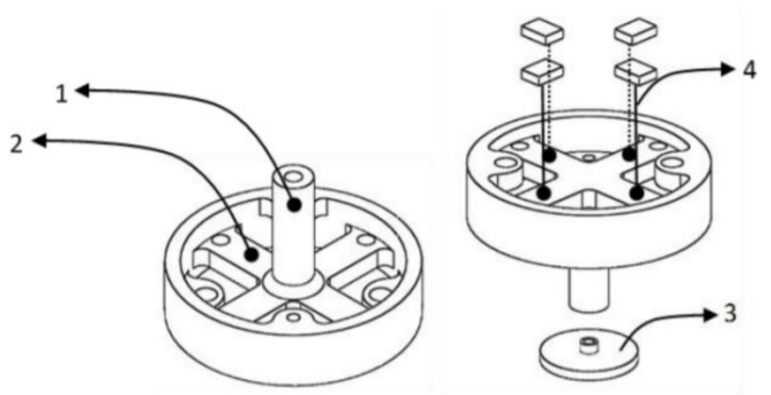

Figure 3.1 - Mechanical parts of the FFS (Borgonovo-Santos, 2018).

This third chapter describes the practical activities carried out during the internship. Besides the social adjustment, preparing periodical tasks (e.g. submission of weekly and activity reports to Riedel) or assisting with the data acquisition and data processing of experiments held outside the office, other activities were carried out. There were three main activities: the systematic review (second chapter), an analysis of gains and performance variables, and a 360º load calibration.

3.2 Methodology

An experimental approach was applied, in which six sensors were evaluated for each experiment, three sensitive (Maltese cross of 2 mm), and three other robust ones (Maltese cross of 3 mm). For each sensor, the experiments were repeated three times to test its repeatability. In order to perform the experiments, a load cell built by the team hub was used. In the calibration table (Figure 3.2) where the load cell is incorporated, there is:

- An electronic integration system, which transmits the data from the load cell and sensor to the computer;
- Three axial platform (x, y, z) that allows millimetre-scale movements. It also features locking handles that prevent the sensor from moving during the application of load;
- A housing in which the sensor is placed, having a feature that allows the rotation of the sensor to adjust the angle of the applied force;
- Table levels, that need to be calibrated to prevent surface stresses affecting the sensor.

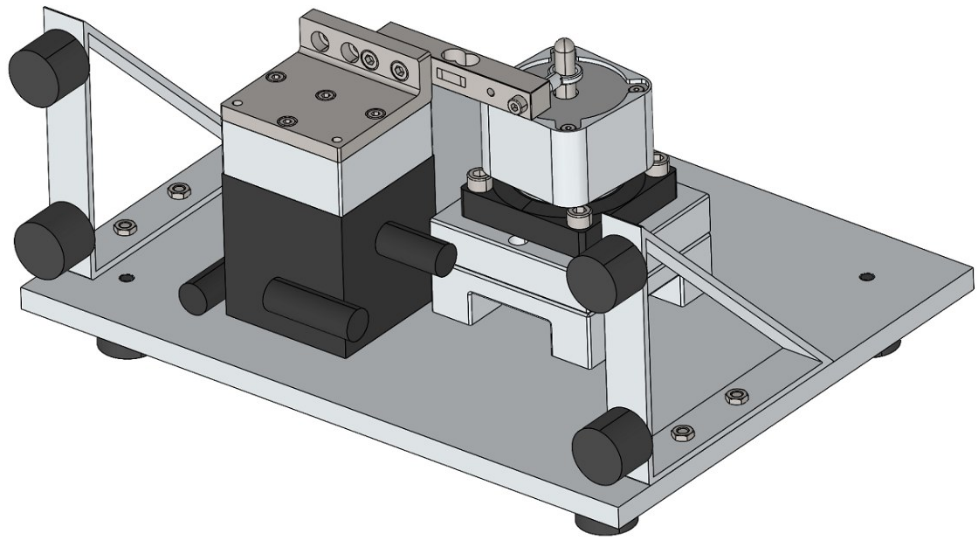

Figure 3.2 – Drawing provided by Riedel Communications of the calibration table in its early stages.

