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Development of a Sensor-based Portable Data Collection System for Climbers

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Abstract

Motivation The Internet of Things is widening our conception of the internet and has become one of the most interesting technological fields of the moment. Thanks to its versatility, it can find applications in several fields, including home automation, healthcare, and sport. Particularly in the sports domain, there are many possibilities to enhance the athletes' experience with intelligent solutions.

Problem statement While wearable devices and sensors-based solutions are proving successful in collecting and analyzing data about many activities, climbers do not have a portable, reliable and integrated system to collect data about their sport. Given the rise in popularity of climbing, this thesis aims to define the implementation of a system that allows collecting data about indoor climbing activity.

Approach The first step was to outline the problem, identify possible requirements for the candidate solution, and study possible existing solutions. After that, this thesis describes the architecture of a prototype system based on accelerometers, gyroscopes, and magnetometers, along with the validation tests conducted on it.

Results The developed prototype could comply with the defined requirements and proved to be an effective solution to collect information about climbing against several unit tests, although the solution still lacks long-term on-field tests.

Conclusions The presented solution is a stable system for data sampling in indoor climbing environments. In addition to this, its flexibility and portability open the possibility of applying the same solution to outdoor climbing and other sports activity, with few minimal adjustments.

Riassunto

Motivazione L'Internet delle Cose sta estendendo la nostra concezione di Internet, diventando uno dei campi tecnologici più interessanti del momento. Grazie alla sua versatilità, può trovare applicazione in diversi campi, tra cui domotica, medicina e sport. Specialmente in ambito sportivo, ci sono molte possibilità per migliorare l'esperienza degli atleti con soluzioni intelligenti.

Problema Mentre i dispositivi *wearable* e le soluzioni basate su sensori si sono dimostrate efficaci per raccogliere e analizzare dati su vari sport, arrampicatori e arrampicatrici non hanno un sistema portatile, affidabile e integrato per la raccolta di dati sul loro sport. Vista la crescita in popolarità dell'arrampicata sportiva, questa tesi si pone l'obiettivo di definire l'implementazione di un sistema che permetta la raccolta di dati sull'arrampicata sportiva in palestra.

Approccio Il primo passo è stato delineare il problema, identificare i requisiti per la soluzione proposta e studiare varie soluzioni già esistenti. In seguito, questa tesi descrive l'architettura di un prototipo, basato su accelerometri, giroscopi e magnetometri, e presenta una suite di test condotti per valutarne la validità.

Risultati Il prototipo sviluppato è stato in grado di soddisfare i requisiti definiti e si è dimostrato una soluzione efficace per raccogliere informazioni sull'arrampicata a fronte di diversi test unitari, nonostante la soluzione manchi ancora di test sul campo a lungo termine.

Conclusioni La soluzione proposta si dimostra un sistema stabile per il campionamento dei dati in ambienti di arrampicata al chiuso. Inoltre, la sua flessibilità e portabilità consentono di applicare la stessa soluzione all'arrampicata all'aperto e ad altri sport, con poche, minime modifiche.

Zusammenfassung

Motivation Das Internet der Dinge erweitert unsere Vorstellung vom Internet und hat sich zu einem der gegenwärtig interessantesten Technologiebereiche entwickelt. Dank seiner Vielseitigkeit kann es in verschiedenen Bereichen Anwendung finden, darunter Heimautomatisierung, Gesundheitswesen und Sport. Vor allem im Sportbereich gibt es viele Möglichkeiten, das Erlebnis der Sportler mit intelligenten Lösungen zu steigern.

Problemstellung Während sich tragbare Geräte und sensorbasierte Lösungen zur Erfassung und Analyse von Daten über viele verschiedene Aktivitäten als erfolgreich erweisen, gibt es für Kletterer und Kletterinnen kein tragbares, zuverlässiges und integriertes System zur Erfassung von Daten über ihren Sport. Angesichts der steigenden Popularität des Kletterns zielt diese Arbeit darauf ab, die Implementierung eines Systems zu definieren, das es ermöglicht, Daten über Indoor-Kletteraktivitäten zu sammeln.

Ansatz Der erste Schritt bestand darin, das Problem zu umreißen, mögliche Anforderungen an die zu entwickelnde Lösung zu ermitteln und bereits vorhandene Lösungen zu untersuchen. Anschließend wird in dieser Arbeit die Architektur eines Prototyps beschrieben, der auf Beschleunigungs-, Kreisel- und Magnetometern basiert, sowie die daran durchgeführten Validierungstests.

Ergebnisse Der entwickelte Prototyp konnte die definierten Anforderungen erfüllen und erwies sich als effektive Lösung zur Sammlung von Informationen über das Klettern anhand verschiedener Einheitstests, obwohl die Lösung noch nichtlangfristig in der Praxis getestet wurde.

Fazit Die vorgestellte Lösung erweist sich als ein stabiles System für die Datenerfassung in Kletterhallen. Zusätzlich eröffnen seine Flexibilität und Tragbarkeit die Möglichkeit, dieselbe Lösung mit wenigen geringfügigen Anpassungen auch beim Klettern im Freien und bei anderen sportlichen Aktivitäten einzusetzen.

This thesis would not have been possible without the support of my family, friends, colleagues, and mentors.

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Chapter 1

Introduction

1.1 Motivation

More than 30 years have passed since a modified Coke machine at Carnegie Mellon University became the first internet-connected appliance, officially introducing the concept of a "network of smart devices" [1]. In the forthcoming years, this idea will develop until, in 1999, Dr. Kevin Ashton will define it with the now well-known expression "Internet of Things" (IoT). As Dr. Ashton stated, "The Internet of Things has the potential to change the world, just as the Internet did. Maybe even more so." [2] and in 2022, it is safe to state that the IoT has grown to become one of the core topics of modern technology, with various fields and applications, including but not limited to home automation, healthcare and medicine, industry 4.0 and sport.

Notably, the sports domain offers several possibilities to develop and engineer solutions that employ connected devices to enhance the athletes' experience. Using modern technologies, in fact, it is possible to increase safety, to reduce risks of incidents, or provide faster and more practical support if needed. In addition, an exhaustive collection and analysis of data allow an in-depth evaluation of a sports performance, which in turn can help identify weaknesses, mistakes, and possible improvements, thus significantly supporting the athletes' development [3].

1.2 Objective

In the last years, climbing has grown to be a viral activity [4], thus causing an increased interest in developing technological solutions to improve the climbing experience. This has been confirmed by the debut of climbing as a discipline in the last 2020 Tokyo Olympic Games program [5]. This thesis aims to compare possible pre-existing technologies and present an IoT-system architecture that uses sensors to collect data about indoor climbing activity.

1.3 Approach

To design the Data Collection System for indoor climbing activity, the first step was a study of the climbing environment to have a better, more precise perception of the project's scope. Next, a research phase was conducted, which allowed us to find a series of possible solutions and approaches to the problem. Finally, we compared the alternatives to reach the envisioned solution after defining a series of requirements used to evaluate it. This solution was designed carefully regarding said requirements and was tested and evaluated during field experiences.

1.4 Structure of the thesis

This thesis is divided into seven sections; it starts with an introduction (Chapter 1), pointing out the problem at a high level, the objective and giving an overview of the applied approach. Then it goes over the problem statement (Chapter 2), which describes the requirements we envision for the proposed tool, defines the system's context at a deeper level, and provides a series of definitions related to the problem's domain. The subsequent section gives an overview of the state of the art (Chapter 3) of the different data collection strategies and technologies that can be applied in the climbing environment. Following that, (Chapter 4), an illustration of the envisioned solution and a description of the system's architecture illuminate the system from different viewpoints. After that, the next section (Chapter 5) will present the method used to validate and test the developed solution. The successive section (Chapter 6) will report the evaluation results and the implications they suggest about the initial research question. Finally, the last section (Chapter 7) summarizes the major activities that were conducted, their relevance, and illustrates faced technical problems and some possible future work.

Chapter 2

Problem Statement

The goal of this thesis is to describe the implementation of a technologically stable solution that allows collecting information about indoor climbing activity in gym halls to improve the climbing experience for both gym personnel and athletes.

This chapter aims to provide a more extensive outline of the problem, complemented by several definitions that can be useful to fully understand the problem's domain and the judgments reached throughout this work.

2.1 System Context

As depicted in the Context Diagram (Figure 2.1), the system will have three main stakeholders: the climbers, who will use the system and generate data to be sensed, the gym staff, responsible for maintaining the system, and the administrator, responsible for performing higher-level operations. Furthermore, the solution will interface with external systems by uploading sensed data to a backend service responsible for data analysis and leveraging GitHub as a Version Control System.

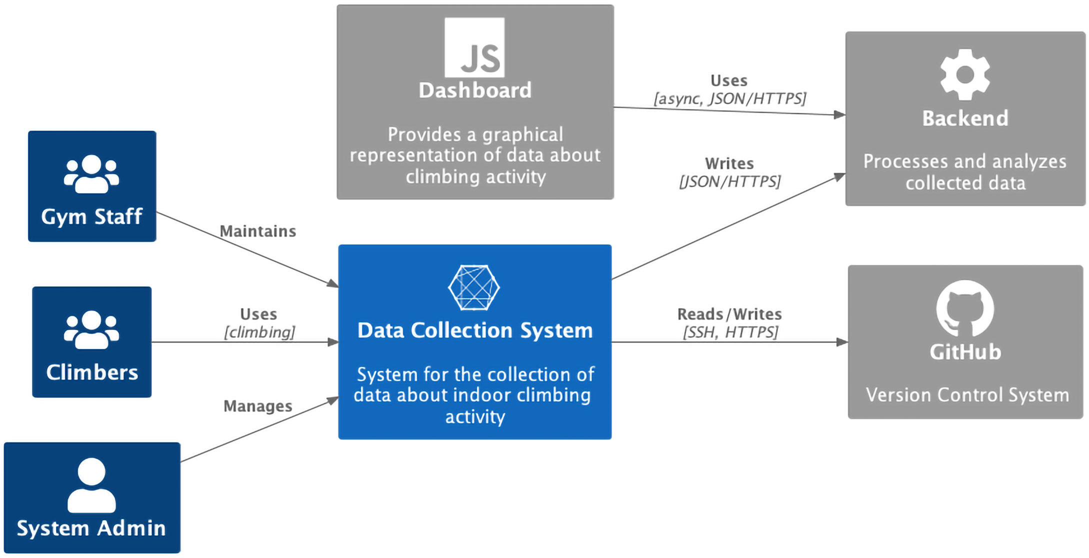

Figure 2.1: Context Diagram of the Data Collection System

2.2 Sport Climbing

A quick introduction to Sport Climbing and some technical definitions are now presented to understand the possible alternative solutions that can be adopted to tackle the problem.

