A Sensor System to Track Individual and Social Animal Behavior in the Wild

BY

RICCARDO PRESSIANI
B.S, Politecnico di Milano, Milan, Italy, 2016

THESIS

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Defense Committee:
Tanya Berger-Wolf, Chair and Advisor
Ian Kash
Marco D. Santambrogio, Politecnico di Milano

All men dream, but not equally. Those who dream by night in the dusty recesses of their minds wake up in the day to find it was vanity, but the dreamers of the day are dangerous men, for they may act their dreams with open eyes, to make it possible.

– T.E. Lawrence, *Seven Pillars of Wisdom: A Triumph*

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Being a graduate student and a researcher does not mean that you can pause your private life. I am still struggling to handle this, but there are several people that I have to thank if I was able to have a really good time during these years.

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LIST OF ABBREVIATIONS

3D	3 Dimensional
3V3	3.3 Volt
API	Application Programming Interface
BLE	Bluetooth Low Energy
CSV	Comma Separated Values
dBm	Decibel-milliwatts
dBFS	Decibels Relative to Full Scale
DoF	Degrees of Freedom
FSA	Finite State Automata
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GPS	Global Positioning System
GND	Ground
HEX	Hexadecimal
IMU	Inertial Measurement Unit
LiPo	Lithium Polymer
MEMS	Micro-Electro-Mechanical System

NMEA	National Marine Electronics Association
PDM	Pulse Density Modulation
RF	Radio Frequency
RTC	Real-Time Clock
RSSI	Received Signal Strength Indicator
RMC	Recommended Minimum data for GPS (ver. C)
RST	Reset
SD	Secure Digital
SCLK	Serial Clock
SDIO	Serial Data I/O
SPI	Serial Peripheral Interface
SQW	Square Wave
SoC	System on Chip
USB	Universal Serial Bus
VHF	Very High Frequency
VIN	Voltage Input

SUMMARY

In recent years, the field of animal tracking experienced significant growth. The miniaturization of technologies and large-scale consumer demand allowed engineers to take advantage of technical improvements from other industries. The result is the possibility to build integrated devices equipped with several different sensors. Manual analysis of the massive amount of data collected by these devices is not feasible. However, by coupling the data collection with machine learning algorithms it is now possible to extract hidden information and knowledge that can open the way to new scientific discoveries and research directions.

The expected outcome of this project is a long-term deployment of a sensor system to remotely extract movement and behavioral data from social wild animals (initially designed for Olive baboons, which have been our targeted species for this stage of the project). For this reason, the specifications for the device to be developed raised a set of new challenges to be addressed in order for it to be deployable in an uninstrumented environment. Among them, the whole system will need to be tolerant to possible hardware faults while the energy consumption is limited and monitored. The list of requirements redacted with the help of biologists has guided the design of the whole system.

In this thesis research work, I developed a system composed of a main sensor unit (located in a collar for the baboons) and at least one secondary unit (in a bracelet for the baboons). The main unit is composed of a GPS, an accelerometer, a gyroscope, a magnetometer, and a microphone. The collar also has Wi-Fi and Bluetooth connectivity to allow the main and secondary units to communicate, as well as to extract the data from the system remotely, without having to remove the devices from the animals. Moreover, we exploit the Bluetooth Low Energy technology to implement a proximity sensor to track other primary units in close proximity. The secondary unit is equipped with a 6 axis movement sensor (accelerometer + gyroscope).

The proposed work will allow scientists to have a deeper and more granular understanding of animal behavior on a long-term basis. We believe that the two main benefits of this setting will be empowering the scientific community with useful data and information to address animal conservation issues. Moreover, we believe this technology could be adapted to other environments other than the wild one, such as the possibility to study animals in agricultural, domestic, and habituated settings (such as zoos). This will make an impact on the productivity and efficiency of farms, veterinary health, and well-being of domesticated animals.

CHAPTER 1

INTRODUCTION

Animal tracking is an important part of biologists and behavioral ecologists research activities. The behavior of every living organism is defined by movement [1]. Animals always move to satisfy a need. Whether they are looking for resources such as food or shelter, they are migrating or they are looking for a partner, each of these activities is characterized by movement. In order to study these processes, the tracking of animal behavior and group dynamics on a long-term basis becomes necessary. The behavior and group dynamics of some species, such as fish and birds, can be modeled by simple local mathematical rules. However, answering the same questions for species with more complex behavioral structures, such as primates, requires the development of complex observation-enabling technologies.

Animal tracking and behavior analysis has been conducted for a long time before the advent of the first tracking technologies. From the beginning and to the present day, biologists have been using manual observation techniques of animal behavior. These techniques have been studied and documented for decades by many recognized experts [2, 3]. Field observations allow biologist to go and experience the exact same places where the animal objects of study live. However, field observation is a difficult, expensive, and resource-consuming activity.

Because of all the reasons just mentioned, biologist and behavioral ecologist began to work on technological solutions for animal tracking since the 1960s [4, 5]. Since the 60s, animal tracking solutions went from VHF radio telemetry to satellite positioning systems such as Argos and

GPS. During the recent years, we have experienced a rapid transition from very inaccurate, expensive and heavy devices that only big and robust animals could carry to high-resolution, cost-effective and light-weight tags. Nowadays, almost every animal species can be tracked, from massive elephants to small birds [6–18]. Marine animal tracking is also a field in great expansion [19–23].

The increasing large-scale consumer demand for this kind of electronic component has lead to the introduction on the market of off-the-shelf miniaturized, efficient, and cheap components. Engineers working in the field of animal tracking have started to exploit this trend by integrating these technologies into the newer units [24]. This allowed animal tracking solutions to evolve from simple tracker devices to powerful integrated devices with many different types of sensors. As of today, several research projects that have tried different sensor configurations can be found in the literature. We can find examples of units that have been equipped with cameras [25–28], accelerometers [29–32], EEG sensors [33, 34], and microphones [35].

High-resolution data, especially regarding the movement of the animal with respect to both the environment and the fellow individuals, has allowed extending animal behavior analysis on multiple layers of aggregation. Due to the improvement in the technologies and the lower costs, it is now possible to track full groups of animals. This not only allows to study individual behavior in a more granular way but also dyadic interactions and group dynamics based on accurate and precise data.

The huge amount of collected data has required the introduction of computational approaches to data analysis. Indeed, the size of the collected datasets has entered the realm of big data. This means that if in the past a team of biologist could work directly on the collected data, today the massive amount of data need to be processed and analyzed by experts in order for the biologists to understand the underlying information. Today, machine learning, artificial intelligence, and data analytics techniques are massively exploited in order to extract patterns and knowledge from the available data. In particular, classification techniques have recently been of extremely high interest.

Another important aspect of animal tracking is ethical animal treatment and experimental procedure. The ultimate goal of animal behavior tracking activities is to be able to build models and extract knowledge about animal behavior. Therefore, it is important that the designed solutions to carry out such studies are conceived to be comfortable and safe for the targeted animals. Moreover, most of the animals need to be sedated in order to attach the tracking devices. Capture and sedation can be highly traumatic events in animal life. If these processes are not executed by experienced veterinaries respecting the designated protocols they could cause both physical and psychological permanent damage to the animal. For this reason, it is imperative to design reliable solutions that can guarantee successful data collections in order to reduce to the minimum the number of repetitions of the experiments. There are several institutions that regulate and control that the rules and protocols are respected, such as the Institutional Animal Care and Use Committees in the United States [36].

Animal tracking is not only useful for the sake of knowledge. There are many ways in which animal movement and behavior could impact the world and even have consequences for human lives. With all the sensors that can be fitted into a small tracking device, today animals could really become our eyes on the planet [24]. As a matter of fact, the sensors embedded in these devices could be used to collect data about the surrounding environment. Moreover, the ecological processes of which the animals are a part, such as food and resource searching, could be indicators of other ongoing changes on our planet. Animals are also carriers of migratory diseases. Being able to track animal migration and the spread of the diseases would allow humans to study new techniques of prevention and prediction of diseases outbreaks. The impact of these ecological processes is valued at many hundreds of billions of dollars every year [37]. Thus, it is important to design tracking solutions capable of providing insight into these processes.

Integrated hardware and software solutions to track animal behavior are scalable to other settings such as zoos and farms. As a matter of fact, zoos could track their animal health and well-being through this kind of devices. In particular, delicate animals that require special environmental conditions to be maintained could be tracked in real-time in a very granular way. In the case of farms instead, it would be useful for owners of massive establishments in order to keep a continuously updated report of the well-being of its animals [38]. Such reports could not be done otherwise unless a large number of veterinaries and employees are hired to conduct fine-grained checks on the animals. An interesting use case could be the prediction of illnesses based on early detection of symptoms. In this way, the farmer could intervene in a more direct and effective way.

To conclude, animal behavior tracking testing is a great opportunity to study innovations that could be introduced in human activity tracking solutions.

In the following chapters, we will present the research work that has been done to design and develop a new behavior tracking solution for animals in the wild. In Chapter 2, the related work that has been analyzed and taken into account to determine the state of the art will be presented and discussed. In Chapter 3, we will provide the challenges and requirements of the solution to be developed, along with the problem description. In Chapter 4, the overall system architecture will be presented and the architectural details that satisfy the given requirements will be described. In Chapter 5, the implementation details of our proposed solution will be provided. A section of this chapter will be also dedicated to the implementation choices that have been adopted to make the whole system reliable and fault tolerant. In Chapter 6, the experimental testing conducted to assess the quality and reliability of the implementation, as long as the related results, will be provided. In Chapter 8, we will discuss a series of possible future direction that might be pursued both in terms of improvements that could be brought to the current solution and possible new interesting features to be added. In Chapter 7, we will recap all the presented work.

CHAPTER 2

RELATED WORK

In this chapter, the literature related to this project will be presented and discussed. The first part is based on the research projects that have been conducted in the field of animal tracking. Several technologies have been used to track animal movement in the environment, VHF radio transmissions and satellite systems among them. In the second part, instead, the animal behavior identification scenario will be presented. The most affirmed biology techniques to study animal behavior require a lot of time spent in the field. However, technology innovation is opening the way to new interesting and effective solutions. The last part of the chapter will be dedicated to present the actual state of the art: e-obs collars.

2.1 Animal Tracking

Animals have been tracked by biologists and ecologists since the 1960s. Lord et al. in [4] describe how they tracked the respiration of flying ducks using radiotelemetry. Other experiments with VHF radio tracking had been conducted to study grizzly bear pre-hibernation and denning activities [5]. At that time, VHF tracking was a very time-consuming technology. As a matter of fact, to retrieve the animal location, a manual triangulation of the signals had to be done. In 2011, Kays et al. developed ARTS, an Automated Radio-Telemetry System [39], solving the manual effort required to triangulate. However, the data collected were too sparse

(12 locations/h with an expected error of approximately $50m$) and the infrastructure required to extend the action range was unsustainable.

Satellite positioning systems allowed to develop solutions for tracking in uninstrumented environments. VHF tracking required the use of big antennas that the researchers had to bring along in the field. Satellites systems do not need any kind of antenna on the ground but only a receiver on the device that is required to be tracked.

The first satellite system that had been used in the field of animal tracking was Argos [40,41]. Argos was created in 1978 thanks to a collaboration agreement among CNES, NASA, and NOAA. The original purpose of the system was to enable the development of projects that involved the collection of data regarding meteorological and oceanographic data. The source of the data could have been located by exploiting the Doppler effect of the signal.

Since Argos was originally designed to be used in oceanic environments, the system drove numerous research project about marine wildlife. For example, in 2002 Hatase et al. were able to track a turtle for 35 days. They collected a total of 57 transmission corresponding to a calculated path of $781km$. However, the accuracy of the samples ranged between an expected error of $150m$ to more than $1000m$ [19]. Myers et al. instead decided to couple the Argos tag with a pressure sensor to study the dive profile of leatherback turtles. They were able to collect information about 229 dives profile [20]. The Argos satellite network has been also used for applications related to migratory birds [42]. Pennicuick et al., in particular, studied how weather and light conditions influenced the migration movements of Whooper Swans [43].

Argos was a breakthrough in the field of wildlife tracking. It was the first system that allowed not to have antennas deployed on the ground. Although, the accuracy of the location samples was too low and the deployment too expensive [44]. Vincent et al. made an assessment of the accuracy of these tags using captive Grey Seals. The outcome of the experiments revealed that only 2 days of the 61 seal-days collected could have been considered as reliable [45].

The field of animal tracking exploded after the U.S. Department of Defense removed the policy of degrading the accuracy of civilian GPS [46, 47]. GPS provides a more cost-effective solution for tracking and allows to reach a high spatial and temporal granularity. Location data retrieved from GPS module can reach a sub-second frequency. Because of the size and weight of the first GPS tags developed, especially due to the high energy consumption, the first experimentations could have been conducted only on large vertebrates, such as elephants [6], moose [7, 8] and bears [9, 10].