3.2.1. Analysis of Gains and Performance Variables

In this experiment, different values of total gain were used to analyse the performance variables of three sensitive and three robust sensors, including the noise range without load, the signal-to-noise ratio (SNR), the maximum load values, and the g/ADC conversion factor. Therefore, the performance variables were analysed in relation with 15 (if robust) or 16 (if sensitive) values of gains. This difference refers to the behaviour of the two groups, for example, a sensitive sensor will react more to slight changes in gains values. Each analysis was performed three times with each sensor.

In order to analyse the variables, SerialPlot v0.12 was used, which provided text log with the ADC values of both channels x and y of the corresponding applied load. In addition, only when the commands were changed with the desired gains and offset values, the data acquisition at an 80 Hz frequency began. The total gain value is calculated from the multiplication between the first (FSG), the second (SSG), and the third stage gain. The combination of the gains was obtained from FFS Datasheet.

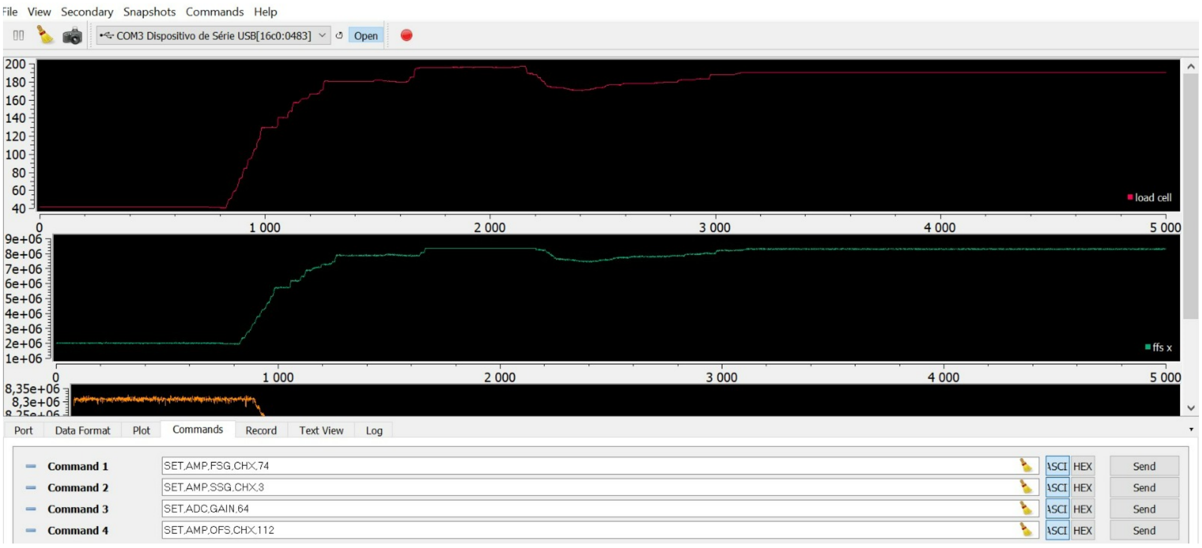

Figure 3.3 – Representation of ADC values of the channel x (green graph) responding to the appliance of load in grams (red graph) with gain values as input (the commands) displayed in the program SerialPlot.

The experiment was conducted on the axis x (0º angle) after preparing the table, inserting the sensor, aiming it at 0º and setting the requested gains. First, the lower and higher threshold values of ADC were obtained to determine the noise range without load. Then, the maximum load that could be achieved depending on the gains was implemented on the sensor, and the corresponding ADC values were collected. However, with some gain values the maximum load was calculated because the maximum could not be reached since the load cell is only capable of applying 400 grams. Consequently, the average value of ADC with and without load could be calculated, thus determining the range of ADC. Based on these values, the signal-to-noise ratio, maximum load values and the conversion factor were calculated.

3.2.2. Load Calibration 360º

This experiment began with installing the sensor into the calibration table. Afterwards, the load calibration process was conducted by applying a dynamic load from zero to 400 grams in slow motion so the program SerialPlot v0.12 could detect the maximum number of samples. The load application was performed at eight different angles (0º, 45º, 90º, 135º, 180º, 225º, 270º, and 315º). Since channel x is oriented along the axis of 0° to 180°, and channel y along the axis of 90° to 270°, both of them are affected differently depending on the applied angle. In this case, and given the sensor's geometry, it was crucial to perform a crosstalk analysis. Crosstalk occurs due to the rigid nature of the system, which causes a coupling between channels. Consequently, the output of each channel considers both channels as a result of a matrix calibration designed to solve the crosstalk.