The general definition of Sport Climbing, provided by F.A.S.I. *(Federazione Arrampicata Sportiva Italiana)*, states that "Sport Climbing is an individual sport discipline, consisting of natural climbing (i.e., without the aid of artificial means that could help progression), for competitive, amateur, and educational purposes. It can be carried out either on natural or artificial walls, along routes controlled from the base, or on appropriately equipped boulders" [6]. The objective of athletes who try their hand at Sport Climbing is to overcome different routes, usually of increasing difficulty, using specific, limited equipment, which includes a climbing harness, a rope, and, according to the specific discipline, quickdraws or belay devices. It is also customary to use climbing shoes, gloves, and a chalk bag, although they are not strictly necessary.

For simplicity, it was decided to develop a solution applied to indoor, artificial walls, which can provide a more stable and isolated testing environment. However, for future developments, it will be of interest to extend the solution to also monitor outdoor, natural walls. The three main styles of indoor climbing, better explained in the upcoming subsections, are **Top Rope Climbing**, **Lead Climbing**, and **Bouldering**.

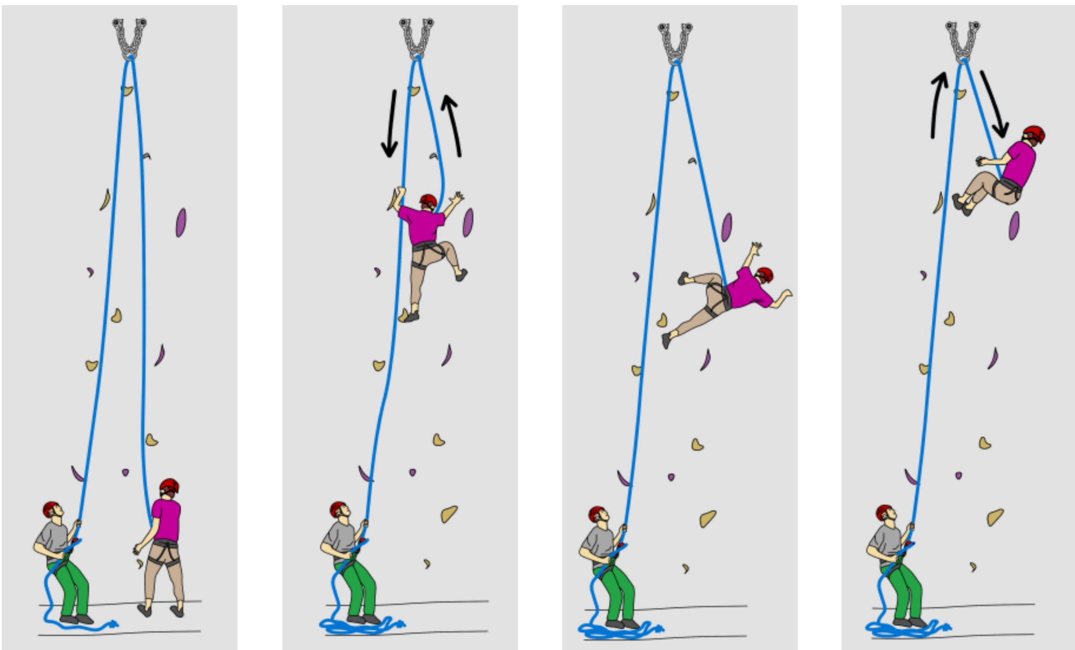

Figure 2.2: Schematic Representation of Top Rope Climbing. *Courtesy of Vdiff Climbing* [7]

2.2.1 Top Rope Climbing

Top Rope Climbing (also called Top Roping, Figure 2.2) is a style that requires two people: a climber and a belayer. The climber is secured to a rope, which is passed through an anchor system positioned at the top of the route. Finally, the belayer, who remains on the ground at the base of the wall, holds the rope's other end. While the climber proceeds up the wall, the belayer is tasked with taking in the slack rope through a belay device. This procedure ensures that if the climber loses grip, he/she would only fall for a short distance since the rope is kept tight by the friction created from the rope running through the belay device.

Top Rope Climbing is frequent in indoor climbing, is generally considered safer, and requires less skill, thus being the most suitable climbing style for beginner athletes [7].

2.2.2 Lead Climbing

While deemed more challenging and for more experienced climbers, in Lead Climbing, as represented in Figure 2.3, instead of relying on a top anchor system, the climber clips the rope into quickdraws as he/she climbs. In this variant, if the climber falls, the belayer can hold the fall via the rope running through the highest secured quickdraw: this means that, when practicing Lead Climbing, there is a higher fall potential since, in the event of the climber falling right before reaching a quickdraw, there will be a free fall (which in some cases can be of several meters) before being secured by the last reached quickdraw.

Lead Climbing can be performed outdoors and indoors, with slight differences between the two variants. In indoor Lead Climbing, gym halls are already equipped and provide quickdraws on the walls, on which climbers have to clip the rope. In outdoor Lead Climbing (i.e., on natural walls), lead climbers have to carry their quickdraws, which have to be secured on permanent bolts, nuts, or cams, before the rope can be clipped to them [7].

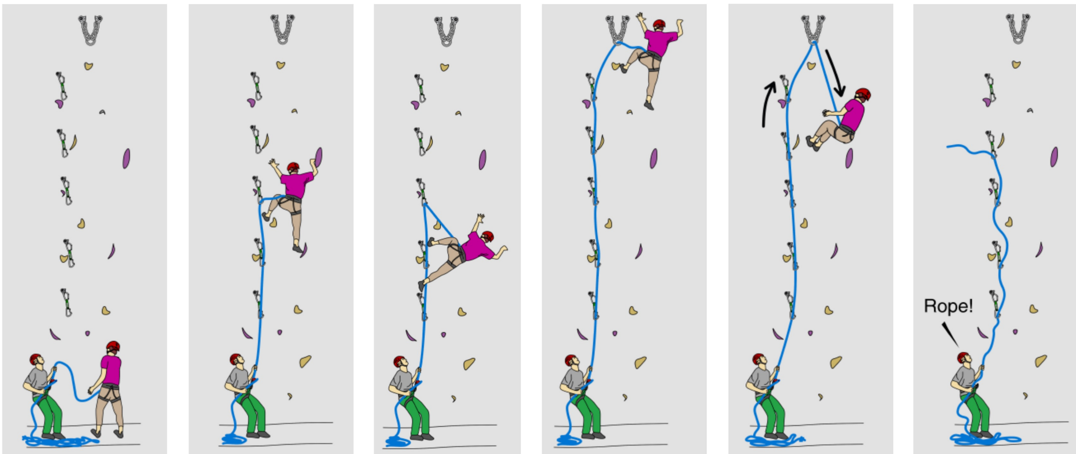

Figure 2.3: Schematic Representation of Lead Climbing. *Courtesy of Vdiff Climbing* [7]

2.2.3 Bouldering

Of the three indoor climbing styles, Bouldering is the only one that does not require a rope. For this reason, unlike walls for Lead or Top Rope Climbing, which can well exceed 15 meters, walls dedicated to Bouldering (i.e., boulders) are generally 3-4 meters tall. Additionally, they have padded mats beneath them, which are used to absorb the falls and reduce any risk of injury. Given the absence of ropes, quickdraws, and anchors, a fall during Bouldering results in landing directly on the mat; therefore, it is crucial to learn how to fall correctly to minimize hazards [7].

2.3 Privacy

One of the most critical topics when collecting data of any nature, as well as an open challenge for the IoT, is privacy. The upcoming subsections are devoted to defining the concept of privacy and exploring related implications and risks throughout this project.

2.3.1 Definition of Privacy

The concept of privacy is highly fluid, meaning its definition varies according to several factors, mainly related to the political, cultural, and social context. Professor of Law Dr. Daniel Solove [8] provides a general definition by defining six core concepts that allow conceptualizing privacy:

1. **Right to be let alone:** privacy includes the privilege of every individual to plan his/her own affairs [9].
2. **Limited access to the self:** similar to the *Right to be let alone*, limited access to the self can be seen as a more sophisticated formulation that defines an individual's desire to be apart from others [8].
3. **Secrecy:** one of the most common conceptions of privacy, secrecy defines the concealment of sensitive information about the self [8].
4. **Control of personal information:** one crucial attribute of privacy is that individuals (or groups and institutions) should be free to decide what, when, and how information about them can be shared with other parties [10].
5. **Personhood:** unlike the previous points, the concept of privacy as personhood defines an attainable goal of privacy, which is the protection of the integrity of an individual's personality [8].
6. **Intimacy:** the theory of *privacy-as-intimacy* views privacy as a form of limited access or control, but it adds the idea that privacy is also essential to human relationships instead of being limited to individual self-fulfillment [8].

2.3.2 Privacy-related implications in the project

Since the main activity of this project regards collecting data about climbing activity, some implicit privacy and moral implications need to be tackled. A fundamental aspect, considered a non-functional requirement, is respecting the stakeholders' privacy. The collection of data of any nature always raises many different implications for the privacy of every involved stakeholder. Since the collected data concerns both the gym halls and the climbers, during every step of the collection and the processing of the project, it is crucial that the data remains anonymous: this can be easily achieved by not collecting any sensitive data about the climbers in any step of the project.