Since these technologies are widespread and can be exploited in several different fields, it is even more interesting for industries to push research and development. This fast-growing market has led to newer, cheaper, smaller and more performing off-the-shelves microcontrollers and batteries to be introduced in the market. Nowadays, the tag size has been reduced to a level that makes it possible to track small animals such as wolves [11], pigeons [12–15], flying foxes [16, 17], and mallards [18]. GPS-based solutions have proved to be effective and reliable also for marine applications. Some examples of animals that have been tracked are African penguins [21], sea lions [22] and sea turtles [23]. Water causes an important amount of interference with signals in general, for this reason, the complexity of this application is mostly due to being able to exploit the moments in which the animals resurface.

This whole new technological ecosystem led the way to several innovative projects exploiting the raw data collected from GPS tags. Indeed, movement is the key information to every study in animal ecology. Being able to have data about the movement dynamics of animals opens the way to understand several other aspects regarding the life of the studied individuals. As an example, GPS data have been used to study animals home range formation [48, 49]. An animal home range is defined as the area in which an animal spends most of its time and that it actually defends from predators [50, 51]. Other studies exploited GPS data retrieved from the different individuals to extract models about the collective movements of animal groups [52–54]. Li et al. [55] instead studied the inverse process. They developed a method to predict the future location of an individual starting from the information about the movement of all the other individuals of the group. This project involved GPS data retrieved from wild Olive baboons, the same species that we are targeting at the current state of our work. The same data used by Li et al. has been used by Amornbunchornvej et al. to study leadership processes in coordinated activities [56–60]. GPS data have been also taken into account to asses if memory plays a role in determining how animals orient themselves or plan their movements [61, 62].

Nowadays, new technologies are being studied and tested in the field of animal tracking. The ICARUS (International Cooperation for Animal Research Using Space) initiative [63, 64] is working on solutions to be deployed in the space. On August 15, 2018, an antenna has been installed on the exterior of the ISS (International Space Station) [65]. This antenna will be used to track signals coming from small tags deployed on selected species every time the ISS passes over them.

2.2 Behavior Tracking

As it has been mentioned in the previous section, being able to retrieve data about an animal allows studying its relationship with the environment. It also allows studying some aspects of the collective behavior of a group if a high enough number of individuals are tracked simultaneously. Although, biologists and ecologists are interested in studying also animal behaviors on a more granular basis [66]. What are the activities that define the daily routine of an individual? How do individuals interact with each other? These are just examples of the questions that researchers are interested to find an answer to.

Indeed, tracking the movement allows identifying some behaviors of an animal. For example, with the technology available today, it is pretty trivial to say if an individual is still, walking or running by looking at GPS tracks. But how can we distinguish actions such as sleeping, laying down, grooming or foraging? The activities just mentioned are simple examples of different activities that the GPS location does not help to classify. In fact, the animal is always in the same position during the whole duration of these activities.

In order to have a more granular idea of animal behavior, scientists have been studying them by observing the animals in their habitat. There is a set of techniques used for field observation that have proved to be effective. Two well-established methods are scan and focal sampling [2,3]. In focal sampling, a single individual is continuously observed for a prolonged amount of time. For this reason, it is considered the most accurate technique to collect information about animal behavior. However, there are several issues that could make this process unfeasible. It could be difficult to get close to an individual if the group is not habituated to human presence, identify an individual could not be trivial if the species does not present distinctive traits or thick vegetation could interrupt the sampling process. For all these reasons, in some cases, scan sampling could be preferred over focal sampling. Scan sampling is a process repeated at regular intervals. Every time a scan is done, information about the activities and the placement of the group individuals is recorded. Scan sampling does not provide as detailed information about an individual as focal sampling, although it makes possible to track more individuals simultaneously. However, the two techniques described are highly time-consuming, they require the deployment of a large number of human resources in the field and therefore are not cost-effective.

The recent technological process has provided new hardware components smaller in size, cost-effective and customizable on the specific application requirements. This has allowed researchers to integrate a variety of new sensors on classic animal GPS trackers. By deploying small cameras on animals, researchers are validating behavioral hypothesis exploiting the animal view perspective [25]. Parrish et al. studied the foraging processes of Hawaiian monk seals using AVED (animal-borne video and environmental data collection) systems [26–28]. Having a camera recording allows us to have information about the oceanic environment and conditions that could have not been available otherwise.

The miniaturization of MEMS Inertial Movement Units allowed researchers to collect information about behaviors related to the movement of the body of the individual that correlates to energy expenditure [29]. Extensive use of behavior tracking tags equipped with accelerometers has been carried out to determine cattle health and well-being achieving very high accuracy measures [30, 31]. Accelerometers have been used also to study captive adults Sprague Dawley rats [32]. The researchers targeted the recognition of three activities: standing, eating, and grooming obtaining interesting results. However, the authors experience some issues in the behavior classification due to calibration issues.

Continuous measurement of heart rate, body temperature, and electroencephalographic measures are other examples of physiological parameters that have been used to study animal behavior. Signer et al. used these types of parameters to perform long-term monitoring of ruminants in harsh field conditions [33], while EEG measurements have been conducted on sloths to study functional differences of sleep between wild and captive individuals [34].

Microphones are another interesting source of information. Microphones array have been used to track both location and animal behavior [35]. In particular, Lynch et al. deployed tags equipped with microphones on Odocoileus Hemionus mule deer collecting over 3300 hours of acoustical recordings from ten individuals over a 2-week period [67]. Among the activities that they were able to collect there are browsing, mastication and rumination.

2.3 State of the Art

As of now, the state of the art technology for animal behavior tracking is the e-obs collar [68,69]. The e-obs collar is a device conceived to track mammals. It weighs $12.5g$ (batteries and enclosure excluded) and its dimensions are 39x22x12mm. It is equipped with a GPS module and a 3-axis accelerometer. It has a series of programmable settings that can be used to choose the duty-cycle intervals and the sampling frequencies. It also provides an on-board RTC which is synchronized with the GPS time in order to have correctly timestamped data. It is provided with VHF radio transmission on $868MHz$ radio band. The VHF radio-link is used both to activate a pinger to remotely locate the device and to download the data if the dedicated base station is in range. The device specifications indicate a transmission range between $15000m$ and $500m$ depending on the surrounding environment.

e-obs collars have been extensively used to track several species of mammals, such as roe deers, baboons and cheetahs [55, 70–72]. In particular, Crofoot et al. used this technology to build a dataset about baboons tracking [73]. The dataset contains data collected from a troop of 26 baboons for 12 hours a day on a 35 days period. They collected about 20 million GPS locations and ∼700 million accelerometer records [24, 55].

2.4 Summary

In Chapter 2, a series of applications in the field of animal tracking have been discussed. It is also possible to see how fast technology improvements open new possibilities both in term of improved accuracy and new data sources. The first experiments in this field used VHF radio transmitting to track animals. Although, VHF could only cover a restricted instrumented area and the location samples accuracy was too low. Nowadays, satellite positioning systems allow tracking an individual everywhere in the world, potentially with a sub-meter precision if a series of conditions are satisfied. Moreover, new technological solutions, such as MEMS Inertial Measurement Units, also allowed to make giant leaps in the field of animal behavior tracking.

Although, the questions that ecologists and biologists want to answer require a more detailed and in-depth ethogram coverage. In Chapter 3, based on the current state of the art, the challenges that need to be addressed in order to achieve scientists' goals will be discussed. After that, a list of requirements that the sensor system to be developed will need to satisfy will be redacted.

CHAPTER 3

PROBLEM DESCRIPTION

In this chapter, the challenges that still need to be addressed in the field of animal behavior tracking will be discussed. Based on what has been presented in the previous chapter, we will go through a series of goals that ecologists and biologists want to address nowadays. Then, the problem definition this research project will be provided. The last part of the chapter, instead, provides a set of requirements and specifications that will need to be met in order to achieve the goal claimed in the problem definition.

3.1 Challenges

In Chapter 2, we described the e-obs collar which is considered as the actual state of the art in the field of animal tracking and in particular for mammals behavior tracking. In our work, we will be focusing on Olive baboons, which have been the targeted species for many other projects of our collaborators at the Crofoot Lab [74]. The data that they have been able to gather from baboons with this device [73] allowed to design data analysis framework to recognize some of the animal behaviors. Li et al. [75] developed an algorithm called *Adversarial Sequence Tagging* which they tested on this dataset to recognize baboons' activities. The dataset they used allowed them to classify activities such as sleeping, hanging out and coordinated progression. However, biologists are interested to answer questions that require a more granular understanding of the daily routines of these animals. This means that a solution needs to be developed in order to be able to have data that allow distinguishing more activities of the baboons' ethogram. An ethogram is a hierarchical description of all the activities of an animal species [66]. Figure 1 represents a sample of an ethogram of baboons behaviors.

At the moment, we can classify with a pretty high level of confidence a set of individual activities. Especially, we have methods to classify activities that are characterized by different energy expenditure by the animal (laying down, walking, running), since the energy effort is related with the data we can retrieve from accelerometers.

However, the individual part of the baboons' ethogram includes a set of behaviors that are difficult to recognize by having a single point of data acquisition on the animal (i.e. the collar around the neck). A couple of examples of this kind of behavior are grooming and foraging. During both these behaviors the animal body is still, therefore it is practically impossible to distinguish them by GPS or accelerometer data collected from the neck of the animal. In fact, the two mentioned behaviors are highly characterized by the movement of the arms. Self-scratching is another example of an interesting behavior for biologists which is characterized by the movements of the animal's limbs.

Dyadic behaviors and interactions are another part of the baboons' ethogram yet to be explored in terms of tracking solutions. GPS solutions are continuously improving the accuracy of the location data. Other systems such as GALILEO [76] and GLONASS [77] are expected to provide sub-meter positioning. However, it is still premature to adopt these technologies in this field, both because of costs and the fact that the systems are not yet fully deployed.

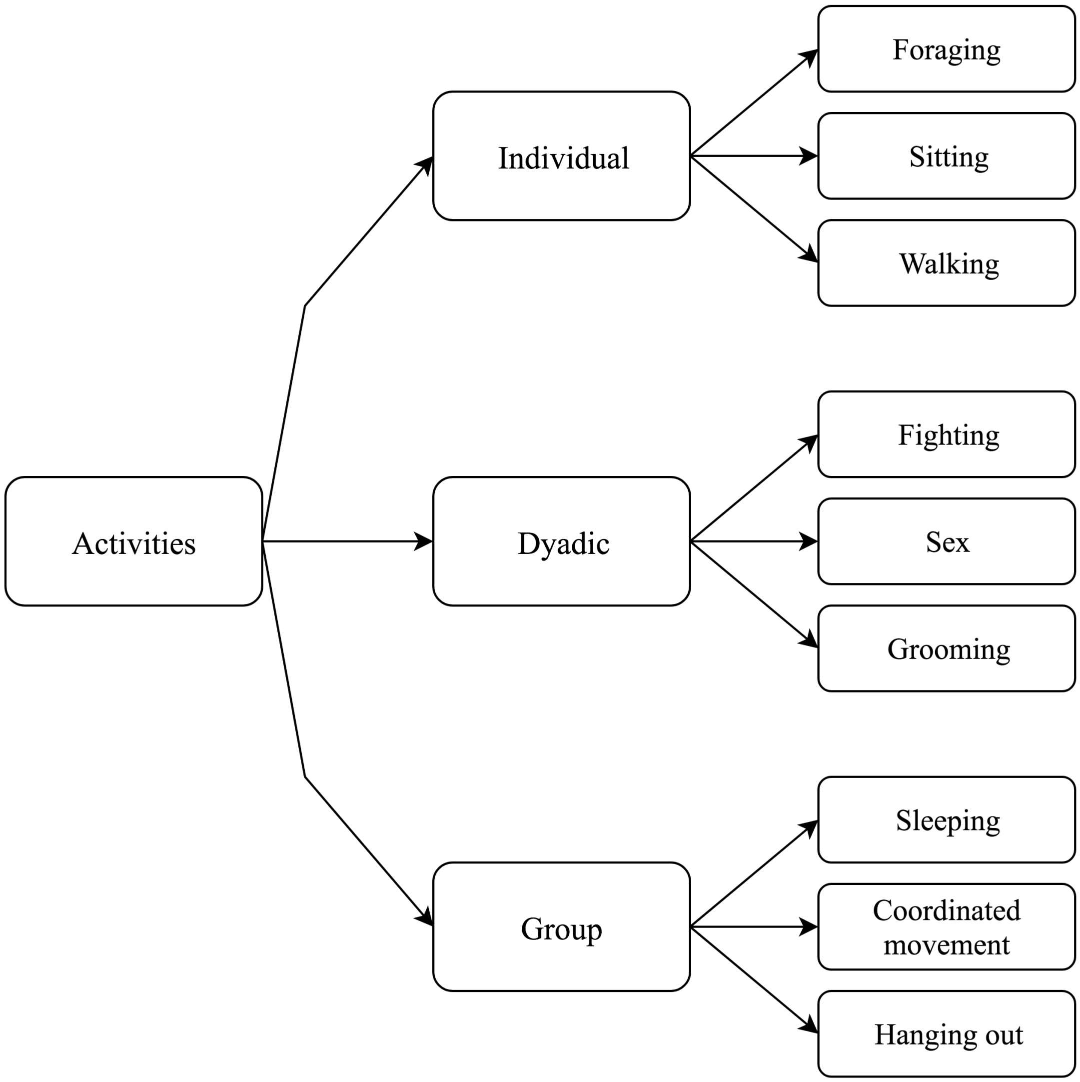


Figure 1: Animal activities are described by biologists using ethogram. The figure shows a sample of a baboon ethogram. The activities are characterized by the cardinality of baboons involved (i.e. individual, dyadic and group).