3.2.3. Data Processing

Data processing begins with a careful inspection of the data to identify problems such as anomalies and discrepancies. At this stage, it is already possible to apply statistical methods with the means to detect anomalies and define the best strategy to deal with them. Some examples of tasks performed during data cleaning processing were the deletion or replacement of duplicate, null, or inconsistent values. It is important to remember that data cleaning is also part of quality control, so one can conclude that this processing is essential for reliable results.

As part of the data processing, Excel macros were developed to automate the process. Macros are stored sequences of commands and functions used to complete tasks faster and more efficiently. Thus, the developed macros proved to be very useful when it came to reducing the time spent on repetitive tasks, such as importing text files into Excel, arranging data in tables, and automating calculations.

3.2.4. Statistics

In order to interpret the results of an experiment, the resultant data of an experiment must be analysed statistically. Choosing a test to analyse data depends on its type and some key properties. These experiments were conducted using three robust and three sensitive sensors, repeating each sensor three times before representing them with its mean and standard deviation.

Then, it was decided to conduct an analysis of variance (ANOVA), since it finds significant differences between the means of three or more independent groups. Since the analysis of gains, contained only one independent variable (values of gains), the One-Way ANOVA was chosen (Neideen & Brasel, 2007) to see if there were any significant differences between sensors of the same group. Additionally, in the ANOVA test there are two possible hypotheses: the null hypothesis (no difference between the groups and equality between means) and the alternative hypothesis (difference between the means and groups). As each sensor underwent three trials, repeated measures ANOVA was used in both experiments to test its repeatability, testing performance variables in the first experiment and equation coefficients in the second experiment.

3.3 Results

3.3.1. Analysis of Gains and Performance Variables

As previously mentioned, a total of three robust and three sensitive sensors were subjected to testing. Below are the results of the first experiment already represented by mean and standard deviation. The Table 3.1 shows the results of the three sensitive sensors, while Table 3.2 displays the results of the three robust sensors.

Table 3.1 - Mean and standard deviation of the performance variables of the three sensitive sensors.

Sensitive Sensors								
Gains	Noise Range		Maximum Load		g/ADC Conversion Factor		SNR	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
66560	631616	67109	0.033	0.004	0.000003726665	0.000000087980	13.28	2.38
33280	329155	28486	0.064	0.004	0.000007426213	0.000000134167	25.11	3.83
25702	268804	26621	0.083	0.002	0.000009631248	0.000000177275	30.42	1.92
10281	113062	2353	0.191	0.012	0.000024101939	0.000000486482	66.70	5.43
6426	64831	1845	0.305	0.026	0.000038629452	0.000000860912	117.58	15.69
3974	40040	3499	0.476	0.011	0.000062377871	0.000001210019	164.71	13.68
3201	30928	1448	0.671	0.129	0.000077343577	0.000001511539	171.33	7.69
2496	25278	368	0.986	0.110	0.000099404704	0.000001935231	160.95	6.78
1792	17485	1381	1.363	0.140	0.000138631555	0.000002687192	167.58	14.62
832	8447	660	2.273	0.396	0.000297483790	0.000005790457	161.19	10.61
520	5112	321	3.998	0.100	0.000475569964	0.000009250017	165.41	7.72
402	4009	179	5.206	0.069	0.000617161499	0.000011834004	163.61	10.62
245	2448	191	8.524	0.181	0.001013748999	0.000019786944	163.44	11.50
155	1627	106	13.857	0.619	0.001597644211	0.000031478907	155.60	7.85
97	976	50	21.877	1.900	0.002557257734	0.000049820832	162.03	7.61
28	298	8	87.108	9.138	0.008878145578	0.000176608505	152.46	4.36

Table 3.2 - Mean and standard deviation of the performance variables of the three robust sensors.