Additionally, when working with privacy-related topics, also the social impact appeared to be of great importance: in fact, some of the tested options, while being utterly respectful towards the athletes' privacy from a legal point of view, still raised many concerns, resulting in an unpleasing experience for the athletes. For this reason, the adopted solution should be as non-intrusive as possible, requiring little to no additional action from athletes or gym personnel.

2.4 Requirements Definition

The next chapter of this work presents possible solutions and works related to the design of the Data Collection System. To provide a scientific method for evaluating the available options, this section outlines a list of ideal requirements and parameters to back up the comparison of the viable alternative approaches.

- **Non-intrusiveness** - The system shall not interfere with the sports activity. This is crucial, firstly to avoid introducing possible safety risks that could arise from interfering with the activity, and secondly, so as not to affect or alter the climbers' experience.

- **Accuracy of data** - The collected data needs to be processed and analyzed by an external backend system. For this reason, the measurements must be accurate and reliable without presenting vagueness or interference.

- **Respect for privacy** - As mentioned in Section 2.3, the system shall respect the privacy of all stakeholders, particularly athletes and gym staff. To do so, it is desirable to conduct the collection of data *in an anonymous form*.

- **Broad accessibility and availability** - Every athlete shall be able to employ the system. For this reason, the data collection shall not depend on the athletes' equipment and shall not rely on the athletes to purchase any particular gear or devices.

- **Universal applicability to preexisting climbing facilities** - The system's installation shall not require an invasive renovation of the climbing facilities. Instead, the system should adapt to the existing structures by defining a simple and subtle installation process.

- **Zero-to-low need for maintenance** - The system shall not appoint additional work to the gyms' personnel. While it is nearly impossible to design a system that runs entirely free of maintenance, the selected one must not require constant care and attention from the staff.

- **Cost-effectiveness** - The installation and usage of the system shall not have excessive economic weight for gyms.

- **Compatibility with all climbing styles** - Despite the differences between the indoor climbing styles, it is desirable to conceive a system that can monitor climbing activity for all styles indiscriminately.

Chapter 3

Review of the state of the art

3.1 Sensors

When applying the Internet of Things to the sports environment, one of the most significant challenges is designing a seamless pipeline to collect data and information about the activity. In doing so, the data collection process must not interfere in any way with the athletes' performance. Sensors play a significant role during this process since they allow the collection of various data that can later be interpreted for the project's purposes. The following paragraphs describe the different components and sensors more in-depth.

3.1.1 Microcontroller

The microcontroller is the core of a sensor. A microcontroller is a System on Chip (SoC) responsible for processing and storing all the data. Unlike a standard microprocessor, a microcontroller is a complete system that reduces many different components with their related tasks to one unique chip. This has a clear advantage in applications like wearable devices and tiny sensors since it allows one to coalesce multiple different chips into one, thus preserving physical space. In addition to this, it also results easy to program and configure, and cheaper to produce while still being able to control complex IO devices, including graphical displays and other sensors, including but not limited to accelerometers, gyroscopes, and heart rate monitors.

Like any computing system, a microcontroller comprises different parts. A processor is tasked with processing information that is then used to produce output data. A Random Access Memory (RAM), a Read Only Memory, and Flash Memory are responsible for storing information with different persistence and performance levels. Lastly, ports allow the microcontroller to connect with other peripherals and sensors [11].

To properly design a solution that uses sensors to collect data, some design considerations can be affected by the programming language used to configure microcontrollers. While Visual Basic is a widespread language to program microcontrollers, wearable devices and sensors can also use Java, Swift, Python, Arduino, C, or C++ [12].

3.1.2 Accelerometers

The accelerometer is a ubiquitous sensor found in everyday devices, from smartphones to laptops. Accelerometers are electromechanical sensors used to measure *proper acceleration*, defined in physics as a body's acceleration (the rate of change of velocity) relative to its instantaneous rest frame [13, 14]. There exist two classes of accelerometers, AC-response and DC-response accelerometers. According to the sensing technology adopted, there can be advantages and compromises, specifically when regarding the durability and reliability of accelerometers in extreme environments (i.e., at high or low temperatures) [15]. However, for the purpose of this project, the choice of sensing technology of the accelerometers does not affect the precision of the collected data.

3.1.3 Gyroscopes

Another sensor, often found in devices alongside accelerometers, is the gyroscope. Gyroscopes, however, are different from accelerometers because they allow measuring only angular accelerations. While accelerometers are sufficient to collect data about acceleration in most applications, in some cases, combining the outputs of the two sensors allows for more precise results and filters any noise or errors that might arise in the data set.

Gyroscopes are classified into three categories, depending on the technology they implement. Mechanical gyroscopes are the most common category, and consist of a spinning mass (usually a disk) mounted on gimbals that generate a displacement when angular acceleration is sensed. Gas-bearing gyroscopes are more precise while still relying on a rotating mass: the difference from mechanical gyroscopes is that the mass is suspended in a pressurized gas, thus reducing friction between the moving parts and allowing for more accurate measurements. Finally, optical gyroscopes do not use any moving part and instead exploit two coils of fiber optic cable spun in opposing directions and rely on the *Sagnac Effect* to measure the angular acceleration whenever the gyroscope is tilted [16].

Due to sizing and costs, wearable devices, and generally most consumer-oriented solutions, implement mechanical gyroscopes. However, they produce less accurate results and are less durable than the other technologies.

3.2 Fitness Wearables

Smartwatches and fitness bands are one of the most widely adopted technologies for fitness tracking and monitoring sports activity. They implement multiple sensors, including accelerometers, gyroscopes, pedometers, and heart rate sensors, to collect and process data about different sports.

The exponential interest in self-tracking of physical activity, which led to over one billion connected wearable devices in 2022 [17], has two main drivers. On the one hand, monitoring fitness-related metrics, like daily steps, or activity time, allows one to change an individual's lifestyle to keep active. On the other hand, with the technological advancements done so far, fitness tracking devices are reaching an accuracy that also allows to satisfyingly improve the safety of athletes in some dangerous events [18]. One example can be found in Apple Watch devices (models SE, 4 or later): using accelerometers and gyroscopes, Apple's smartwatches can detect when users wearing the watch suffer an accident during cycling activity. If they do not move or respond within a short time after the fall, the watch can perform an automated call to the emergency services [19].

Despite the growth in interest, technological advancements, and availability, commercial fitness wearables cannot measure sports-specific metrics in the climbing sector and are unable to collect data that can provide meaningful insights to improve the athletes' performances. Concerning sports that involve the use of force, smartwatches are only able to collect very vague information about movements like pull-ups, hangs, and climbing. Instead, even the top-of-the-notch smartwatches marketed by brands like Garmin, Casio, or Coros[1] can only provide data about altitude, pressure, or heart rate. To sample data about the climbing activity using wearable devices, it is, therefore, necessary to design custom-tailored sensors, as done in the two upcoming works.

3.2.1 ClimbAX

Ladha et al. introduced *ClimbAX* [20], an infrastructure for analyzing climbing performance that seeks to replicate professional evaluations. The goal of this project is to lay the foundations for the development of a fully automated coaching system for climbers. To sample data about the activity of the climbers, this project employs a pair of wrist-worn watch-like devices, each containing a triple-axis accelerometer able to measure movements and vibrations. The authors showed the accuracy of the performance evaluation by comparing the predicted scores of 53 climbers during a competition with the official competition results, demonstrating a remarkable connection between the two sets of results.

3.2.2 ClimbSense

In 2015, German researchers Kosmalla, Daiber, and Krüger introduced *ClimbSense* [21], a monitoring system that tracks and instantly identifies an athlete's route while climbing. The prototype used in this project consists of a pair of wrist-worn wearable devices, each containing a triple-axis accelerometer, a triple-axis gyroscope, and a triple-axis magnetometer. This setup allows sampling orientation and movement data during the climbing activity. In their work, the authors present the system, supported by cross-validation methods, outlining the results of a user study conducted in a local climbing gym.

3.3 Stereo Cameras and Computer Vision

A common technique to analyze sports activity involves the usage of stereo cameras and computer vision to generate 3D models of the climbing environment automatically. These can be interpreted, for example, to understand the athletes' position with respect to the climbing wall. Several applications of computer vision in sports already exist to improve training or support referees live during games [22].

Another example of the application of this technology is the *Microsoft Kinect*, a low-cost sensor commercialized from 2010 to 2016, initially used by some videogames on Microsoft's *Xbox 360* and *Xbox One* consoles. However, this sensor also allowed indoor environment mapping, object recognition, and analysis of hand gestures, which third-party application developers could use [23].

To test this approach, a *StereoLabs ZED 2 Camera*[2] was installed in a climbing hall. Using the camera and the *ZED Software Development Kit*, it was possible to track climbers on the walls with acceptable precision and map the surrounding environment.

[1] Reference models: Garmin MARQ® Driver, Casio Pro Trek®, Coros Vertix® 2

[2] StereoLabs ZED 2, `https://www.stereolabs.com/zed-2`

3.4 Smart Harnesses

A different approach leverages sensors on the climbing harness to collect information about the athletes' movements. The idea behind this solution is to use accelerometers, gyroscopes, and magnetometers to collect data about the movement of athletes in a reliable way. This strategy is very similar to the one adopted by other wearables, like smartwatches and fitness bands. By using small sensors, it is possible to enhance any existing harness without interfering in any way with the athletes.

3.5 Smart Climbing Wall

A final approach to the problem uses sensors directly installed on the climbing wall. This option still uses sensors to detect the positions and movement of climbers, but unlike previous techniques, sensors are not required to be worn by the climbers or installed on their equipment. Instead, they are placed directly on the walls and they can provide various information, including the climbers' progress on the wall, i.e., which height they reached, which previously mentioned strategies could not do easily. The upcoming subsections aim to present different sensing technologies that use sensors applied on climbing walls.

3.5.1 Q-Training Smart Grips

Professor A. Colombo [24] of the Politecnico di Milano developed *Q-Training*, a system that employs multi-axis force transducers installed on climbing grips, to provide insightful information on climbing mechanics. The sensors transmit measured data on a device (typically a smartphone or a computer) using wireless or cable communication. The device uses software to analyze and interpret the data. This approach is mostly used to monitor the force distribution for rehabilitation purposes, but it can be extended to monitor more information during climbing. This system is compatible with preexisting grips and paths and provides exact and accurate measurements of force and mass centering during the ascension process.