Moreover, satellite positioning systems performance is also highly influenced by other factors such as weather conditions and satellites availability in the area of interest.

Another challenge that needs to be addressed when designing solutions for this kind of application is that the devices to be developed will be deployed for a long time in a non-instrumented wild environment. This implies that the devices need to be both physically robust and reliable. Moreover, a correct trade-off between batteries lifetime and the operational sample rates need to be studied.

3.2 Problem Definition

The aim of this research work is to develop a reliable and robust sensor system to track individual and social animal behavior in the wild. The system will have a broader set of data sources with respect to the state of the art solutions in order to be able to identify a wide set of behaviors among the one listed in the species' ethogram. The system should also provide a method to remotely download the data collected considering the chance that it might be not possible to recover the devices after the deployment.

3.3 Requirements

In this section, the requirements of the new system to developed are listed. The following requirements have been discussed and approved by both the parts involved in the project (i.e. the computer engineers team from the Computational Population Biology Laboratory at the University of Illinois at Chicago and the biologists from the Crofoot Lab at the University of California, Davis).

3.3.1 Broader Set of Identifiable Behavior

As discussed earlier, there are challenges that need to be addressed in order to expand the set of identifiable behaviors in the ethogram (Figure 1). Activities in the ethogram are aggregated at three different levels: individual, dyadic and group. The goal of the following requirements is to improve the effectiveness of the data collected in the activity recognition process.

Regarding the individual behaviors, the existing solutions allow discriminating activities highly correlated with the macro movement of the animal body. However, the ethogram describes a set of activities that are defined by the movement of the animal peripheral body parts. The system to be developed should include one or more peripheral units to track high-resolution data about the movement of these body parts. These units must be very light-weight in order to not interfere with animal activities.

For what concerns dyadic and group behavior, GPS systems provide useful data about coordinated movement, but in order to expand biologists understanding of these categories of behaviors, the system should provide a more accurate local positioning of the animals. This translates to having a way to understand which individuals are close to the observed one and especially if two individuals are actually interacting with each other or not. This level of positioning will allow recreating a social network of the group based on the relative position among the animal rather than an absolute position relative to a map.

Moreover, animal orientation should be included as a new data source of the device. This kind of data would be key to understand if two nearby animals are really interacting with each other or if they are looking at two different directions.

3.3.2 Macro vs Micro Location Tracking

The device to be developed should track both the macro and the micro-location of the animal. Macro-location is intended as the location of the animal with respect to a map. It is useful to have this information the correlate the animal movement with the environment and to study how the two entities influence each other. However, in order to study the dyadic and group social interactions, it is necessary to gather information about what we call micro-location.

Micro-location can be described as the relative position of one individual with respect to other ones that are within a defined radius from it. Classical satellite positioning systems can track an individual everywhere on the earth but the accuracy achievable is between $1m$ and $5m$ with the current technologies. The device should have a data source able to track distance between individuals below the GPS accuracy threshold. Having this information would allow computer scientists to reconstruct a social network of the group of study and biologists to have a better understanding of the social dynamics of the group.

3.3.3 Fault Tolerance

The device to be developed should be reliable and fault-tolerant both on the hardware and on the software level. Solutions need to be adopted in order to assure that the device will work providing a minimum set of guaranteed features even if some of the components fail. In addition, a reliable on-board storage solution needs to be provided so that can be persisted on the device and possibly retrieved manually in case the remote download fails.

Reliability and fault tolerance are particularly important in the field of animal tracking. As a matter of fact, baboon individuals, like many other species, need to be sedated to fit the tracking units on them. This could be a very traumatic experience for the animal and, for this reason, the sedation needs to be conducted as few times as possible. The ultimate goal of animal tracking is to have unbiased data about the animal daily activities. Precautions need to be taken in order to preserve the animal well-being and survival during these procedures. Moreover, going in the field to conduct this kind of experiments is both economically and time expensive. For all these reasons, the devices should be tested and production-ready before being deployed and the fault tolerance need to guarantee that minimum requirements about the data collection will be satisfied in order to have some results even if part of the system fails during the deployment. This will allow to preserve the animal well-being and to assure data collected will be available for multiple research project [78].

In the United States, animal research is regulated by Animal Welfare Act (AWA) [79], which is administered by the Animal and Plant Health Inspection Service (APHIS) [80] of the United States Department of Agriculture (USDA). In particular, the principle of the 3Rs [81, 82] is implicitly included in the Animal Welfare Act. The 3Rs stand for *Replacement*, *Reduction*, and *Refinement*. The replacement principle requires to avoid animal use in research if substitutes can be found. However, since our research is directly about animals, we cannot work on this principle. Instead, we can address through the design of the device, and in particular its reliability and fault tolerance, the two other principles. In fact, the reduction principle requires to minimize the duration and number of experiments on the animals while the refinement principle requires to reduce as much as possible the animal suffering and preserve its well-being. Both of these principles can be addressed by having a reliable device that produces clean, informative and reusable data.

3.3.4 Remote Data Retrieval in Uninstrumented Environments

In a setting like the one we are targeting for the deployment, it becomes fundamental to be able to remotely extract the data from the units. First of all, the environment in which the devices will be deployed is not instrumented. Neither already deployed Wi-Fi connections or stable 3G can be expected to found connectivity. The e-obs technologies feature VHF radio connectivity to download the data. However, other types of connectivity will need to be evaluated to cope with the large amount of data that will need to be retrieved.

3.3.5 Battery Lifetime

The previous experiments conducted with the e-obs collars lasted about a month collecting GPS locations at $1Hz$ and 3-axis accelerometer records at $12Hz$, The minimum requirement in terms of battery life for this project is to equal the duration of the e-obs collars by collecting the same data with the same parameters configuration. Although, the goal is to gather higher resolution data from all the data sources of the system, not only the GPS and the accelerometer.

Moreover, the device should provide the possibility to configure the operational parameters both before and during the deployment. The idea is to provide different configuration settings that could provide trade-offs between the battery lifetime and the resolution of the data collected. To give an example, the device could provide three different operational modes. The first one would provide very high-resolution data but with lower battery life. The second one would be a balanced option between lifetime and data resolution providing, for example, a month of collection. Finally, another operational mode would provide a year of data collection but with really sparse sampling. This could be useful for example to track migrations which do not require a high-resolution representation of the individual.

The possibility to configure the device could also be useful during the deployment. As a matter of fact, based on the analysis of the remotely retrieved data, if the operators notice that the device is consuming too much energy, they could modify the operational parameters to prolong the collection duration.

3.3.6 Weight

The weight of the devices used to track animals is one of the factors that ecologist and biologist are most careful about. As a matter of fact, the issue is two-fold: on one hand, it is a matter of ethics in terms of being respectful of the animals and to avoid any possibility of harming them. On the other hand, the ultimate goal of animal tracking is to study their behavior in an as unbiased as possible way. For this reason, the shape, size, weight, and features of the devices have to be designed to minimize the effects on animal behavior [24]. As thoroughly described by Boitani and Todd in [51], in order to achieve the goals mentioned above, the total weight of the devices placed on an animal should be between 5% and 10% of the animal body weight. We decided to aim at not going above the 5% threshold.

3.3.7 Animal Related Issues

The devices will be deployed in a hostile environment for a long period. In particular, baboons are pretty aggressive and strong animal. This fact needs to be taken into account during the design of the solution and of the related enclosure. The device should be shockproof and for this reason not equipped with components that could alter their operational performance in case of strong hits. The enclosure instead needs to be animal-proof, but animal compatible too. This means that it will need to be as light and as robust as possible at the same time. In particular, baboons have a really strong bite that could pierce the enclosure.

A pierced enclosure could destroy the device and therefore cause a data loss. Even if the device is not destroyed at the moment of the piercing, a hole in the enclosure could undermine the waterproofness of the whole unit. In addition, this kind of incident could have even worse consequences in terms of animal safety. Regulations on animal experimentation are very strict and require to take all the precautions possible to avoid the animal to swallow any kind of electronic part. Moreover, damages to the battery could cause very nasty incidents such as fire, explosion, and poisoning.

Particular care needs to be put in the design of the attachments. First of all, they have to be comfortable for the animal. The devices should not distract the animal during his routine activities. Second of all, if it is uncertain whether it will be possible to remove the device from the animal or not in a short period of time, the animal growth rate needs to be taken into account. Especially if the devices are used to track young individuals, the attachments will need to be designed so that they will not interfere with the animal physical development.

Animals are also more sensible than humans to some signal frequencies. For example, ultrasounds are often used in some commercial sensor and animals behavior could be strongly influenced by this kind of signals.

3.4 Summary

In this chapter, we described the challenges that need to be addressed to improve the existing solutions in the field of animal behavior tracking. We highlighted two main aspects. The first one is related to finding a solution to detect all those activities that cannot be correlated to macro-movement of the animal and are not distinguishable from an accelerometer placed on the neck too. The second one instead regards the need to have a better description of the micro-location of the animal and of the position of the nearby individuals.

Then, after providing the problem description of this research project, we listed and described all the requirements that need to be met in order to have a complete solution. Among them we have the need of having a peripheral unit to expand the identifiable behavior, a solution to have more accurate and precise information about the micro-location of the animal and minimum fault tolerance requirements. We also stated the need for having a method to extract the collected data remotely and to find a balance between performance and battery lifetime. To conclude, we discussed some non-functional requirements about the compatibility of the devices and the related attachments with the animals.

In the next chapter, the overall system architecture will be presented. In particular, we will focus on the aspects of the designed system that satisfy the previously described requirements.

A brief description of the architectural choices made to provide fault tolerance will follow the presentation of each element of the architecture.

CHAPTER 4

SYSTEM ARCHITECTURE

In this chapter, the overall system architecture is presented. In particular, for each of the three elements of the system, we discuss the design choices that have been made in order to satisfy the system requirements described in Section 3.3. Figure 2 shows a representation of the three elements of the system architecture and the related technologies to make them communicate with each other.

4.1 Bracelet

The requirements state that the system should have data sources about the movement of the peripheral body parts of the animal (Section 3.3.1). For this reason, we introduced in the system a peripheral unit conceived as a bracelet. The literature does not provide examples of peripheral units in addition to the main one (usually a collar for mammals) to track animal behaviors. However, we believe that the movement of the peripheral part of the animal arm could highly improve the quality of the features extracted to detect more granular individual behaviors. Our intuition has been confirmed by the biologist team we are collaborating with. Based on their knowledge about the targeted species and the several hours of observation conducted in the past, we have concluded that the arms and especially the wrist of the animal are good points to collect data.

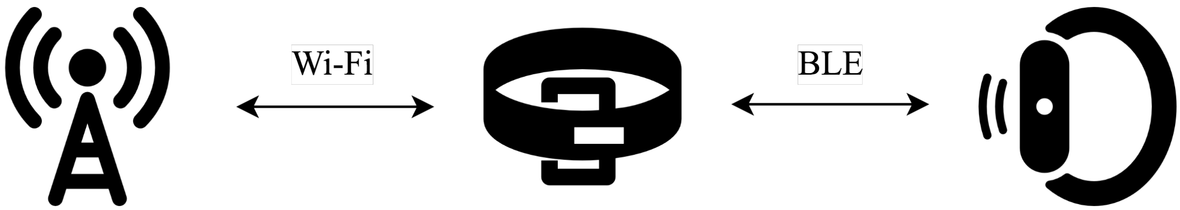


Figure 2: In this diagram, the overall system design is represented. From right to left, the first element is the bracelet, which sends the data collected to the collar via BLE. Then, the collar store the data received from the bracelet along with the one collected from the sensors it is equipped with. Finally, the hub is used to retrieve all the data via Wi-Fi.

The bracelet unit will be equipped with an IMU. We opted for 6 degrees of freedom in order to be able to describe all the types of movement of the unit. Moreover, in case it will be requested to reproduce the unit's movement in a 3D representation, the gyroscope data can significantly improve the quality of the reconstruction [83].

Bluetooth Low Energy has been chosen as the communication technology to transmit data collected by the bracelet to the collar. First of all, BLE is a low energy consumption solution which is a critical point in the bracelet design process. In fact, the strict requirements about the size and the weight of the unit (Section 3.3.6) require to keep the complexity of the unit as low as possible. For this reason, we can have neither a big storage solution on-board nor large batteries. Therefore, since we must continuously transmit the data collected by the bracelet to the collar to store them, we must pay particular attention to the energy aspect in the design phase of this unit.

4.2 Collar

The main unit of the system has been designed as a device to deploy as a collar. The neck of the animal is the most suitable point both in terms of attachment design and data source. The collar unit can be considered as the most critical element of the entire system. As a matter of fact, the collar unit is a single point of failure with respect to data storage and retrieval. In addition, since the bracelet unit does not provide any kind of storage, the collar unit is the only element of the whole system that can and need to be connected to the bracelet in order to retrieve the data coming from it.