Robust Sensors								
Gains	Noise Range		Maximum Load		g/ADC Conversion Factor		SNR	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
66560	869052	197282	0.083	0.011	0.000011353739	0.000000210146	8.08	2.64
33280	453688	95324	0.178	0.011	0.000022653652	0.000000354261	16.56	4.08
25702	346114	79842	0.241	0.035	0.000029326429	0.000000460120	23.03	5.27
10281	136361	27141	0.558	0.012	0.000073124413	0.000001159281	41.46	8.76
6426	85743	17318	0.881	0.074	0.000117063936	0.000001767859	41.21	8.12
3974	54203	9544	1.990	1.087	0.000189391057	0.000002970612	40.11	6.68
3201	40812	10368	2.706	1.307	0.000234705809	0.000003587093	43.73	10.67
1792	23554	5631	5.682	2.169	0.000420848198	0.000006534382	42.12	9.54
832	11231	2358	7.071	0.561	0.000902309569	0.000014727759	40.96	8.75
520	7194	1669	11.771	0.367	0.001442652460	0.000024005235	40.19	8.32
402	5561	1370	15.597	1.420	0.001872826032	0.000030806576	40.08	8.99
245	3386	795	25.822	2.742	0.003078978823	0.000048033805	40.12	9.54
155	2107	531	39.719	2.631	0.004851053962	0.000077588989	41.30	10.32
97	1267	317	67.905	8.963	0.007749841608	0.000131772321	42.65	9.59
45	602	162	157.142	92.179	0.016808890354	0.000295730260	41.82	11.04

In order to determine these variables, the following calculations were carried out:

$$Noise\ range = ADC\ Higher\ value\ without\ load - ADC\ Lower\ value\ without\ load$$

$$Maximum\ Load(kg) = \frac{(Maximum\ Load\ manually\ achieved) \times (Maximum\ ADC\ value\ that\ can\ be\ achieved)}{Maximum\ ADC\ value\ manually\ achieved} \times 0.001$$

$$Conversion\ factor\ \left(\frac{g}{ADC}\right) = \frac{|Maximum\ Load\ manually\ achieved|}{|ADC\ range|}$$

$$SNR = \frac{|ADC\ range|}{|Noise\ Range|}$$

After the practical part, as each sensor was put through the experiment three times, the repeated-measure test was used to assess repeatability, and no significant differences were found, since in every statistical test made the p-value was always greater than 0.05 (Table 3.3). Afterwards, the p-values of each group of sensors were evaluated to see if there were differences among the sensors of the same group, but no significant differences were found. (Table 3.4).

Table 3.3 - Statistical test between repeated measures.

Anova: Single Factor - Between tests	
Sensor	P-value
Sensitive nº 1 (S1)	0.999985
Sensitive nº 2 (S2)	0.999998
Sensitive nº 3 (S3)	0.999998
Robust nº 1 (R1)	0.999993
Robust nº 2 (R2)	0.999997
Robust nº 3 (R3)	0.999878

Table 3.4 - Statistical test between sensors of the same group.

Anova: Single Factor	
Group	P-value
Sensitive Sensors	0.998753
Robust Sensors	0.998676

3.3.2. 360º Calibration

For this experiment other three robust sensors and three sensitive sensors were chosen to go through testing. An algorithm developed in MATLAB provided the results of the axis correction, root mean square error, angle deviation, conversion factor, and crosstalk factor, and these factors led to equations for a regression model. The next set of images will show the results associated with the sensitive sensors first test.