3.5.2 Smart Quickdraws using Accelerometers and Gyroscopes

The second strategy, to install sensors on the climbing wall, still utilizes accelerometers and gyroscopes, like smart harnesses or fitness eearables. However, in this case, sensors are installed on the quickdraws used for Lead Climbing. The sensors will then send the sensed data to a different device responsible for collecting it wirelessly. By analyzing the movements of the quickdraws on a three-dimensional plane with respect to the climbing wall, it is possible to determine the current climbing phase, sense the clipping of the rope to the quickdraw, or detect falls.

3.6 Comparison of the possible solutions

After presenting the different possible approaches to sample data about climbing activity, this section compares and evaluates them with respect to the requirements elicited in section 2.4.

Firstly, the usage of mobile, wearable devices provides universal applicability since it does not depend on the climbing facilities. While commercial smartwatches and fitness bands do not provide accurate measurements for climbing activity, it is possible to achieve precise results by employing custom-designed devices with low-cost components and sensors. In addition to this, the sensed data can be used in all indoor climbing styles. However, the solution we seek needs to be available to all users of a climbing gym without requesting additional steps for climbers. Relying on wearables would require the athletes to wear the devices on their wrists, which could also interfere with the sports activity if the devices are not small and ergonomic.

Secondly, stereo cameras and computer vision monitoring proved accurate during on-field tests without interfering with the climbers while they practiced. Furthermore, this approach does not foresee an invasive installation process and can detect any indoor climbing style. However, by installing the camera on the floor directly beneath the climbing wall, the image was frequently obstructed by other athletes walking in front of the device. Moreover, and most importantly, the installation of a camera, constantly monitoring the activity on a climbing wall, raised many privacy-related concerns: it appeared that athletes felt this video recording violated their privacy. Additionally, some athletes reported that being filmed during their training felt like an evaluation of their skills, and they did not want to feel pressured by the monitoring system since it negatively affected their personal comfort.

Next, the installation of sensors on harnesses, while providing less detailed information about the movement of the athletes, has the advantage of allowing for better anonymization of the collected data, thus removing the concerns related to privacy. In addition, the collected data is more consistent since there are no obstructions or physical interferences, as opposed to the approach with stereo cameras. The application of sensors on the gear is simple, does not require any modification to the facilities, and would not cause any disturbance to the climbers. Nevertheless, this technique introduces a significant disadvantage. While climbing gyms frequently rent climbing gear, including harnesses, to athletes, most regular and experienced climbers have their own equipment. For this reason, it would be impossible for gyms to install the sensors on every harness athletes use on a given wall. Therefore only athletes who rent the gear from the gym would actually be using the sensor system. In addition, harnesses are not used in every climbing style; hence, this solution would not be able to sample data, for example, about Bouldering.

Lastly, applying sensors directly on the climbing walls provides broad accessibility and availability since a sensor-enhanced wall would allow every athlete to employ the system without depending on their equipment and with a complete absence of impact or interference. It would not require any action from the athletes' point of view since sensors are already installed on the walls. Since there is no mean for the system to collect personal information and no images or videos are saved, it can also guarantee anonymity. However, the two different presented sensing strategies introduce different disadvantages.

On the one hand, using force transducers and smart grips foresees an invasive installation process. However, it is compatible with every climbing style and can be employed with preexisting grips. The Q-Training project, in fact, has been conceived for rehabilitation purposes, and therefore it has been used in rehabilitation environments, which use smaller climbing walls with fewer grips. To monitor a standard-sized wall, a higher number of sensors would need to be purchased and installed.

On the other hand, installing sensors on quickdraws would be more cost-effective, with a more straightforward installation process. However, since the sensors would need to be completely wireless, to avoid wires that might interfere with the climbers, they would have to be battery-powered, which means that maintenance would be needed whenever the batteries need to be replaced or recharged. Furthermore, by relying on quickdraws, this approach reduces the scope of the project, since quickdraws are employed exclusively in Lead Climbing.

Table 3.1: Comparison of data collection strategies with respect to the requirements defined in Section 2.4. ● symbolizes a completely satisfied requirement, ◗ defines a partial satisfaction, while the absence of symbols defines a non-fulfilled requirement

Requirement	**Wearables**	**Cameras**	**Harnesses**	**Grips**	**Quickdraws**
Non-intrusive	◗	●	●	●	●
Accurate	◗	◗	◗	●	●
Respects Privacy	◗		●	●	●
Anonymous			◗	●	●
Accessible		●		●	●
Easy to Install	●	●	●		●
Low Maintenance	●	◗	●	◗	◗
Cost Effective	◗	◗	●		●
For all climbing styles	●	●		●	

Chapter 4

Problem Solution

The purpose of this chapter is to present the adopted solution to collect information about indoor climbing activity in gym halls.

4.1 Data Collection Strategy

Among the possible strategies presented in Sections 3.3, 3.4, and 3.5, the least intrusive method to collect data about the climbing activity is to use sensors placed on the climbing wall. Using sensors placed directly on the wall, athletes can train and climb while data is being collected and processed, without needing to modify the athletes' equipment and without the privacy concerns raised by using stereo cameras and computer vision.

When comparing force transducers with smart quickdraws, however, it is clear that both approaches provide advantages and disadvantages. Although the approach to use force sensors has already proven to be successful in collecting meaningful data about climbing for rehabilitation purposes [24], its disadvantages outweigh its advantages. Firstly, only processing information related to the force applied to the handhold, while allowing to quantify rehabilitation progress and measure even mild motor deficits, precludes a complete view of the athletes' performance from a sportive perspective [25]. Secondly, installing this technology is excessively invasive for the climbing facilities and foresees higher costs.

For the reasons mentioned above, it was chosen to sense data using accelerometers and gyroscopes on quickdraws, despite restricting the application's domain exclusively to Lead Climbing. As shown in Figure 4.1, small sensors can be applied on quickdraws. From the positioning and orientation of quickdraws, it is possible to determine information about the climbing activity, detect falls, and evaluate the athletes' performance. This strategy is straightforward to implement since it only requires the application of small sensors on the pre-existing quickdraws of a climbing wall. However, some aspects still have to be evaluated, including the choice of sensors, the device used to collect sensor data, and the technologies used for communication between all the network components.

4.2 Hardware Infrastructure

This section will explain in detail the hardware chosen to collect data about the positioning and orientation of quickdraws with respect to a climbing wall.

Figure 4.1: Movesense HR+ applied to climbing quickdraw

4.2.1 Bluetooth Low Energy

Bluetooth Low Energy (BLE) is a wireless standard for short-range communication, developed by the *Bluetooth Special Interest Group* in 2004. BLE was born to allow smaller devices to have wireless radio connections to other terminals without the high power consumption and costs connected with standard Bluetooth, WiFi, or other wireless technologies [26].

For this application, sensors in climbing halls must require as little maintenance as possible. One of the primary reasons for maintaining sensors is the need to replace the sensors' batteries; therefore, the sensors must consume as little energy as possible. Concerning fitness sensors, wireless communication is a significant energy expenditure source. For this reason, BLE is often used by smaller IoT devices, which need special consideration for energy consumption. Since, when compared with other wireless technologies, BLE proves to consume very little energy, it results in being a suitable communication technology for this application [27].

4.2.2 Sensors

After determining the communication technologies and the relevant metrics for this application, the next step appears to be selecting the sensors' model. To approach the decision with rigor and method, it is worthwhile to outline a list of parameters that can aid the assessment of different candidate sensors:

1. **Power Consumption** - The installation of sensors in the climbing halls must not be a source of extra work for the staff. Since this technology's primary maintenance source lies in battery replacement, the chosen sensors should use state-of-the-art ultra-low power components to reduce the need for new batteries.

2. **Compatibility and Documentation** - The sensors will be integrated into a custom, *ad-hoc* IoT infrastructure. For this reason, the chosen sensors should feature an open *Application Programming Interface* (API) that allows them to communicate with a software component responsible for data collection and processing. In addition to this, it would be beneficial to avail comprehensive and precise documentation. Finally, the availability of a *Software Development Kit* (SDK) and the adoption of Open Source licenses would be suggested but are not required.

3. **Size and Weight** - To refrain from getting in the way of athletes during the activity, the size and weight of the sensors should be minimized. This also allows for higher and better versatility when mounting the sensors to quickdraws on climbing walls.

4. **Stability and Accuracy** - The sensed data should be as accurate as possible to have precise outcomes for the project. In addition, the connections between the devices on the IoT network must be stable to avoid errors due to abrupt disconnections and reduce maintenance.

5. **Robustness** - Since sensors will be used in sportive environments, it is safe to assume that they might be exposed to shocks, impacts, or other physical stresses. Therefore, evaluating the sensors' build quality and materials is essential to minimize the risk of damage, which would inevitably lead to unexpected costs.

6. **Type of Sensors** - For this application, it is necessary to collect data from an accelerometer and a gyroscope, which need to be supported by the selected sensor. Any additional form of sensing, including but not limited to magnetometers, altimeters, or temperature, is not necessary but can still be valuable for possible future additions to the project.

Suunto Movesense HR+

Table 4.1: Technical Specifications of Movesense HR+, as reported in the sensor's documentation on movesense.com [28]

Specification	Movesense Sense HR+
Sensors	Accelerometer, Gyroscope, Magnetometer, Temperature, Heart Rate, ECG
Sampling Frequency	12.5/26/52/104/208/416/833Hz
Accelerometer Accuracy	±2/±4/±8/±16g
Gyroscope Accuracy	±125/±245/±500/±1000/±2000°/s
Battery Life	Up to several months *(declared)*
Wireless Technologies	Bluetooth 4.0/5.0, BLE radio
Dimensions	36.6mm diameter, 10.6mm thickness
Weight	9.4g *(with battery)*
Build Material	Swim and shock proof plastic polymer
Software support	SDK, C++ API for firmware customizability, Open Source Android[1] and iOS[2] Applications
Others	Water Resistance, Wireless Updates

The sensor used for this application is the **Movesense HR+**, manufactured by *Suunto*, a Finnish company that manufactures high-end smartwatches, compasses, and precision instruments for sports [29]. The upcoming paragraphs aim to provide a rationale for adopting this sensor, outlining advantages, disadvantages, and trade-offs concerning the parameters outlined in Section 4.2.2.