Regarding the data collected by the sensors mounted on the collar unit, the movement of the animal is by far one of the most informative features to identify behaviors. The collar unit board is equipped both with a GPS module and a 9-axis IMU. The former allows to continuously track the animal position with respect to a map. The latter provides information about the overall body movement of the animal, thanks to the accelerometer and the gyroscope. In particular, the neck is a good point of acquisition for the animal body movement since this data will be highly correlated with animal energy expenditure.

The collar unit is the element of the system which addresses the requirement about micro-location tracking described in Section 3.3.2. As a matter of fact, the secondary controller of the collar unit implements a proximity sensor exploiting the BLE packets RSSI. With the due attention in the implementation phase and data processing, RSSIs are a valid indicator of the relative distance of the individuals in a radius determined by the transmitting power of the signal. Other solutions have been taken into account to retrieve this kind of information but a solution based on Bluetooth Low Energy has been considered as the most appropriate and effective one. As an example, ultrasound-based sensors are often used to implement proximity sensor solutions [84]. However, ultrasounds are not an option for our application settings since they can be dangerous for the well-being of the animal.

In order to improve even further the micro positioning task, the IMU used is also equipped with a magnetometer. The aim of this component is to to be able to understand in which direction the animal is looking at. As a matter of fact, it could be the case that two animals are detected to be really close by combining the GPS and the proximity sensor data. However, if their look is directed in two different directions it is very likely that the two individuals are not actually interacting with each other.

Based on the literature in the field of animal behavior tracking [35, 67] and in order to develop a complete solution, a microphone has been also added among the components of the collar.

For what concerns the requirements about the battery lifetime (Section 3.3.5), there is a set of parameters that can be tuned regarding the operational settings of the collar in order to set a trade-off between performance and energy consumption. First of all, the device will provide the possibility to set the sampling rate of each sensor. We expect to have the possibility to modify these parameters both before and during the deployment. Then, the RF power of the proximity sensor could be tuned. The lower the RF power, the higher the battery lifetime, but with a lower expected distance range for the proximity detection. Finally, it will be possible to set the duty cycle of the device and, for example, turning it off during the less informative periods of the day (e.g. during the night).

4.3 Hub

The last element we decided to introduce in the system architecture is the hub. The targeted deployment environment will not be instrumented and will not have a stable 3G connection. For this reason, it has been necessary to introduce a third element in the system which is a base station used to connect and communicate with the deployed devices.

The main goal of the hub is to retrieve the data collected by the devices. As it has been discussed in Section 3.3.3 and 3.3.4 of the previous chapter about requirements, it is critical for biologists to make the most out of every deployment because of the cost and the possible dangerous consequences on the animals. For this reason, the possibility that it might be difficult to recover the devices at the end of the experiment makes it necessary to have a reliable method to retrieve the data remotely.

Besides this aspect, having a communication channel with the deployed device is interesting since it allows to change the operational parameters of the devices during the deployment. A battery which is discharging too quickly or the need to change the collection sample rates based on what it has been learned from the data already collected are just a couple of example of use cases in which it would be useful to connect with the deployed devices.

We chose Wi-Fi as the communication protocol to connect the collar unit with the hub. Wi-Fi provides high bandwidth to allow quick data transmissions and a theoretical distance range that allows the field operator to get close enough to the animal group or to deploy the hub in the field and cover the area occupied by the entire group. Moreover, Wi-Fi is a commercial solution highly adopted that therefore has a large community and support for development.

4.4 Summary

In this chapter, we presented the three components that compose the system architecture. We presented a peripheral unit conceived as a bracelet. We expect to extract useful information about the movement of the animal's arm thanks to the IMU mounted on this component. Then, we introduced the collar unit. The collar unit is the core of the system. It is equipped with an extensive set of sensors, including a custom implemented proximity sensor. It is also in charge of storing all the data, including the ones retrieved from the bracelet unit via BLE, and to send them to the hub when requested. The hub is the last element of the architecture and it has been introduced as the unit in charge of retrieving the data back from the deployed devices.

In the next chapter, details about the software implementation of the three devices will be provided. The second part of the following chapter, instead, will provide a discussion about a set of implementation choices that have been made in order to guarantee a certain level of fault tolerance for the whole system.

CHAPTER 5

IMPLEMENTATION

In this chapter, the implementation details regarding the three elements of the system architecture are be provided. For each element, a list of the components used is provided along with some details about the interesting features of those specific components. For the bracelet and the collar unit, the schematics of the units are reported. Finally, the code implementations are described. First, a high-level view of the procedures is provided, then we will dive in the details of each part of the different implementations.

The prototype boards (Figure 3 and Figure 5) have been manufactured by electronic engineers at NECSTLab - Politecnico di Milano, based on the schematics that we provided.

5.1 Bracelet

In this section, the details about the work done on the bracelet unit are presented. The bracelet unit is the element of the system architecture that allows us to get information about the movement of the animal's arm. In the following subsections the components used, the schematics of the bracelet unit board and code implementation are described. Figure 3 shows the bracelet prototype board that has been produced for the first testing phase which will be described in Section 6.2.

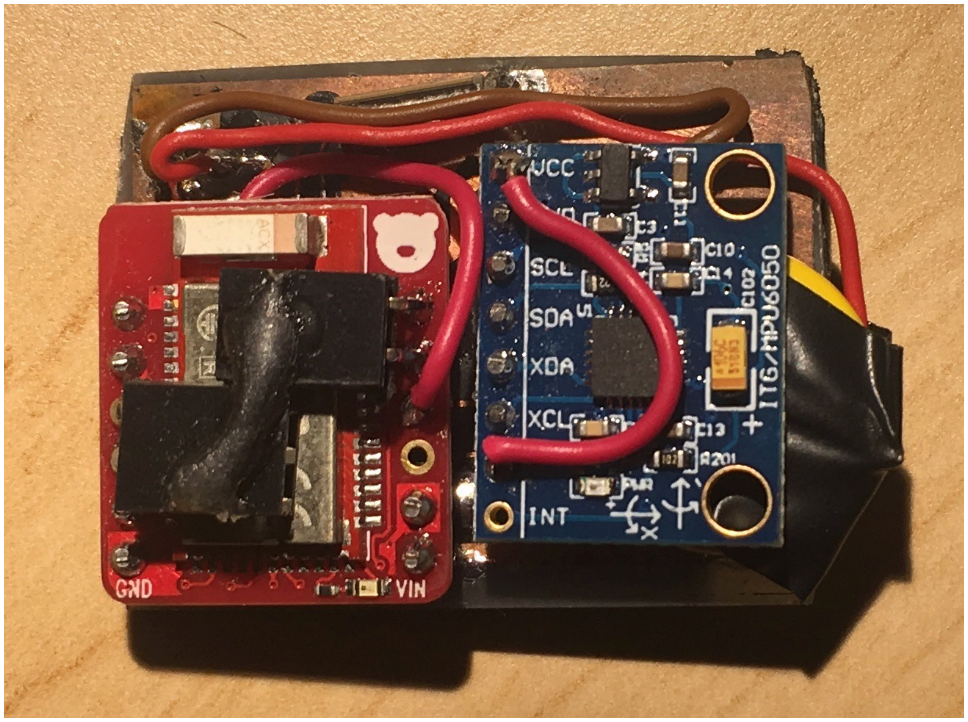


Figure 3: Bracelet prototype board

5.1.1 Components

The bracelet unit is equipped with a RedBear Nano V2 controller [85]. The Nano V2 is a very light-weight controller equipped with the nRF52832 [86] SoC. The nRF52832 offers an ARM Cortex-M4 processor and BLE connectivity.

As Inertial Measurement Unit, we decided to use a breakout board equipped with the MPU6050 [87]. The MPU6050 is a 6-axis IMU that means it has both an accelerometer and a gyroscope. It is one of the most used 6-axis IMU in the community.

TABLE I: LIST OF THE COMPONENTS MOUNTED ON THE BRACELET UNIT

Type	**Mfr.**	**Description**	**Weight**
Controller	RedBear	Nano V2	6g
IMU	TDK	MPU6050	2.1g
RTC	Adafruit	DS3231	2.1g

In order to precisely keep track of the time, we decided to include a Real-Time Clock. The chosen component is an Adafruit DS3231 [88]. The interesting feature of this component is that the 32kHz timing crystal is integrated into the chip along with a temperature sensor. As a matter of fact, the crystals used for this kind of chips are subject to a slight drift due to temperature changes. Having a temperature sensor allows the component to compensate for the frequency changes, guaranteeing precise timekeeping [89, 90].

The gross weight of the bracelet unit (board and case) is $107g$. The net weight of the electronic board is $11g$. These values meet the requirements described in Section 3.3.6.

Table I reports a list of all the components mentioned above along with the related weight of each component.

5.1.2 Schematics

Figure 4 shows all the connections among the bracelet unit components. In order to upload the firmware of the controller a RedBear DAPLink [91] programmer is needed. The controller

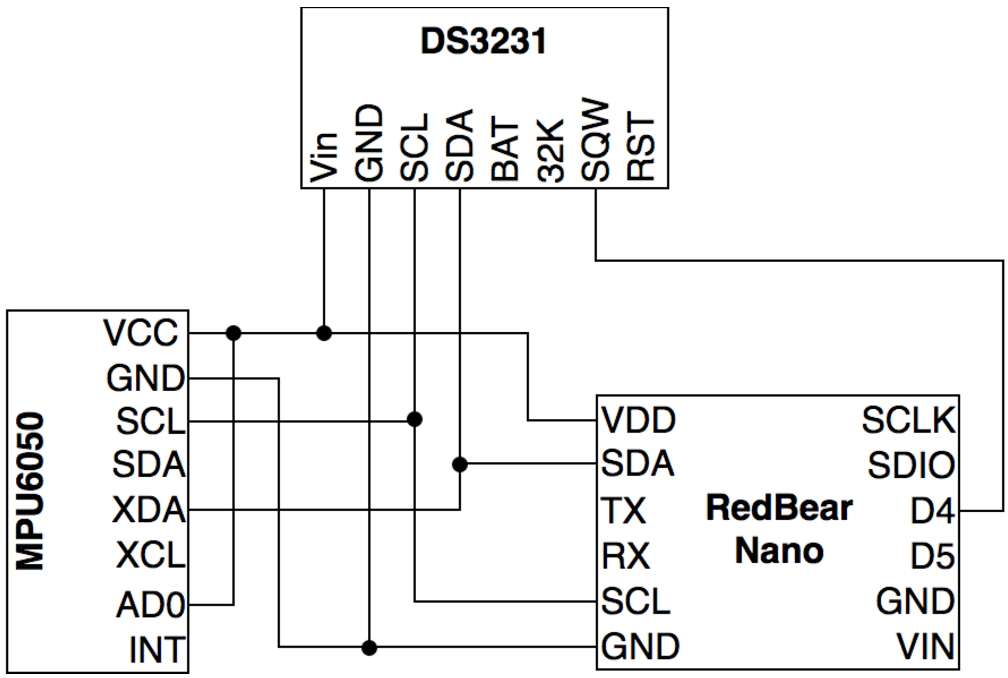


Figure 4: This figure shows the schematics of the connections among the components mounted on the bracelet unit.

and the programmer needs to be connected through the SCLK and SDIO pins. During the programming phase, it is necessary to connect the controller and the programmer grounds together in order to set a common reference point between the devices.

5.1.3 Implementation

Most of the bracelet unit implementation complexity is due to the fact that in order to keep the unit as light as possible in terms of weight, computational power, and energy consumption. As a matter of fact, the bracelet unit has strict weight, shape and size requirements. For these reasons, we opted not to do any kind of processing online, but to send all the data retrieved to the collar in order to process them afterward.

The bracelet code procedure structure can be summarized in two phases: setup and loop. First of all, during the setup phase, the 6DoF IMU (accelerometer and gyroscope) is initialized along with the RTC. The RTC initialization includes also the setup of the SQW pin so that it will raise interrupts with a frequency of $1Hz$ to keep the collection synchronized. Moreover, the RTC time is set with the time of the last compilation of the firmware. Since the RTC on the bracelet is powered by an external coin battery and the code is always recompiled before being uploaded, this allows the data analysis to detect easily the delay between the GPS time of the collar unit and the RTC time on the bracelet unit.

After that, before starting the loop phase, the BLE stack is initialized. The device starts advertising its identifier using the GAP protocol, waiting for a collar unit to initialize a connection to it. The *Generic Access Profile* protocol is a connection-less protocol. The specifications of this protocol imply the use of very light-weight packets. For this reason, the GAP protocol is usually used as a handshake mean to establish BLE connections [92, 93].

Once a connection is established, the loop phase begins. The device will collect data with a frequency of $8Hz$ and send them to the collar unit using notification packets. This kind of communication is done using the *Generic Attribute Profile* protocol. The GATT protocol is a connection-oriented protocol and is meant to be used to transmit larger amounts of information than the packets in GAP protocol [92, 94]. For this reason, we decided to opt for this protocol to let the collar and the bracelet units communicate.