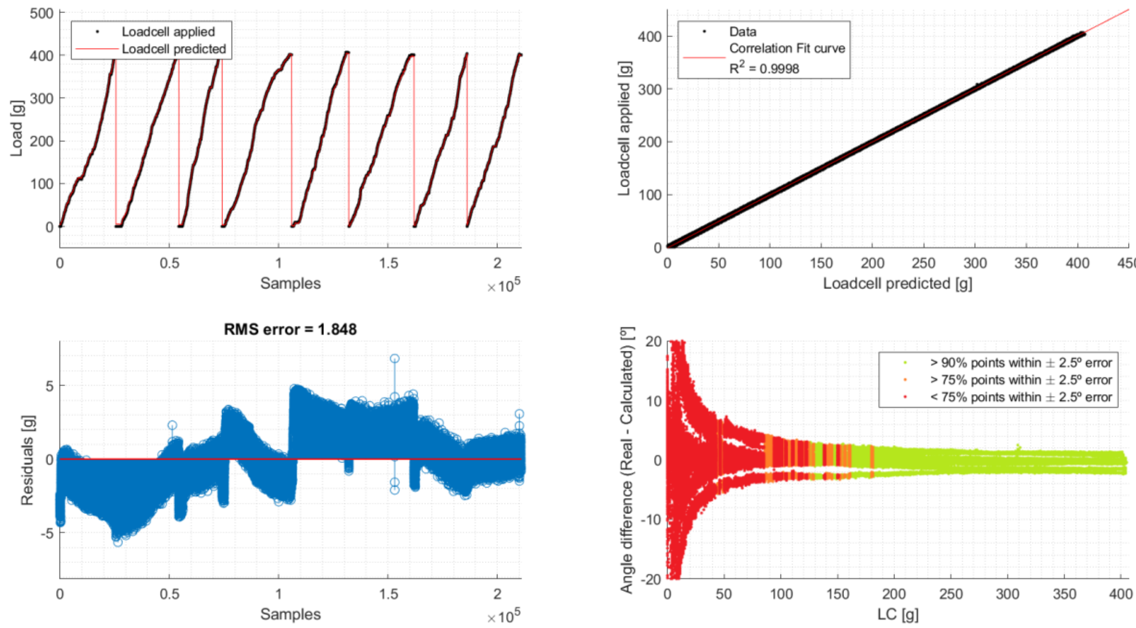

Figure 3.4 - MATLAB results of S1 first test with the associated simulation of the applied load, correlation fit curve with the coefficient of determination, the root mean square error and the deviation of the angle applied.

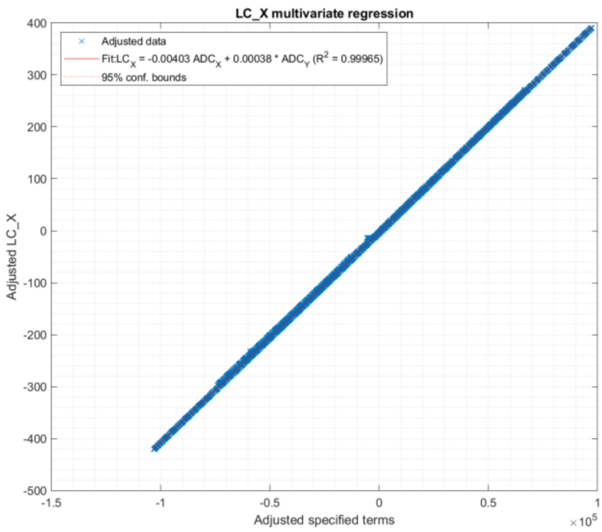

Figure 3.5 - MATLAB results of S1 first test with axis X associated equation

(Load Cell$_x$ = Coef.$_{11}$ * ADC$_x$ + Coef.$_{12}$ * ADC$_y$)

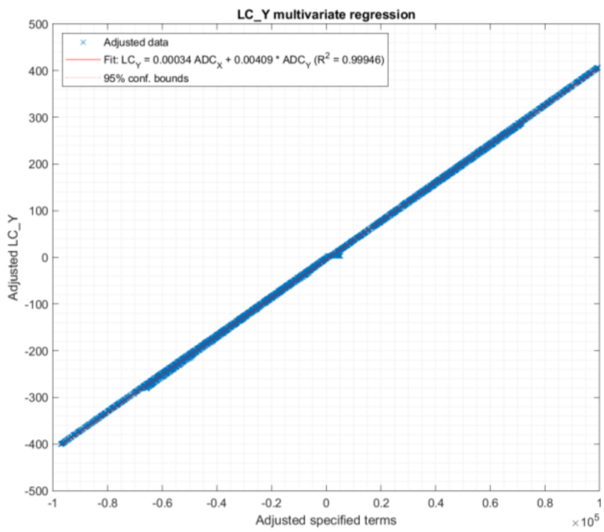

Figure 3.6 - MATLAB results of S1 first test with axis Y associated equation

(Load Cell$_y$ = Coef.$_{21}$ * ADC$_x$ + Coef.$_{22}$ * ADC$_y$)