[1]Android, `https://www.android.com`
[2]iOS, `https://www.apple.com/ios`

Firstly, the Movesense HR+ allows for a high degree of versatility. As presented in Table 4.1, the device includes several sensors, in addition to the required accelerometer and gyroscope. This leaves significant headroom for future extensions of this application, to adapt it to collect and process new metrics about climbing or other sports activities. The high versatility is backed up by an SDK and by C++ libraries that allow to develop and deploy tailored firmware for the sensors, providing total hardware operability and freedom of customization with comprehensive and up-to-date documentation and developer resources [30].

Secondly, from a physical perspective, these sensors have very contained dimensions and weight. This allows for a non-invasive installation that does not interfere with the athletes during the climbing. However, despite the small size, the device is manufactured using shock-resistant plastic materials, which keep it resistant to any incidental impacts it can likely be subjected to. Furthermore, for the installation, Movesense sensors provide a *snap-in* system, which facilitates a simple yet robust attachment to clips, surface mounts, wristbands, and other accessories. This can be done due to a patented *Movesense Connector* that allows a strong connection while remaining less than 2mm thin [31].

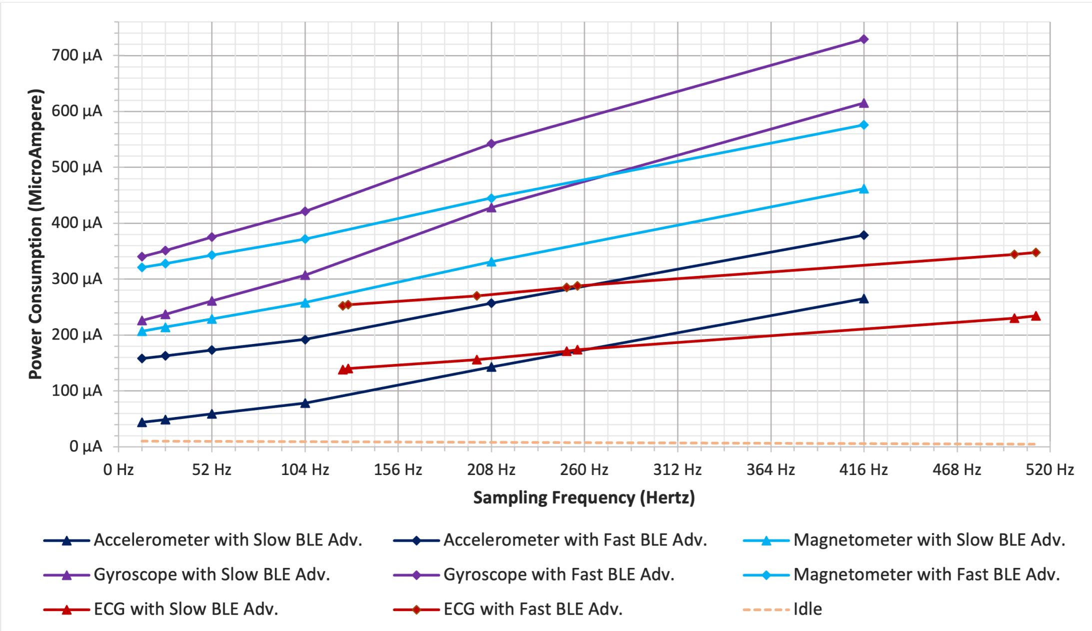

Figure 4.2: Battery consumption of different Components of the Movesense HR+ [30]

$$Battery\ life\ (in\ Hours) = \frac{Battery\ capacity\ (in\ mAh)}{Device\ Consumption\ (in\ mA)} \tag{4.1}$$

Finally, Suunto claims that the Movesense HR+ achieves exceptional battery duration, spanning as many as several months. To have more precise insight into the average battery life of the device, the online documentation provides a detailed schematic of the power consumption of each of its components. All the measurements are in microAmpere (µA). This information makes it possible to estimate the lifetime of a fully charged battery by using Formula 4.1. Firstly, it is necessary to compute the total consumption: this value is given by the BLE connection (96 µA), the usage of the different sensors, and the Bluetooth advertising. As Figure 4.2 illustrates, the consumption of the individual sensors depends on the sampling frequencies (represented on the X-axis). As noted in Movesense documentation, the accelerometer always functions, when gyroscope and magnetometer are used. The consumption also changes between slow Bluetooth advertising (represented with ▲ in the graph) and fast Bluetooth advertising (represented with ◆ in the graph). For this computation, we consider the gyroscope (which, as said, also includes the accelerometer's consumption), with a 26Hz sampling frequency, and slow BLE advertising. After computing the consumption, which adds to 364.7 μA, it is necessary to define the battery's capacity. The battery model of the HR+ is the CR2025, which has a capacity that, depending on the brand, can span between 150mAh (Milliamp-Hour) and 175mAh. For this estimation, we consider the average case of 160mAh. Finally, the average lifetime of the sensor when using accelerometer and gyroscope at 26Hz with slow Bluetooth advertising is 438 hours, or 18 days and 6 hours. Although this estimation is lower than the declared battery life, it is still a satisfactory result, which allows for a low degree of maintenance.

This result can be obtained due to *Nordic Semiconductors*' nRF52832, the microcontroller that powers Movesense sensors. The nRF52832 is a multi-purpose SoC with extremely low power consumption that has applications in several IoT areas, including wearables, medical and smart home devices. The BLE technology combined with an adaptive power management system directly embedded in the microcontroller allows the sensors to sample data using very little energy [32]. In addition to this, the wide range of sampling frequencies and sensors' accuracy settings provided by the Movesense HR+ can be calibrated to achieve the desired balance between power consumption and data accuracy.

4.2.3 Bridging Device

The final step in designing the hardware infrastructure for the project is selecting a bridging device. The sensors cannot connect directly to the Internet since a WiFi connection results more power-consuming than BLE [33]: for this reason, there is a need for a BLE-enabled device that can connect to the sensors, sample data from them, and upload data on a backend server tasked with processing them. It is worth mentioning that it is convenient to define this device only after choosing the sensors since the latter could set compatibility restrictions.

There are not many requirements to be defined for the choice of a bridging device. Firstly and most importantly, the device should be compatible with BLE and the Movesense SDK. Secondly, the bridging device should maintain a stable and durable connection with the sensors, supporting multiple sensors concurrently, with a minimum (or possibly absent) performance degradation. Unlike with the sensors, there are no physical restrictions for the bridging device since it can be placed behind the wall and out of the climbing area; therefore, its size will not affect the climbers.

Raspberry Pi

The first candidate bridging device was the *Raspberry Pi 4*[3]. Leveraging the Movesense SDK and API documentation, a script was developed using Python[4] 3.9.10. The script used the *bleak*[5] library to handle BLE devices. After discovering BLE in the network and connecting to

[3] Raspberry Pi 4, `https://www.raspberrypi.com/products/raspberry-pi-4-model-b/`
[4] Python, `https://www.python.org`
[5] Bleak, `https://www.bleak.readthedocs.io/en`

the sensors, the method `get_characteristic(UUID)` is invoked to retrieve the GATT characteristics corresponding to the accelerometer and gyroscope services. To receive all the measurements of the sensors, the script used the `start_notify(GATTcharacteristic)` to activate notifications on the characteristics mentioned above, thus automatically receiving all sensors values when they changed.

However, the usage of a *Raspberry Pi 4* was excluded for two main reasons. Firstly, the connection between the Raspberry and the sensors was not stable enough, with frequent and abrupt disconnections causing a critical issue when collecting data from the sensors. Secondly, when connecting more than two sensors concurrently, there was a significant performance degradation, with some notifications from the sensors getting lost, thereby leading to poor accuracy in the sampled data.

Android Smartphone

To overcome the issues of the *Raspberry Pi*, a Samsung Galaxy S7 was adopted as a bridging device. The reasons behind this choice are smartphones' increased computing capability and stability. In addition to this, Movesense provides an Open Source Mobile Library[6], containing an application used to showcase the sensors' capabilities that can provide a solid foundation for the development of the data collection software.

To ensure the adequacy of the device and to test the viability of this solution, the *Movesense Showcase* application was installed on the Samsung Galaxy S7. During the tests performed on the sensors, the smartphone did not exhibit any problems related to connection stability or performance degradation, thus meeting all the requirements presented in Section 4.2.3.

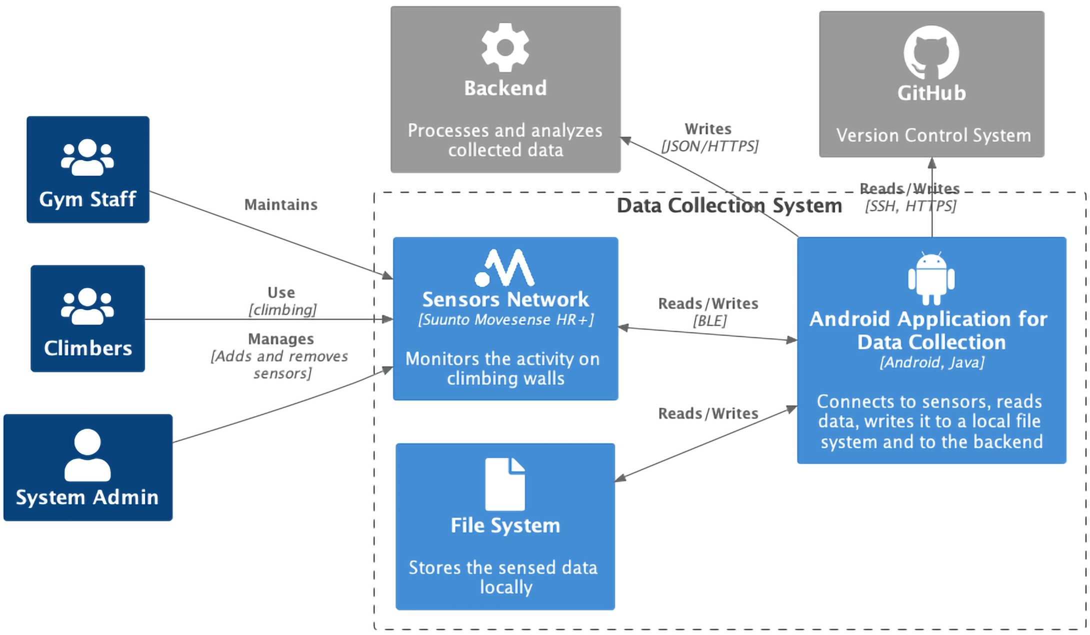

Figure 4.3: Container Diagram of the Data Collection System

[6]Movesense Mobile Library, `https://www.bitbucket.org/movesense/movesense-mobile-lib`

4.2.4 System Containers

Since the hardware infrastructure has been defined, it is possible to represent the Data Collection System in a Container Diagram (Figure 4.3). This graphical representation shows the high-level technical building blocks of the system and the relations between them.