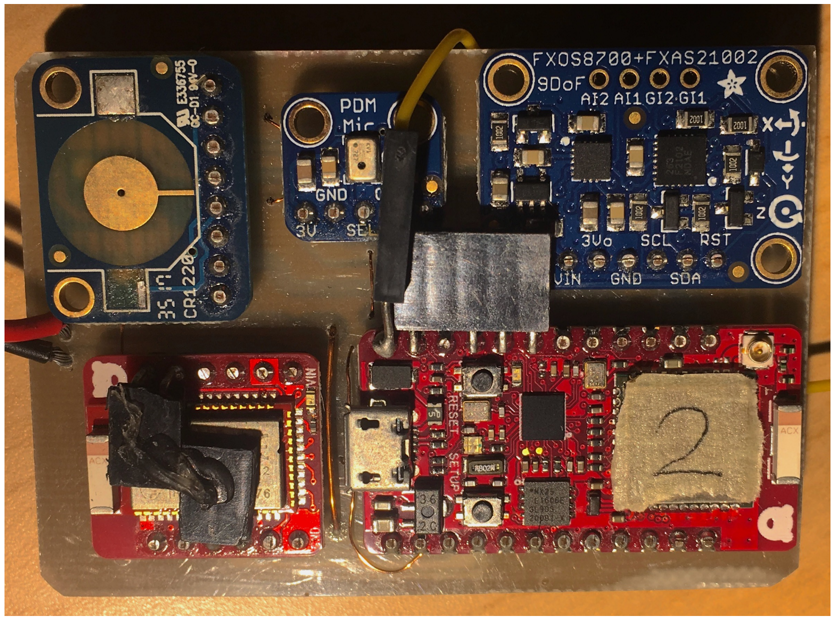
The frequency of $8Hz$ has been chosen as a trade-off between the amount of data collected and both the computational power of the controller and the BLE channel bandwidth. The amount of data transmitted has been calculated in order to exploit most of the BLE bandwidth but not to saturate the transmission.

5.2 Collar

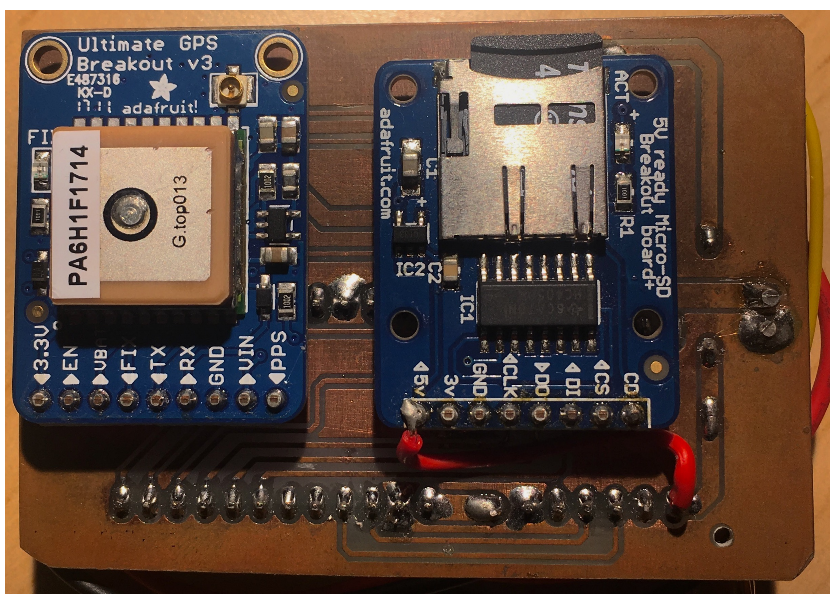
In this section, the details about the work done on the collar unit are presented. The collar unit is the most critical element of the whole system architecture. It gets information about the location and movements of the individual. In particular, all the data are stored in the collar unit before being retrieved by the hub. For this reason, it is imperative to have a robust and reliable design for this unit. Below, the components used, the schematics of the board and the code implementation details are provided. Figure 5 shows the collar prototype board that has been produced for the first testing phase which will be described in Section 6.2.

5.2.1 Components

The collar unit is equipped with two different controllers: a RedBear Duo and a RedBear Nano V2. More details about why it has been decided to opt for this solution will be provided later in this section. The RedBear Nano V2 is exactly the same component that can be found in the bracelet. Its description can be found in Section 5.1.1. The RedBear Duo [95], instead, mounts an ARM Cortex-M3 processor with 128 KB of SRAM and 1MB of flash memory. In terms of connectivity, the RedBear Duo is equipped with a Broadcom BCM43438 [96] chip that offers both Wi-Fi (802.11n - 2.4GHz only) and Bluetooth 4.1. This chip has an integrated antenna with the option to connect an external one.



(a) Collar board front side



(b) Collar board back side

Figure 5: Figure (a) and (b) respectively show the front and the back side of the collar board.

TABLE II: LIST OF THE COMPONENTS MOUNTED ON THE COLLAR UNIT

Type	**Mfr.**	**Description**	**Weight**
Controller 1	RedBear	Nano V2	6g
Controller 2	RedBear	Duo	17g
IMU	Adafruit	Precision NXP 9-DOF	2.1g
RTC	Adafruit	DS3231	2.1g
GPS	Adafruit	Ultimate GPS	8.5g
Microphone	Adafruit	PDM MEMS Microphone Breakout	0.5g
SD Breakout	Adafruit	MicroSD card breakout board+	3.43g
SD Card	Swissbit	S-45u Series	0.4g

The IMU that has been chosen for the collar unit is the Adafruit Precision NXP 9-DOF [97]. This IMU combines an FXOS8700 3-axis accelerometer and magnetometer and an FXAS21002 3-axis gyroscope.

The RTC adopted for the collar unit is the same as the one chosen for the bracelet unit. Its description can be found in Section 5.1.1.

In order to track the location of the individual, we decided to opt for Adafruit Ultimate GPS [98] breakout board. It provides $-165dBm$ sensitivity, 10 Hz updates and 66 channels. In particular, the sensitivity value is pretty good considering that typically, taking into account several environmental factors, $-125dBm$ and $-150dBm$ is the standard RF power level range received by an antenna on the ground [99]. Regarding the antenna, this module provides an internal patch antenna with the possibility to add an external active antenna to its u.FL connector.

The collar unit also comes with a PDM MEMS Microphone Breakout [100]. It provides a digital Pulse Density Modulation output interface, instead of an analog one that this kind of components usually offer, and $-26dBFS$ sensitivity.

For what concerns the storage, the collar unit is equipped with a MicroSD Card Breakout Board [101] that is used with a Swissbit S-45u Series microSD card [102]. The choice of this specific brand and model of SD cards has been driven by an analysis of its estimated power consumption with respect to other possible options [103].

The gross weight of the collar unit (board and case) is $194g$. The net weight of the electronic board is $44g$. These values meet the requirements described in Section 3.3.6.

Table II reports a list of all the components mentioned above along with the related weight of each component.

5.2.2 Schematics

Figure 6 shows all the connections among the bracelet unit components. In order to upload the firmware on the RedBear Duo a RedBear RBLink [104] programmer is needed. The pins that need to be connected are 3V3, RST, GND, D6, D7. The process to program the RedBear Nano on the collar unit is the same as the one explained for the bracelet unit in Section 5.1.2.

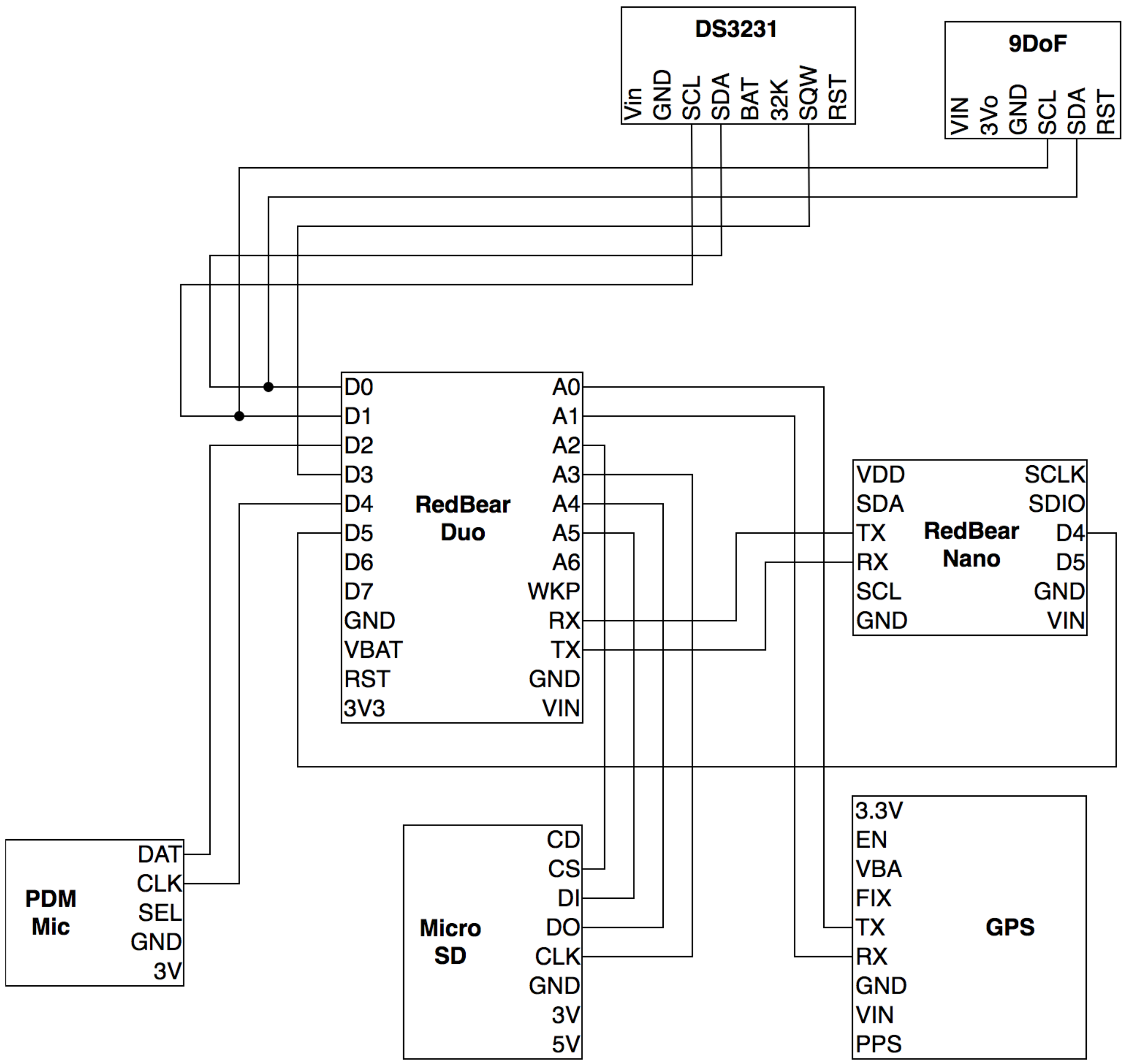


Figure 6: This figure shows the schematics of the connections among the components mounted on the collar unit.

5.2.3 Duo Implementation

The collar unit life-cycle can be described by four states: Boot, Collection, Wi-Fi and Downloading mode. The possible transitions among the different states are described in Figure 7.

In order to describe the states and transitions of the FSA in Figure 7, some definitions are needed. First of all, we will use the following symbols to refer to the different states: B (Boot), C (Collection), W (Wi-Fi) and D (Downloading). The operational cycle of the device is composed of two phases, I_C and I_W, as represented in Figure 8. We will use I_C to refer to the set of timestamps in which the device is in Collection mode (Equation 5.1).

$$C \iff I_C \tag{5.1}$$

I_W, instead, will be used for the interval of timestamps in which the device is in *Wi-Fi* or *Downloading*. We will consider the *Downloading* state as a separate state with respect to the *Wi-Fi* state, but as a window inside the *Collection* phase (Equation 5.2).

$$W \vee D \iff I_W \tag{5.2}$$

To complete the set of definitions, we will use t_x to refer to the current timestamp. Moreover, *conn* will be used as a boolean value that is true if the device detects an active connection with a hub, false otherwise.