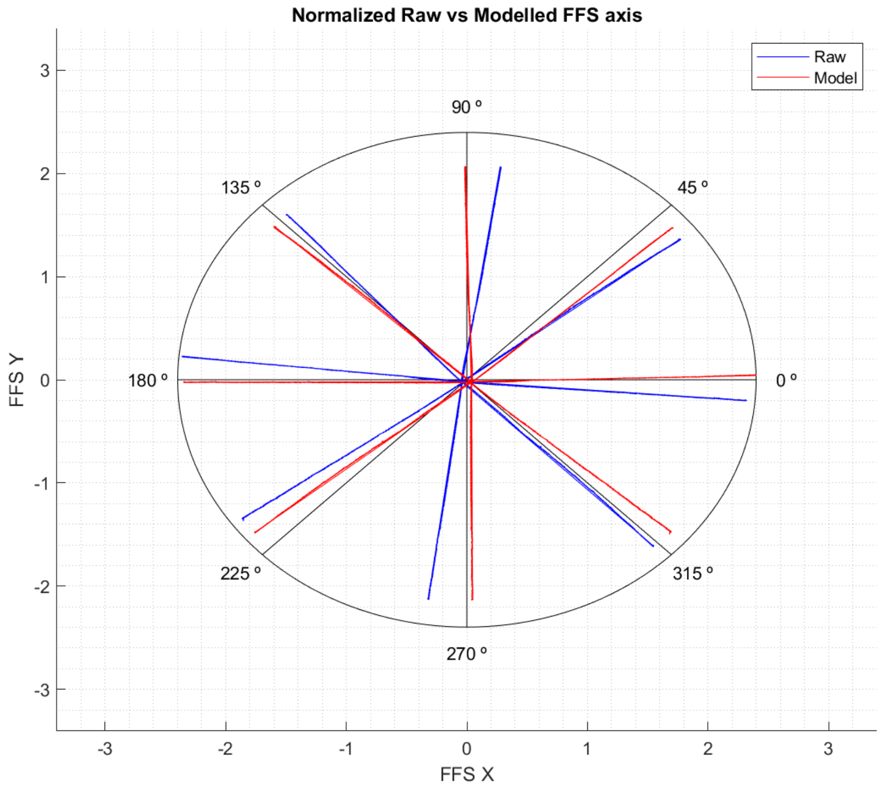

Figure 3.7 - MATLAB results of the axis correction adjustment of S1 first test.

As mentioned previously, each sensor was tested three times, so tests of variance of repeated measures were performed and the p-value was always higher than 0.05, so no significant differences were found between tests. Then, each sensor mean coefficients were represented, and a between-sensor test of variance was conducted, and no significant differences were found (p-value > 0.05). As a result, using all the regression models derived from the coefficients of the equations, another model could be constructed that summed all three sensors of each type. Below are the regression models constructed for sensitive and robust sensors (Tables 3.5 and 3.6); however, the third sensitive sensor malfunctioned during testing, so there are no results available.

Table 3.5 - Constructed regression model of the sensitive sensors.

FFS_Sensitive_001				FFS_Sensitive_002			
Average Trials Coefficients				Average Trials Coefficients			
C_{11}	C_{12}	C_{21}	C_{22}	C_{11}	C_{12}	C_{21}	C_{22}
-0.004047118114	0.000434402521	0.000350438638	0.004086504497	-0.003959217642	0.000425502690	0.000420955291	0.003923987566
Sensitive Sensors - Average Coefficients							
C_{11}		C_{12}		C_{21}		C_{22}	
-0.004003167878		0.000429952605		0.000385696964		0.004005246032	
Regression Model ($F_X = C_{11}*ADC_X + C_{12}*ADC_Y$)				Regression Model ($F_y = C_{21}*ADC_X + C_{22}*ADC_y$)			
$F_X = -0.004003167878*ADC_X + 0.000429952605*ADC_Y$				$F_y = 0.000385696964*ADC_X + 0.004005246032*ADC_Y$			

Table 3.6 - Constructed regression model of the robust sensors.