4.3 Android Application for Data Collection

After selecting and testing the hardware infrastructure components, the final step is developing a mobile application for Android. This application is responsible for handling the connection with the Movesense devices, collecting, cleaning, and formatting data, and finally uploading the sensed data to the backend, responsible for processing it. The application's source code and its documentation are stored in a GitHub public repository, available at `https://github.com/LucaTaddeo/bsc-thesis`.

As mentioned in Section 4.2.2, Suunto Movesense devices have broad software support and documentation: all the software stack is open source and can be accessed via the Movesense community Bitbucket account. The Android application used to collect the sensors' data is a modified version of the Movesense Showcase App[7], which connects to Movesense devices and views the sensors' data in real-time. To tailor the application for use in the project covered by this thesis, however, it was needed to implement the following functionalities:

- Support for multiple concurrent sensors
- Utilities to clean and format raw data from the sensors
- Component to write data on local file system
- Component to upload data to the backend

The purpose of the following sections is to explain the functioning of the application's pre-existing modules, as well as to document the newly added components.

4.3.1 Movesense Architecture

The Movesense software architecture consists of two core resources: the device software stack (the `movesense-device-lib`), consisting of all the assets required to develop custom firmware and services to flash on the Movesense devices, and the mobile library (the `movesense-mobile-lib`, or MDSlib), providing the tools required to integrate the sensors in third-party mobile applications.

Figure 4.4 provides a graphical representation of the architecture of the Movesense Software Stack. The Movesense device, represented by the gray box on the left, and the mobile (Android/iOS) device, on the right, present three levels of abstraction. The lowest abstraction is, for both devices, a BLE module (depicted in blue) that handles the communication between the devices. On top of this module, the Movesense device can use the *Whiteboard* library (explained in the upcoming paragraph) or a custom *GATT Service* to make data available to other devices. In turn, the mobile device can also leverage the *Whiteboard* library contained in the `movesense-mobile-lib`, or it can implement a custom *GATT Client*. At the highest level, the Movesense device presents the different sensors and services while

[7] Movesense Showcase App for Android, `https://bitbucket.org/movesense/movesense-mobile-lib/src/master/android/Showcaseapp/`

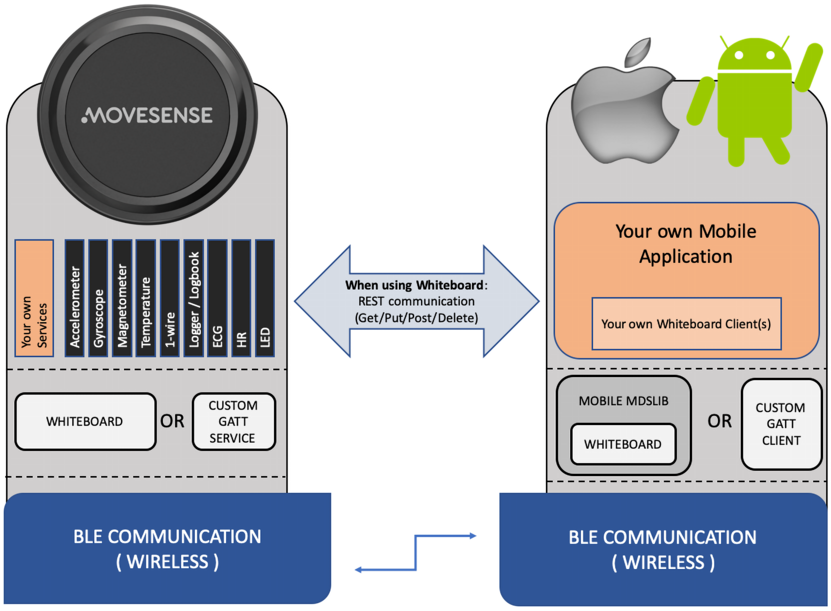

Figure 4.4: Architecture of Movesense Software Stack. *Courtesy of movesense.com* [30]

also allowing the implementation of custom services with the `movesense-device-lib`. Finally, the mobile device's highest abstraction level is represented by a mobile application that can use several functions of the *MDSlib*, to communicate with the Movesense device and achieve the desired goal.

The *Whiteboard* Library

The Movesense stack handles the wireless communication between the Movesense sensors and mobile applications. To do that, it uses a custom system called *Whiteboard* (represented by the gray-blue arrow in Figure 4.4). *Whiteboard* is an asynchronous communication library, based on the REST (Representational State Transfer) architectural style, that enables clients (in this case, the mobile application) to send requests to the different services of the Movesense device. Every sensor of the device (e.g., accelerometers and gyroscopes) are mapped to a service provider and to a unique path, allowing clients to request the different sensors individually. The Whiteboard API uses the request types of REST: GET, PUT, POST, and DELETE.

In addition to asynchronous requests, *Whiteboard* allows clients' subscriptions to service providers. With subscriptions, the clients do not need to constantly request the values of the different sensors. Instead, whenever the value of a service is updated, the service provider on the Movesense devices will automatically notify the subscribed client with the new data. As shown in Table 4.2, for each sensor of the Movesense device, there are specific paths dedicated to subscription handling: clients can make a POST request to subscribe to a service and start receiving notifications containing all the measurements of a given sensor, or they can send a DELETE request to unsubscribe and thereby stop receiving notifications. When requesting a subscription, clients also need to specify the sampling rate, choosing from 7 possible frequencies. For the best balance between data accuracy and power consumption, the application samples data at a frequency of 26 Hz.

Table 4.2: API Endpoints of Movesense Sensors

Sensor	API endpoint for subscription
Accelerometer	`/Meas/Acc/{SampleRate}`
Gyroscope	`/Meas/Gyro/{SampleRate}`
Magnetometer	`/Meas/Magn/{SampleRate}`

4.3.2 Movesense Mobile Library (MDS library)

For the development of the application, the Movesense Device Library will not be used since it suffices to use the devices' stock firmware, and no additional custom services are needed. Instead, there are some components from the Mobile Library that can be leveraged to abstract communications between the mobile application and the devices, as well as notifications and subscriptions to services. In the Component Diagram of the application (Figure 4.5), these components are grouped in the *Movesense Mobile Library* container.

The *Connectivity Manager*, from the `mds.internal.connectivity` package, handles the communication with the devices. It provides methods to establish a connection from a given MAC Address or serial number, listeners and handlers to manage the status of the connection, and functions to send and receive data between the application and the devices.

The *Operations Handler*, from the `mds.internal.operation` package, adds a new layer of abstraction on top of the *Connectivity Manager*. It exposes a set of classes and methods to create operations using the *Whiteboard* library, subscribe to the service providers, and handle notifications. This component then uses the *Connectivity Manager* to handle every device request and receive responses by transmitting data over Bluetooth Low Energy.

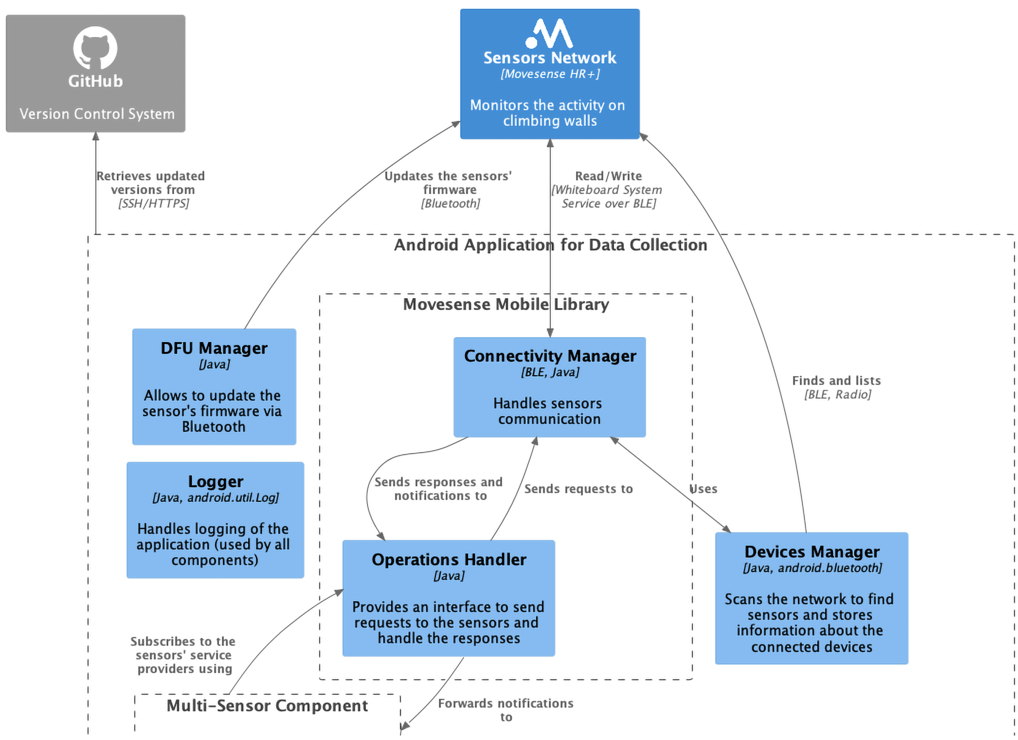

Figure 4.5: Component Diagram of the Android Application for Data Collection (Part 1)