When the device is turned on, its entry state is *Boot*. The *Boot* procedure tests the connections between the controllers and all the sensors. Then, all the components are initialized. After

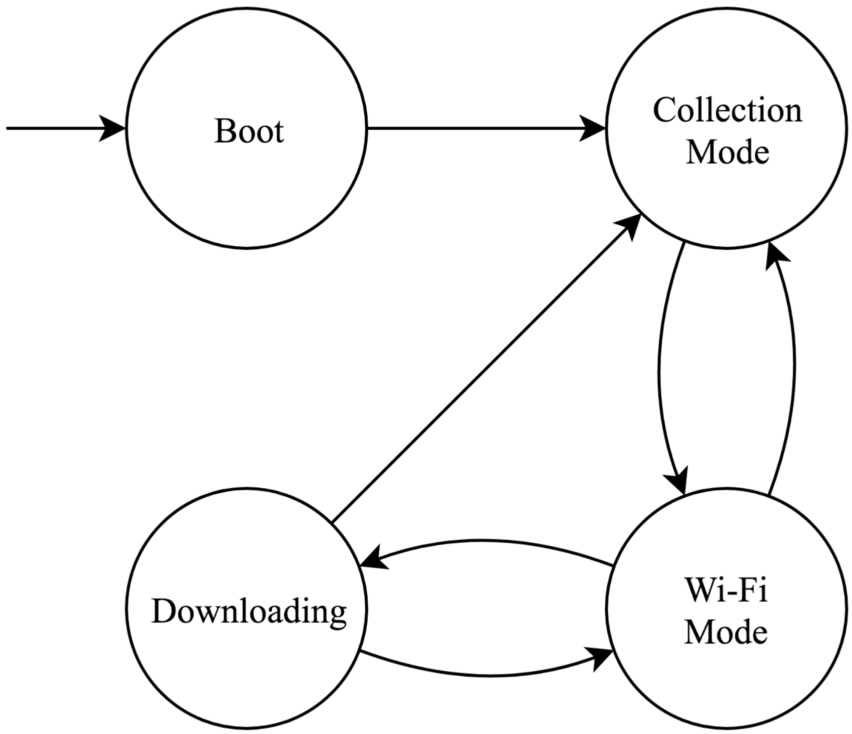


Figure 7: In this figure, the finite state automata describing the different states of the collar's procedure is represented. When the device is turned on, it first goes into *Boot* state in which all the components are booted and initialized. After that, the *Collection* mode starts. In this mode, data samples from all the sensors are collected. In *Wi-Fi* mode, the collection stops and the Wi-Fi antenna is turned on. As soon as the device detects an active connection to a hub, it goes in *Downloading* mode which allows the remote downloads of the collected data.

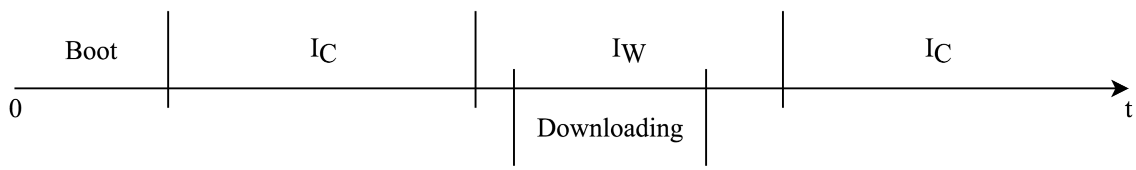


Figure 8: This timeline describes the operational cycle of the collar unit. After the boot procedure is completed, the cycle starts with the collection phase. After that, the Wi-Fi phase starts and the Downloading state is a window inside this phase. When the device exits the Wi-Fi phase it goes again in collection mode.

this procedure is completed, the device goes automatically in *Collection* mode. In this mode, data samples from all the sensors are collected. When the collection interval ends, the transition from *Collection* to *Wi-Fi* is activated. The transition from C to W fires if the condition Equation 5.3 is verified.

$$C \wedge t_{x-1} \in I_C \wedge t_x \in W \tag{5.3}$$

When the device is in Wi-Fi mode, the Wi-Fi module is activated and the device waits for a connection with a hub to be detected. If no hub is found during the Wi-Fi interval, the device goes back in *Collection* mode. The transition from W to C fires if the condition Equation 5.4 is verified.

$$W \wedge t_{x-1} \in I_W \wedge t_x \in C \tag{5.4}$$

Instead, if a connection with a hub is detected while the device is in *Wi-Fi* mode (Equation 5.5), the state changes from *Wi-Fi* to *Downloading*.

$$W \wedge t_x \in I_W \wedge conn \tag{5.5}$$

In the *Downloading* mode, the data collected in all of the previous collection phases can be downloaded. The download will be done through a hub automatically or manually if an operator has the possibility to connect to the hub. Once all the data are collected the connection between the hub and the collar unit will be terminated. If the current timestamp is still in the Wi-Fi interval (Equation 5.6) the device will go back in *Wi-Fi* mode looking for another connection. Otherwise, if the current timestamp is in the collection interval (Equation 5.7) the device will start a new *Collection* phase.

$$D \wedge \neg conn \wedge t_x \in I_W \tag{5.6}$$

$$D \wedge \neg conn \wedge t_x \in I_C \tag{5.7}$$

In Figure 9, the collar code procedure described above is summarized in a flowchart. In the following subsections, each specific state of the procedure will be described in more details.

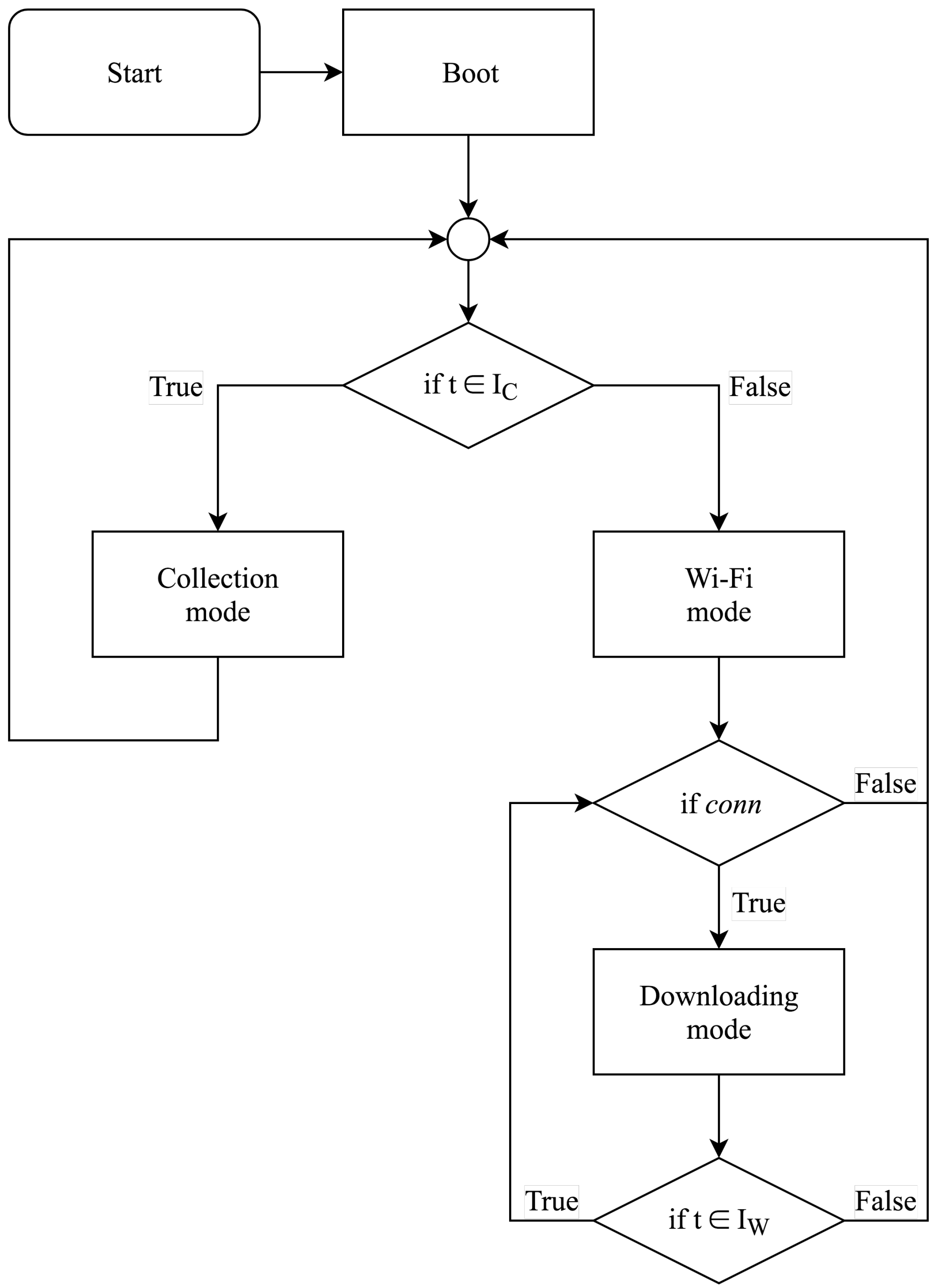


Figure 9: The code procedure of the collar unit is summarized in this figure with a flowchart.

5.2.3.1 Boot

The *Boot* state is the initial state of the collar unit life-cycle. In this state, all the components are initialized and all the connections are tested. A flowchart showing all the steps of the procedure is provided in Figure 10.

First of all, the device can be booted in *dev* mode. In this mode, the serial port connected to the USB connector of the controller is enabled and it allows the user to check on a terminal all the debug messages of the device. The *dev* mode has been thought to help the developers and the user to debug possible issues and to verify existing and new features. It is highly suggested to deactivate the *dev* mode in production because writing on the serial bus is a quite expensive operation both in terms of energy and computational time.

The next step is another serial port initialization. In this case, this serial bus is enabled to communicate with the other controller mounted on the board. This channel is needed to retrieve the data received from the RedBear Nano BLE module. This data includes both the one collected by the proximity sensor and the bracelet. The last part of this step is the activation of the D5 pin to raise interrupts. These interrupts are used to request the data from the Nano controller so that the two controllers can be synchronized during this phase.

After that, the Inertial Measurement Unit is initialized. The collar unit is equipped with a 9DoF IMU, which in our case is composed of two chips, one that embeds a gyroscope, the other one instead integrates both an accelerometer and a magnetometer. In this initialization phase, it is possible to set the sensitivity of the accelerometer and the gyroscope which translate directly to the raw value range. In this case, no modification of these parameters has been done, since the preliminary tests did not show the necessity to do that. The default sensitivity of the accelerometer and the gyroscope is respectively $\pm 2g$ and $\pm 250 rad/s$. A more detailed explanation of the concept of sensitivity can be found in Section 6.1.3 where the results of the tests conducted on the bracelet IMU are discussed.

The next component to be initialized is the GPS. The communication between the controller and the GPS unit is done through another serial bus available on the RedBear Duo. During the initialization, a set of commands are transmitted to the component to set a series of operational parameters. In particular, the following commands are sent:

- PMTK_SET_NMEA_OUTPUT_RMCONLY
- PMTK_SET_NMEA_UPDATE_1HZ
- PMTK_API_SET_FIX_CTL_1HZ

PMTK_SET_NMEA_OUTPUT_RMCONLY is used to request the RMC NMEA sentence. An NMEA sentence is the format used to transmit GPS data. There are different versions of NMEA sentences. In particular, we use the Recommended Minimum data for GPS (ver. C) one. The information included in the RMC NMEA sentence is reported in Table III.

PMTK_SET_NMEA_UPDATE_1HZ and PMTK_API_SET_FIX_CTL_1HZ, instead, are used to set the position update frequency to 1 second, which has been considered as a high enough sample rate for our purposes.

After the GPS, the RTC is initialized. Apart from the internal initialization of the device, there are other three different tasks that are executed in this phase. Firstly, the SQW pin of

TABLE III: THE RECOMMENDED MINIMUM DATA FOR GPS (VER. C) NMEA SENTENCE IS COMPOSED BY THE DATA LISTED IN THIS TABLE. THIS TABLE SHOWS THE TYPE OF DATA WITH THEIR RESPECTIVE RAW AND CONVERTED VALUE.

Type	**Raw value**	**Converted value**
Fix Time	115549	Fix taken at 11:55:49 UTC
GPS Status	V	Status A=active or V=Void
Latitude	2305.218,N	23 degrees 05.218' North
Longitude	04132.000,E	41 degrees 32.000' East
Speed over the ground in knots	024.5	24.5 knots
Track angle in degrees True	036.8	36.8^o
Date	210393	21st of March 1993
Magnetic Variation	003.2,W	3.2^o West
Checksum data	*3E	N/A

the RTC is set to $1Hz$. The DS3231 Real-Time Clock has the possibility to set one of its pins as an interrupter with a fixed cadence. This feature will be used to maintain a precise timing between the start of any sampling cycle, as also described in Section 5.2.3.2. Then, the D3 pin of the RedBear Duo is enabled to receive interrupts from the RTC. The third operation is the setting of the RTC time with a specific custom time. As a matter of fact, after a cold start, the GPS has not fixed the connection with the satellite yet. For this reason, the absolute time is not available at this moment. Since the state change between *Collection* and *Wi-Fi* is determined by a condition that depends on the absolute time, the time set during the *Boot* phase is such that the device will transition to the *Collection* state right after the *Boot* has completed. Once the GPS will fix, the time will be updated.

The last component to be initialized is the SD card. The Adafruit library we have been using for this component handles almost everything automatically. The SD card uses the SPI protocol to communicate with the controller. There are four pins needed to make this protocol work and one of them is the *chip select* pin which has to be added as a parameter to start the communication between the component and the controller.

After all the components have been initialized, there is only one step left in the *Boot* phase. The last operation needed before starting the collection phase is setting what we have called *collection stage*. Every time the device goes in *Wi-Fi* mode, a collection stage ends and in order to keep track of the sequential collection stages we need to keep track of the stage number even in case an unexpected reboot of the device happens. For this reason, the first time a device is turned on, a file is created on the SD card to keep track of the collection stage number previously mentioned. If the device detects that this file already exists in the SD card, it will restart the counting from that point without the risk of overwriting the previous collection stages.