FFS_Robust_001				FFS_Robust_002				FFS_Robust_003			
Average Trials Coefficients				Average Trials Coefficients				Average Trials Coefficients			
C_{11}	C_{12}	C_{21}	C_{22}	C_{11}	C_{12}	C_{21}	C_{22}	C_{11}	C_{12}	C_{21}	C_{22}
-0.011955204033	0.001148416394	0.001152411132	0.011554285706	-0.011399550736	0.002001496590	0.002156055122	0.011516604770	-0.011971850349	0.002039293492	0.001885479593	0.012079351269
Robust Sensors - Average Coefficients											
C_{11}			C_{12}			C_{21}			C_{22}		
-0.011775535039			0.001729735492			0.001731315282			0.011716747248		
Regression Model ($F_X = C_{11}*ADC_X + C_{12}*ADC_Y$)						Regression Model ($F_y = C_{21}*ADC_X + C_{22}*ADC_y$)					
$F_X = -0.011775535039*ADC_X + 0.001729735492*ADC_Y$						$F_y = 0.001731315282*ADC_X + 0.011716747248*ADC_Y$					

3.4 Discussion

As illustrated in the results, the experiments conducted in this work demonstrated the high-quality of the sensor performance.

Regarding the first experiment, it is clear that the sensors always perform precisely as expected, as when gain values decrease, noise range values also decrease, while maximum load, conversion factor g/ADC, and signal-to-noise ratio values increase. Although, the signal-to-noise ratio values reach a certain level of stabilization at some point.

In addition, the performance variables associated with gains were evaluated, allowing it to determine which gains are most suitable for different applications. As an example, the team provided a table converting kilograms of maximum load into velocity (m/s or km/h) and another table indicating the range of speeds that can be reached in various sports:

- Swimming: [0-10] m/s
- Surfing: [0-50] km/h
- Rowing: [0-30] km/h
- Big wave surfing: [0-70] km/h
- Sailing: [0-120] km/h

Furthermore, the 360º calibration demonstrated that the sensors always performed with excellent precision, enabling regression models to be associated with each sensor group. In addition, this calibration has proven effective in removing crossover effects.

3.5 Conclusion

The performed experiments displayed high repeatability and great consistency since all statistical tests to discover any significant differences generated p-values greater than 0.05. Therefore, neither the analysis of gains nor the calibration results showed any significant differences. Aside from one sensor malfunctioning, all sensors exhibited high-quality performance in the sampling processes, which is a promising development for the future work of the company.

Due to the fact that sensors from different groups (sensitive and robust) were developed with a different purpose, they cannot be tested against one another. The robust sensors, for example, were designed to support greater loads than the sensitive sensors and can therefore be used in different sports applications. Consequently, an activity that reaches higher velocity, for example sailing, would require a more robust sensor than surfing, since the applied load on the pin is much higher.

4. General Conclusions

In order to characterize all the scientific knowledge on calibrations and sensors in the most comprehensive manner possible, a systematic review was developed in this work. An overview of the results was presented as a knowledge map, which revealed at least five distinct scientific areas around calibrations: types, characteristics, procedures, methods, and applications.

Having thoroughly reviewed and understood the subject beforehand, the experimental part followed. To determine if the sensors worked as expected, reproducibly and precisely, performance variables in relation to gain values were analysed first, followed by a 360º load calibration. As a result of this stage of the work, it is possible to conclude:

- There was a great deal of consistency and repeatability in the results of the experiments conducted;
- No significant differences were found between trials or sensors of the same group on the analysis of gains or the calibration results;
- The sensors displayed high-quality performance in every experiment;
- Sensors of different types (robust and sensitive) serve different applications, as indicated by their maximum load values.

As a result, it can be concluded that this internship was successfully completed by performing a systematic review, gaining knowledge about calibrations and sensors, performing a load calibration process, and processing and analysing data. In addition, having the opportunity to do an internship at RIEDEL Communications R&D, an environment in which I always felt comfortable, has helped me gain the confidence to face the job market, gain knowledge about the field, and acquire skills that will be useful in a future workplace.

5. Future Work

As discussed previously, there are three types of calibrations required for the fluid flow sensor: load, thermal, and fluidic. Since only a load calibration could be performed in this internship, the next step would be to perform the other calibrations and analyse the results. In the event that the results are as promising as those in this report, and if the sensor is ready, the next phase would be to conduct more experiments outside of the laboratory. The advantage of conducting these kinds of experiments is that the sensor would be used in its intended environment, which has always a greater number of variables to handle than an enclosed environment, such as a laboratory. For this reason, the sensors might even behave differently, making room for future developments. If the product behaves in the same way, it demonstrates that the product has the quality to work perfectly, regardless of the environment.

6. References

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