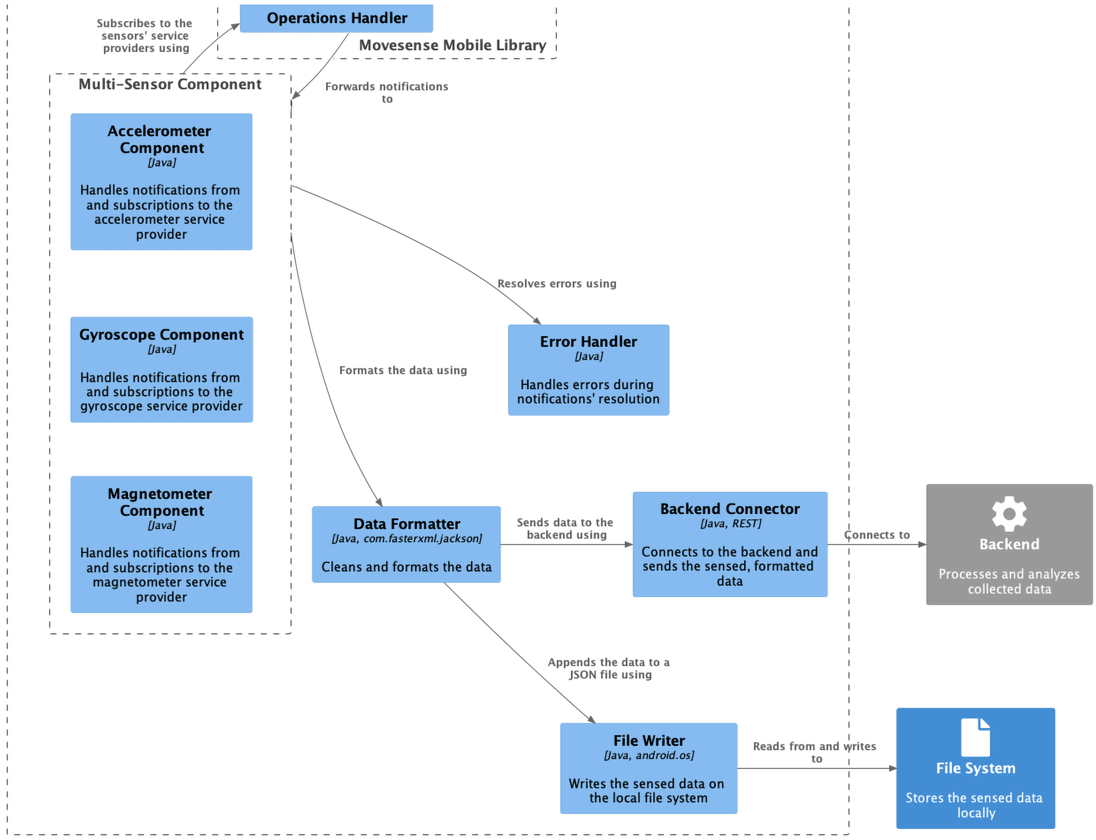

Figure 4.6: Component Diagram of the Android Application for Data Collection (Part 2)

4.3.3 Data Collection

After implementing the MDS library, there is a need to create all the components responsible for collecting data from the different device's sensors (Figure 4.6).

Firstly, a *Devices Manager* is tasked with finding the devices and retrieving their MAC Addresses and serial numbers. This component uses a Scanner Fragment, along with the Bluetooth Adapter from the `android.bluetooth` package, to search for BLE devices and filter the result to only show Movesense devices. Then, the *Connectivity Manager* can use the found addresses and serials to open connections with the corresponding devices.

Secondly, upon successfully establishing the connections with the Movesense devices, the *Multi-Sensor Component* is used to read the measurements of the different sensors. This high-level component groups together one single-sensor component for each sensor: an accelerometer, a gyroscope, and a magnetometer component. Each single-sensor component uses the *Operations Handler* to subscribe to the related service provider of the Movesense devices (e.g., according to Table 4.2, the *Accelerometer Component* will subscribe to the `meas/Acc/26` endpoint of every connected Movesense device). A Notification Listener is instantiated so that upon receiving a notification from the *Operations Handler*, the single-sensor component can extract the data from the notification's body and forward it to the *Data Formatter* component. In case of errors, corrupted data, or missing information, an *Error Handler* is invoked. The advantage of this architecture is that it allows to add or remove single-sensor components, to sample measurements from different sensors: therefore, to start sampling the values, example-wise, of the temperature sensor on the Movesense device, it will suffice to plug a new module in the *Multi-Sensor Component*.

Next, the *Data Formatter* receives a custom data object from a single-sensor component. Each single-sensor component presents its measurements using objects of different classes from the `model` package. The purpose of this component is to format the objects of these different classes to serialize them to a JSON string using the *Jackson* Library[8]. The schema of the serialized JSON measurements is reported in Listing 4.1.

Finally, the *File Writer* component is responsible for creating and managing the persistence of the sensed data using files on the local file system. Every time the sensors are connected and the sampling starts, a new subdirectory is created and named after the time and date of the sampling's beginning. The folder contains one JSON file for each connected sensor. The names of the files follow the pattern `{deviceSerial}.json`. Every file is instantiated with an empty array and will contain objects following the Schema in Listing 4.1. After receiving the JSON object from the *Data Formatter*, it appends it at the end of the array in the corresponding JSON file.

```
"type": "object",
"properties": {
    "Timestamp": {"type": "integer"},
    "Sensor": {
        "type": "string",
        "enum": [
            "LinearAcceleration", "AngularVelocity", "MagneticField",
            "HeartRate", "Temperature"
        ]
    },
    "Value": {
        "type": "object",
        "properties": {
            "x": {"type": "number"},
            "y": {"type": "number"},
            "z": {"type": "number"}
        },
    }
},
"required": ["Sensor","Value", "Timestamp"]
```

Listing 4.1: JSON Schema of the Output Measurements

4.3.4 Data Format

JSON was selected as the output format to represent the collected data in a standardized structure since it is a lightweight, easy-to-parse format compatible with several different programming languages. Every time a notification is received by the Android application, a new Java object of the `Measurement` class is instantiated: this class follows the *POJO* (Plain

[8] Jackson, `https://www.github.com/FasterXML/jackson`

Old Java Object) class model and is used to represent a generic measurement received from a Movesense device. The class contains the following three fields:

- `Timestamp`: this field, of type *long*, is used to store the time and date of the measurement, as indicated in the notification's headers.
- `Sensing`: this field can have a value from the *Sensing* enumerate, indicating which type of measurement is represented by the class (i.e., linear acceleration, angular velocity, temperature).
- `MeasurementValue`: this property, of type *MeasurementValue*, holds the values of the measurement.

The different sensors of the Movesense device can provide measurements in different forms: for example, while the accelerometer, gyroscope, and magnetometer all provide three values corresponding to coordinates in the tri-dimensional plane, the thermometer provides a single temperature value, and the relative time of the measurement. For this reason, the Movesense Showcase Application implements a different class for every type of sensor and then groups these classes in the `model` package. To generalize the `Measurement` class to support objects of these different classes while complying with Java's type system, the `MeasurementValue` is an interface. Three different classes then implement this interface: `XYZmeasurement`, `TemperatureMeasurement`, and `HeartRateMeasurement`. Moreover, the `Measurement` class provides different constructors that can instantiate objects by mapping instances of classes from the `model` package to the right `MeasurementValue`. Listing 4.2 presents three examples of these constructors. Finally, since objects of this class need to be serialized as JSON strings, two annotations from the *Jackson* library, specifically `@JsonProperty` and `@JsonPropertyOrder`, were used to map the parameters of the `Measurement` class to JSON properties.

```
public Measurement(LinearAcceleration linearAcceleration){
    this.sensing = Sensing.LinearAcceleration;
    this.timestamp = linearAcceleration.body.timestamp;
    LinearAcceleration.Array values = l.body.array[0];
    this.measurementValue = new XYZmeasurement(values.x, ↘
       values.y, values.z);
}
public Measurement(Temperature temperature){
    this.sensing = Sensing.Temperature;
    Temperature.Content content = temperature.content;
    this.measurementValue = new TemperatureMeasurement(↘
       content.relativeTime, content.measurement);
}
public Measurement(HeartRate heartRate){
    this.sensing = Sensing.HeartRate;
    HeartRate.Body body = heartRate.body;
    this.measurementValue = new HeartRateMeasurement(body.↘
       average, body.rrData);
}
```

Listing 4.2: Example Constructors of the `Measurement` class

4.4 Backend

As depicted in Figure 4.6, a dedicated component is tasked with connecting to a backend service and sending the sensed, formatted information. It has to be noted that the design of the backend falls outside of the scope of this thesis. Since the development of the *Backend Connector* is tightly coupled with the specifically chosen backend, this component is not implemented in this solution. However, the future integration of this component with the Android application is simple and can follow the same structure used by the *File Writer*.

After a quick analysis of the alternative backend providers, we can suggest the usage of *Parse*[9]. The significant advantages of this platform are that it offers excellent flexibility comprehensive documentation, and is free and open source. Additionally, its API uses the REST Architectural Style, which supports the JSON format used to represent the data sensed by the Movesense devices. Finally, it is compatible with several different platforms, including Android, iOS, JavaScript, and PHP, which will allow complete freedom for future integration with other systems, like a web application, to present the results of the data analysis.

[9]Parse, `https://www.parseplatform.org/`

Chapter 5

Evaluation

The purpose of this chapter is to present the evaluation tactics adopted to assess the adequacy of the proposed solution as a viable way of solving the problem.