5.2.3.2 Collection

The *Collection* state is the first state the device will be in after the *Boot* procedure. This is the most important state of the whole collar unit life-cycle. As a matter of fact, in this state, all the data about the collar and bracelet sensors are collected and stored on the collar SD card. A flowchart showing all the steps of the procedure is provided in Figure 11.

The core component of this state is the collection cycle. This cycle is started every time the RTC raises an interrupt, or rather every second, and it repeats itself as many times as the sample rate set in the configuration options of the device. In Section 6.1.1, we explain how the sample rate has been decided in our case.

The cycle starts by reading the data available on the Nano controller and the GPS serial buses. The idea is to read the data available at every cycle so that the time effort needed to read from the serial buses is distributed on all the cycles and not concentrated in one cycle only. After that, the 9DoF IMU data are updated. Nine values have to be computed, three degrees of freedom, or rather three axes, per each component of the IMU (accelerometer, gyroscope, and magnetometer). Then, the 9DoF IMU data and the ones retrieved from the Nano controller serial bus are stored on the SD card. Before finishing the cycle, the data retrieved from the GPS serial bus are checked to verify if an entire NMEA sentence has been retrieved. In that case, the sentence can be stored on the SD card too. Moreover, if a cold start of the device happened recently, the RTC time might not be synchronized with the GPS time. In that case, the NMEA

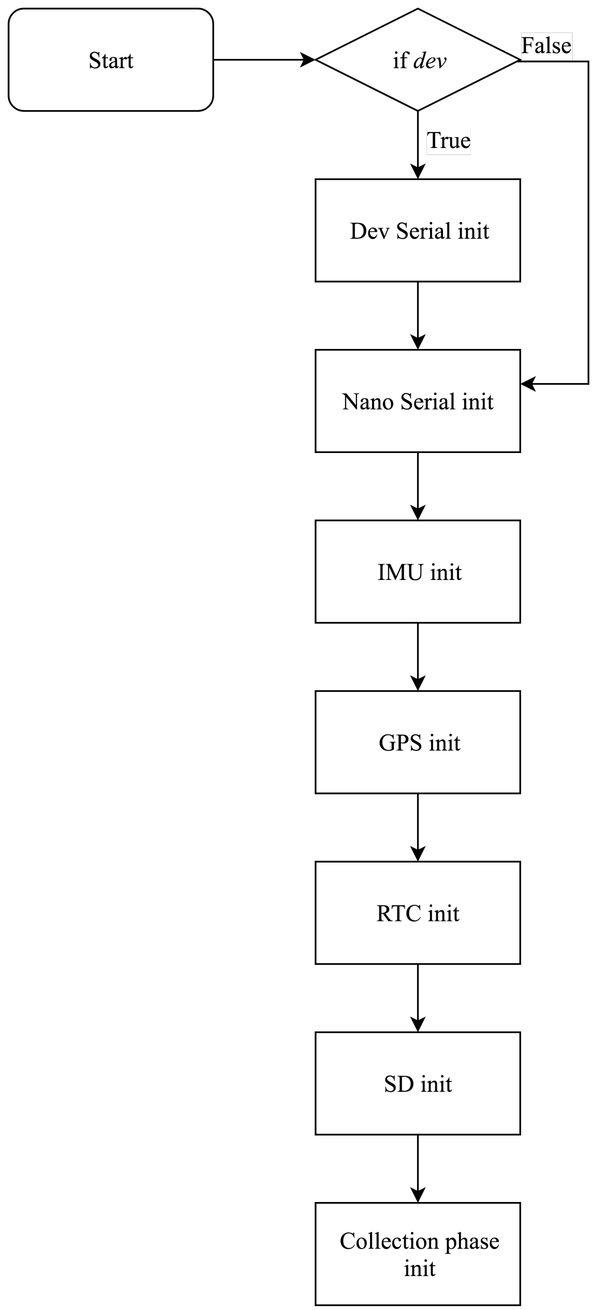


Figure 10: The code procedure of the boot state of the collar unit is summarized in this figure with a flowchart.

sentence is parsed in order to update the RTC time so that all the other timestamped data can be stored with the actual GPS time information. When a cycle is terminated, the device is put to sleep for a few milliseconds. This delay has been calculated (see Section 6.1.2) to be enough to guarantee that the samples are equally distributed in the second.

To conclude, if there are other samples to be collected in the current seconds the cycle is repeated. Otherwise, the device waits for a new interrupt from the RTC to synchronize the data collection.

5.2.3.3 Wi-Fi

When a collection stage ends, the *Wi-Fi* state is activated. In this state, the device initializes the Wi-Fi module of the RedBear Duo controller and waits for a client to connect. A flowchart showing all the steps of the procedure is provided in Figure 12.

The first step of the *Wi-Fi* state is about enabling the idle mode. While in idle mode, the device stops all the operations related to collecting data from sensors and puts in standby the components that can be turned off. For example, a real use case is having the device collecting for 12 hours during daylight and in *Wi-Fi* state during the night. If we assume that animals do not move a lot during the night and so we are not interested in collecting GPS data during this interval, we can completely turn off the GPS module saving an interesting amount of energy.

After this, the Wi-Fi module is initialized. First of all, the Wi-Fi antenna is turned on and the target network credentials are set. Then, the controller starts to look for the target network. If the network is found it starts the server and waits for a client to connect. Otherwise, the procedure goes directly to the Wi-Fi deinitialization step, which will be described later.

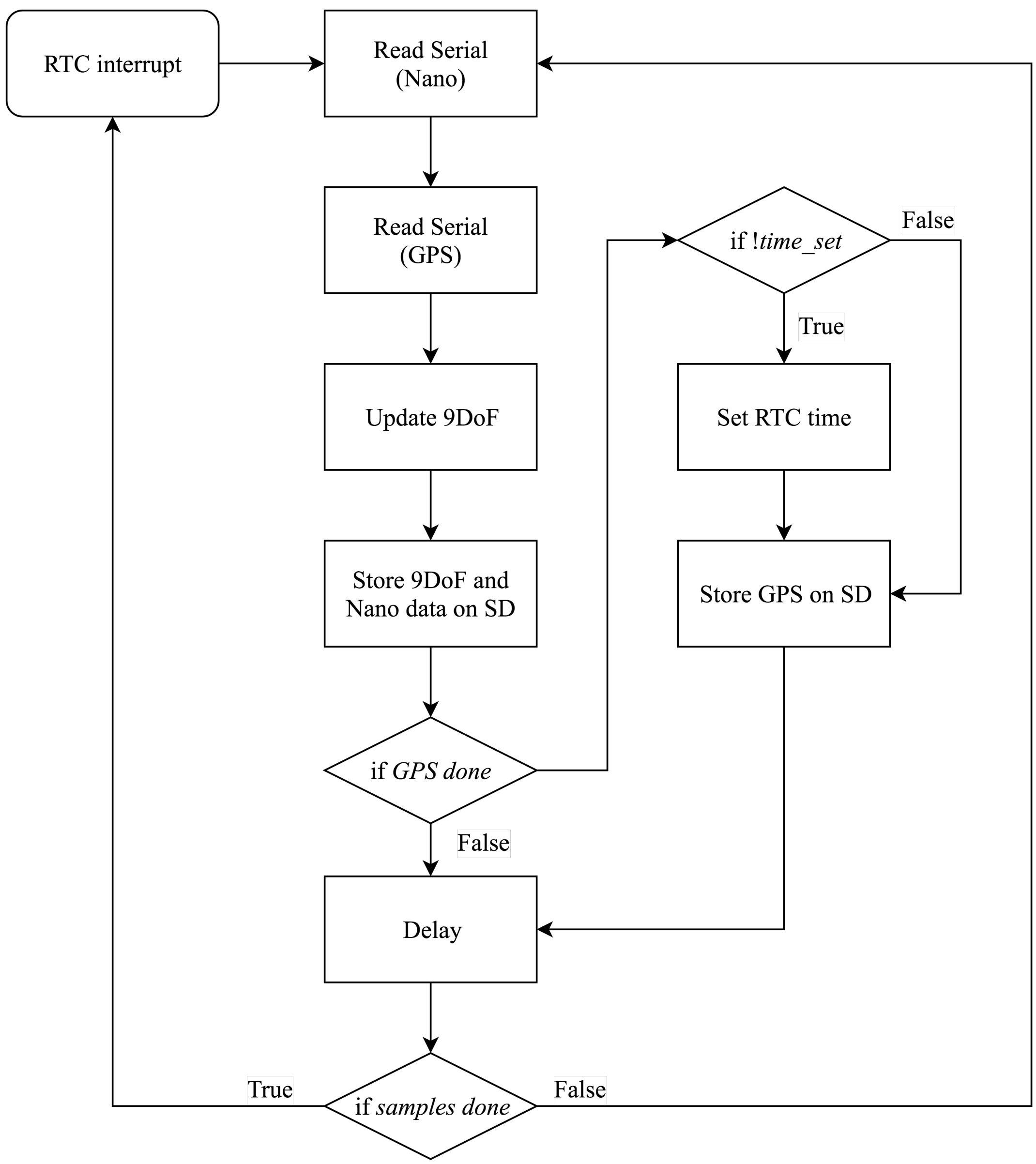


Figure 11: The code procedure of the collection state of the collar unit is summarized in this figure with a flowchart.

When a client connects and the controller detects it, the state can be switched to *Downloading*. Otherwise, if a client is not found or the connection to the target network is lost, the device proceeds with the Wi-Fi deinitialization step. During this step, the server is stopped and the Wi-Fi module, along with its antenna, is switched off. Then, if the device is still in the Wi-Fi interval it starts a sleep period after which it will try again the whole procedure just described. Otherwise, it will execute a set of operations to start a new data collection. In particular, the idle mode is disabled, which means that all the components that were turned off at the beginning of the *Wi-Fi* state will be turned on again. After that, the collection stage number is updated and the device can switch back to the *Collection* state.

5.2.3.4 Downloading

When the device is in the *Wi-Fi* state and a connection is established, the *Downloading* state is enabled. In this state, the connected client can download all the data related to the device collections or to the operational status of the device itself.

When the device enters the *Downloading* state, it means that there is an established connection between a terminal and the device itself. In this state, the device is continuously listening for commands sent by the client. There are two types of command sets that the client can request. The first set of commands is used to request information about the operational status of the device. In particular, as of now, the client can request the debug log, the collection stage and the actual time. The debug log is used to verify if anything went wrong during the collection state or while trying to connect to a Wi-Fi network. The collection stage could be used to check how many collection stages have been done by the device since the last time a

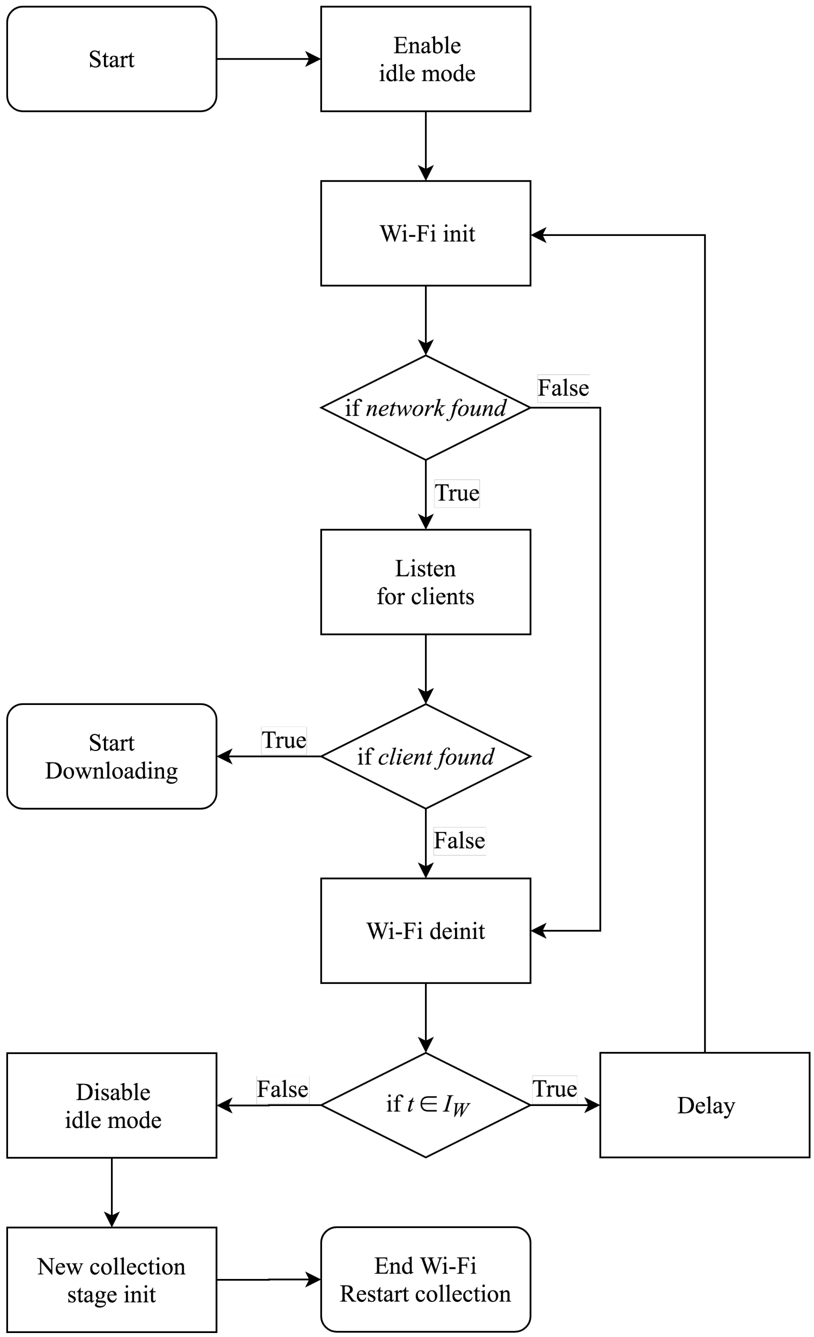


Figure 12: The code procedure of the Wi-Fi state of the collar unit is summarized in this figure with a flowchart.

client connected to retrieve data. The actual time, instead, could be requested to verify that the RTC was set correctly with the GPS time.