The evaluation was performed as a series of unit tests. After pointing out several criticalities concerning the system's requirements, a series of single tests were defined and conducted to evaluate the different possible sources of vulnerabilities.

5.1 Connection Stability

The first concern with applying the proposed solution was the stability of the connection between the Movesense devices and the bridging device. The first evaluation of this point was performed using a Raspberry Pi 4.

The test consisted in connecting a Movesense device to the Raspberry using BLE and running a Python script to subscribe to the accelerometer service provider on the device.

This approach emphasized several critical issues with using the Raspberry Pi 4 to read sensor data. Firstly, frequent crashes occurred when scanning the network for the BLE device and connecting the devices to the Raspberry, which caused the connecting phase to be cumbersome and inconsistent. Secondly, even after a successful connection, the Raspberry could not consistently receive notifications from service providers. Even with the Raspberry connected and subscribed to receive data, upon moving the sensors to trigger a notification, the Raspberry appeared not to receive every movement recorded by the sensor. This issue appeared to be worsened by the subscription to multiple concurrent service providers.

To address this problem, the evaluation of the stability of the connection was newly conducted using a new bridging device, namely an Android smartphone. This smartphone was running the latest version of the Movesense Showcase App, which allowed it to connect to a Movesense device without presenting any connection issues or bugs. Furthermore, the subscription to the service providers also appeared stable, with the smartphone reading every sensor's movement, even if in the narrowest range (e.g., small vibrations of the table on which the sensor was lying). The subscription to multiple concurrent providers using the application mentioned above did not present any degradation in the app's performance, which continued to read every notification consistently.

5.2 Battery Life

One of the most critical aspects of this solution was the need for maintenance due to expired batteries on the Movesense devices. It was, therefore, crucial to ensure that the battery usage of the sensors was satisfactory.

To assess this parameter, as a first step, a new battery was installed in the Movesense device. The battery specifics are the following:

- Battery Model: CR2025
- Battery Technology: Lithium-Ion
- Battery Type: Alcaline
- Battery Voltage: 3 Volts (V)
- Battery Capacity: 165 Milliampere Hour (mAh)

Next, the Movesense device was connected to an Android smartphone. After subscribing to the accelerometer and gyroscope service providers, the application was left running for ten continuous hours in a closed environment, with temperatures between 20°C - 30°C.

To trigger the notifications' submission and to test different types of stimuli, in addition to the vibrations of the table on which it was lying, the Movesense device was periodically moved manually. At the end of the testing window, the Movesense device consumed 2.4% of the battery.

5.3 Consistency of Output

One final aspect to test was the consistency of the output format. With this, it means that the data exported in JSON format should always complain a standardized format to ensure that the output can easily be read by any backend service tasked with its analysis.

To ensure this, first, a JSON Schema was defined (as depicted in Listing 4.1). Next, after connecting 2 Movesense HR+ to an Android smartphone, a series of test measurements were taken to generate a JSON file. This file was then validated with the JSON Schema using an online JSON Schema Validator[1] to check the correct formatting and structuring of the file's content.

To cover a broad set of scenarios, these steps were repeated under different edge conditions:

- Unforeseen disconnection of the sensor: the sensor's battery was removed while it was sending information to disconnect it from the phone abruptly.

- Unforeseen disconnection of the smartphone: the smartphone's Bluetooth was turned off while receiving data to disconnect it from the sensors.

- Fatal error of the application: the application was killed from the smartphone's settings while collecting information to simulate a crash.

- Smartphone's battery empty: the smartphone was shut down to simulate the event of its battery running out.

In all the situations mentioned earlier, the JSON file was not empty, and its validation against the JSON Schema was successful.

[1] JSON Schema Validator, `https://www.jsonschemavalidator.net`

Chapter 6

Discussion

Using Movesense sensors attached to quickdraws is an effective way to collect information about indoor climbing activity in gym halls. When testing its most critical vulnerabilities, it appears that this solution can offer enough flexibility to avoid or at least mitigate any possible issue.

When comparing it with the requirements elicited in Section 2.4, we can safely say that the final solution behaves even better than expected. In fact, one of its possible criticalities was connected with the risk of frequent maintenance due to the replacement of the sensors' batteries. However, the results of the tests demonstrated that the sensors use 2.4% of their battery every 10 hours of usage. This result means that, on average, the sensors' batteries will last over 415 hours, or 17 days. Additionally, it has to be taken into account that sensors will not be used when gym halls are closed to the public, meaning that during nights, they will consume less battery since they will send fewer notifications over BLE. Therefore, it can be concluded that any concern about the need for frequent maintenance is not justified.

Nonetheless, when applying this solution, one of the initial requirements. As extensively mentioned, quickdraws are only used in Lead Climbing; therefore, relying on them to collect data about the sports activity does not allow this solution to apply to other climbing styles, such as Top Rope Climbing or Bouldering. However, given that none of the evaluated solutions could satisfy all the defined requirements, reducing the solution's domain is a sustainable compromise compared with the issues correlated with the other possible solutions.

6.1 Internal Validity

To assess the internal validity of the solution, it is necessary to establish whether it contains errors or not.

While it is impossible to ensure that a software does not contain any error, different edge cases were tested during the evaluation steps, including the simulation of possible errors in both the Movesense devices and the smartphone. In every case, the system produced a stable output compliant with the standard format. Furthermore, one of the axioms behind this solution is that the application should only read the data from the sensors when they are moving. We were able to assess the validity of this statement on several occasions when developing the application. However, there are still some threats to the validity of the solution that must be considered.

One of the main validity threats is that, since the application reads data about any movement of the sensors, it is necessary to find a way to ensure that the collected information derives from the sensors moving due to climbers using them. In fact, the sensors might detect a movement for other reasons. Firstly, even a draught inside the gym hole could be detected, given their high sensitivity. To mitigate this specific threat, it can be helpful to exclude minimal movements from the output by setting a minimum threshold or calibrating the sensors' sensitivity to a lower level. Secondly, usually in climbing gyms, the same wall can be used for Top Rope and Lead Climbing. This means that athletes practicing the former could accidentally move the quickdraws on the wall, generating a movement that the application would read. Unfortunately, there is no way to exclude this measurement from the output data, and the most suitable mitigation strategy would be to train the data analysis model in the backend to discard any accidental movements of the sensors that do not correspond to those generated during Lead Climbing.

6.2 External Validity

Finally, to define the external validity of the solution, we need to analyze the generalizability of the solution across several different scenarios. In the specific case of this solution, there are different levels of generalizability.

A first idea would be to use this system to collect information about outdoor climbing. Thanks to the resistance and durability of the Movesense HR+ sensors and the portability of the wireless BLE network and the Android smartphone, this is technically possible. However, while climbing gyms already provide quickdraws installed on the walls, in outdoor lead climbing, athletes carry them with themselves during the ascension. Then, they clip them to the wall when needed, and only after that they clip the rope to the quickdraw. For this reason, to adapt this solution for use in outdoor lead climbing, it would be needed to recognize the moment in which the quickdraws are clipped to the wall to start the collection of measurements from that moment, to exclude any involuntary movement sensed while the quickdraws were not being used.

A second idea would be to extend the solution to all the climbing styles. As mentioned, using quick throws to collect information precludes the possibility of using this system with other climbing styles. However, it could be possible to use the same sensors and smartphone system by applying them, for example, on the climber's wrist. This, however, would require a more in-depth study of the intrusiveness of wrist-worn wearable devices with climbing activity.

Finally, we can investigate the possibility of using this system to collect information about other sports. Thanks to the high portability of this solution, it is easy to adapt it for different types of activity. For example, Movesense sensors could be applied on bicycles or MBX for fall detection. In addition to this, since Movesense devices are waterproof, they could even be used for water sports: if applied on a windsurf or kite surf sail, for instance, the sensors could detect when the sail falls and remains in the water for a prolonged time, indicating a possible injury or physical ailment of the athlete. This could be used to send an emergency message, including the GPS position of the athlete.

Chapter 7

Conclusion and Further Studies

7.1 Conclusion

This thesis project aimed to design a technologically stable solution that enables the collection of information about indoor climbing in gym halls. First, an analysis of the problem was conducted to define a high-level guideline to assist the evaluation of possible alternatives. The system's context foresees three stakeholders, the Gym Staff, the Climbers, and a System Administrator, and one external backend system responsible for analyzing the collected data. The outcome of this step was the elicitation of eight core requirements that ensure the validity of the solution.

Next, followed an analysis of the available papers and the already existing solutions to understand the possible strategies that can be adopted to tackle the problem. During this phase, it was possible to understand that most systems rely on accelerometers and gyroscopes to measure movements and orientation. The primary outcome of this was a comparison of the different possible approaches and their fulfillment of the defined requirements. It emerged that while wearable devices are the most used and documented strategy to collect data about sports activity, it is not a suitable solution for this problem. Although none of the solutions could fulfill all the system requirements, the one involving smart sensors applied on quickdraws presented the fewest number of trade-offs and was therefore chosen to design the system's architecture.

The next step consisted in the choice of the hardware technology for the construction of the system:

1. Bluetooth Low Energy was chosen as a communication technology due to its low power consumption.
2. After defining six different parameters to assess the alternative sensors, the Suunto Movesense HR+ was chosen due to its versatility, durability, and long battery life.
3. Upon evaluating the possibility of connecting the sensors to a Raspberry Pi 4, an Android smartphone was adopted as a bridging device, responsible for collecting the data sensed by the Movesense devices.

From a software perspective, the smartphone used a custom-developed Android application, based on the Movesense Showcase App, extended with additional required features.

Finally, the solution was evaluated by testing the main possible criticalities in a contained environment. The result was that the application effectively solved the initial problem and could collect data about indoor climbing activity by respecting nearly all the defined requirements.

7.2 Future Work

To better assess the validity of this solution, future work might concentrate on thoroughly testing the long term behaviour of the application *on field* in climbing halls. Additionally, further studies can evaluate the applicability of this solution to other sports. A portable, versatile system to collect data could be used in several other domains by simply readapting the data analysis strategy.

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