The other set of commands is used to retrieve a file relative to a single component and a single collection stage. Therefore, this command type is composed of two parts: an identifier of the file type requested and the number of the collection stage desired.

There are three types of file that can be requested: GPS, 9DOF, and BLE. The GPS file contains all the RMC NMEA sentences collected by the GPS module in a single collection stage. These strings are in a CSV format which makes them easy to be parsed offline. The 9DOF file type contains timestamped CSV strings about the values collected by the 9DoF sensor mounted on the collar unit. The 9DoF IMU internal chip automatically converts the raw values to human readable values. In particular, the accelerometer values are reported in m/s, the gyroscope ones in rad/s, while the magnetometer ones in degrees. The last file type is the BLE one. This file contains all the data retrieved from the Nano controller during a collection stage. The Nano controller handles all the data received as BLE packets. Among these, we have the data related to the proximity sensor, implemented by the Nano controller BLE module and the data related to the bracelet 6DoF IMU. The BLE packets are received in HEX format. We decided not to parse these packets on board to save both computational power and energy consumption. A Python parser has been implemented to parse these files offline. They will be converted into human-readable data and used to feed the data analysis process described by Muscioni in [105].

When the client disconnects, the device goes back in *Wi-Fi* state. The disconnection handling is described in the final part of the previous section 5.2.3.3.

5.2.4 Nano Implementation

The RedBear Nano controller on the collar is the key component to handle all the BLE communication to the collar unit. There are two different types of messages that the collar unit is supposed to receive via BLE. The first type of message is related to the data coming from the bracelet unit. The other type, instead, is about the proximity sensor implementation. All the collars send light-weight advertisement packets containing their identifier. Based on the RSSI, it is possible to determine the relative micro-location among the individuals close to a specific collar unit. Results about tests conducted on the proximity sensor are available in Section 6.1.4.

The structure of the code procedure executed by the Nano controller is pretty simple from a high-level point of view. The BLE stack is initialized in the setup phase. After that, the controller subscribes to three callback: the first one is used to transmit the data received to the Duo controller, then another callback is used to handle the reception of BLE packets related to the proximity, while the last one handles the BLE communication between the collar and the bracelet unit.

During the setup, the D4 pin of the Nano controller is enabled to receive interrupts from the Duo controller. As it will be explained below, this is needed to synchronize the serial communication between the two controllers. After that, the BLE stack is initialized. There are three important steps in this phase. First of all, the advertisement packet is set. As mentioned above, the advertisement packet only contains the identifier of the device and a few other parameters needed by the BLE protocol. Then, the advertisement parameters are set.

These parameters include the frequency of the communication and the transmission RF power. Setting the transmission power is a trade-off between the energy consumption and the expected distance range achievable by the BLE packets. As a matter of fact, both energy consumption and the distance grow linearly by increasing the transmission power of the device. The last part of the setup process is about enabling the BLE scanning. This is necessary to enable the controller to receive BLE packets using the GAP protocol. The three callbacks implemented on the controller will be now explained.

The first callback is the one activated upon the reception of an interrupt from the Duo controller. This callback is used to synchronize the serial communication between the two controllers. As a matter of fact, when data are written in the serial bus, we have to make sure that the entity on the other end is ready to receive these data. When the Nano controller receives this interrupt it means that the Duo has stopped all the other operations and is ready to receive data on the serial channel. Once the serial bus is empty again both the Duo and the Nano controller can resume their operations.

The other two callbacks are related to the reception of BLE packets. One of these two callbacks is used to listen for advertisement packets in the GAP protocol. Since the GAP protocol uses very light-weight packets to transmit data we decided to opt for this solution. There are two types of packets that the Nano controller can receive in GAP protocol. The first one is about the proximity packets sent by other collar units, while the other one is about the bracelet units trying to connect to their associated collar unit. As soon as the controller receives the packets with the identifier of its related bracelet unit, it starts the connection procedure.

Once the connection between a collar and a bracelet unit is established, the collar unit can start to receive data from the bracelet. The packets containing data about the bracelet 6DoF IMU are sent to the collar as notifications packets in GATT protocol. Every time the Nano controller is notified with a bracelet packet, a callback is raised to handle the data received.

More details about the BLE protocols used can be found in Section 5.1.3 where the bracelet unit BLE communications are discussed.

5.3 Hub

In Section 5.2.3.3 and 5.2.3.4 we explained how the remote retrieval of the data works from the collar unit perspective. The hub is the component of the overall architecture of the system that configures itself as the client of the server instantiated by the collar units.

At the current state of the project, we devise two different option for the hub component. One which is manually handled by an operator and another one which is expected to work autonomously and that download the data automatically from the collar units.

The first option is the one that we are currently adopting. We are using an Asus RT-AC88U gaming router which has been evaluated as one of the best in the market in term of network reliability and range [106, 107]. The target local Wi-Fi network to which the collar units are expected to connect is created by the router. In order to download the data from the units, a laptop is also connected to the network. The operator will then start a Telnet [108] connection to the units in order to be able to send them commands and retrieve the requested data. The results of the experiment conducted with this solution can be found in Section 6.1.6.

A second option has been designed to provide the possibility to download the data automatically without the assistance of an operator during the process. In particular, this solution could become really important when the whole system will be deployed on individuals in the wild. As a matter of fact, the downloading phase will be done during the night, when the animals sleep and there is no particular interest in having the device to continuously collect data. Although, the sleep sites of animals, and in particular baboons, could be located in places difficult for researchers to reach during the night (high trees and steep rocks as examples). For this reason, it could be necessary to deploy a hub unit in the field so that the data can be retrieved during the night and then downloaded locally from the hub at more convenient times. To implement this solution, a small processing unit, such as a Raspberry Pi 3 [109], will be deployed coupled with the router. A Python script will be continuously looking for available connections and download the data on the processing unit local storage. At the moment the only way to retrieve the data from the processing unit is to connect directly to the hub unit. However, the possibility to download the data remotely also from the hub will be evaluated for the next deployment.

5.4 System Fault Tolerance

In Section 3.3.3, we discussed all the reasons why it is required to provide a reliable and fault tolerant solution, especially in this setting. In this section, all the implementation aspects that have been introduced in the system in order to make it reliable and fault-tolerant will be described.

First of all, if the bracelet unit stops working the rest of the system will continue to work as expected. The bracelet unit could present two different types of fault: one related to the IMU, while the other to the BLE communication. If the IMU breaks, it would stop collecting data and providing them to the controller so that they can be transmitted to the collar unit. In the other case, the data are collected correctly but are not transmitted to the collar unit and then stored. This could happen because of a fault of the BLE module on the bracelet unit or if for any reason the BLE module is working but it is not able to connect to the collar. In both of these cases, the bracelet unit data would be lost, but the collar would continue to operate without any modification. Not having the bracelet unit data would certainly be a loss for the data collection, but it would still be better to have a reduced data collection than not having anything to work on.

Similarly to what would happen with the bracelet unit in case of failure, all the sensors on the collar are initialized and handled in an independent way. In case a specific sensor fails and stops collecting data, the collar unit continues to collect data from all the other sensors without interrupting the collection.

The last possible fault that we analyzed and provided a solution in order to cope with it is the failure of the Wi-Fi connection between the collar units and the hub. This situation could present itself for two reasons. On one hand, it could be that both the Wi-Fi modules on the bracelet unit and on the collar unit could fail. On the other hand, it could be impossible for the field operator to get in the Wi-Fi range of the deployed collars because of environmental or weather limitations. In order to cope with both of these situations, we make sure that all the data are stored on the collar unit SD card even if they are never remotely retrieved. This means that in case of complete failure of the Wi-Fi connectivity the data would be available on the device when there will be a chance to retrieve it from the animal. Moreover, the amount of data created has been calculated and the SD card deployed will have a large enough capacity to keep all the data collected stored during the entire expected duration of the deployment.

5.5 Summary

In this chapter, we have presented the implementation details of the three elements of the system architecture. We provided the details of all the components that have been chosen for the three units, the schematics and the description of the procedure executed by the three devices. We have given a high-level view of the procedures before diving into the details. Moreover, the chapter is concluded with a presentation of some implementations details that have been introduced in order to increase the reliability and fault tolerance level of the system. In particular, we focused our attention into preserving the data in order to keep the data already collected safe either in case of hardware or software failures.

In the next chapter, we will describe the experimental tests conducted along with the related results. The chapter is divided into two sections. The first one is about the tests conducted in an instrumented environment, both during the development and while we were in Kenya, in order to test the expected performance of each part of the devices. Then, we describe the results obtained from the first deployment in an uninstrumented environment. We deployed three devices on sheep from which we were able to collect more than two hours of data collection.

CHAPTER 6

EXPERIMENTAL TESTING AND RESULTS

In this chapter, all the experimental tests conducted and related results obtained are presented. We have divided the chapter into two sections: instrumented and uninstrumented testing environment. The tests executed in the instrumented environment aimed at testing single implementation aspects of the solution. On the other hand, in the uninstrumented environment part, we will present the first preliminary deployment test that has been conducted in Kenya during August 2018.

6.1 Instrumented Environment

A test set has been conceived during the development of the solution in order to assess the quality and the reliability of our implementation. In this section, we will go through all of these tests that have been conducted by presenting the experimental setup and the related results.

6.1.1 IMU Sample Rate

This test was designed to collect insights about the collection capabilities of our implementation. In particular, we focused on how much we could push the sample rate of the collar and bracelet units' IMUs.

For what concerns the 9-axis IMU mounted on the collar unit, in order to conduct this test, the code part that handles these operations has been isolated. Then, we increased the number of loop cycles per second incrementally. The IMU samples collected by the collar unit are directly stored into the on-board storage and they do not have to be transmitted at collection time. For this reason, the test consisted in doing an integrity check in order to be sure that the requested samples per second were all stored on the SD card eventually, and none of the samples had been partially or completely lost.

The results we obtained indicated that to have the device working in normal conditions, the ideal sample rate is $12Hz$. We were able to push the sample rates to $20Hz$ with the device working in a correct way. However, considered also all the other operations that need to be carried out by the collar unit and the battery requirements, we preferred to keep a lower sample rate as default. This setting allows us to ease the computational effort of the main controller whilst still having the possibility to increase the sample rate dynamically in case of need.

Previously conducted experiments that have been found in the literature, opted for a sampling rate of $30Hz$ for devices equipped with a 3-axis IMU (accelerometer only) [110]. However, the data analysis results obtained with this setting proves that $12Hz$ is a high enough sample rate for our setting. More details about the data analysis results are available in Section 6.2.2.

The restrictive constraint on the IMU sample rate on the bracelet unit was due to the BLE transmission bandwidth. Each sample of the bracelet unit's IMU is made of six values: three 16-bit integers for the 3-axis of the accelerometer and three for the gyroscope. We calculated and tested that transmitting more than 8 samples per seconds to the collar unit would saturate the channel and inevitably led to data losses. Although the machine learning results showed that a sample rate of $8Hz$ for the bracelet unit's IMU lead to good results, we are planning to invest more time investigate the implementation of this communication link to evaluate possible improvements.

6.1.2 Delay Between Samples

Both the bracelet and the collar units are equipped with an RTC in order to keep a precise track of time. The RTC raises an interrupt every second in order to trigger a new collection loop. Each loop repeats the sampling of the sensors as many times as requested by the sampling rate set. The aim of the code is to maintain a constant delay between the samples. As a matter of fact, if the sampling routines are executed one after the other we would get a situation similar to the one described in Figure 13a with a long idle interval at the end of the cycle.

In order to avoid this, we calculate the duration of the idle interval at the end of the cycle and redistribute it among all the samples of a cycle. Figure 13b shows the expected results of this technique. The samples are equally distant in order to provide the true sample rate requested.

6.1.3 IMU Sensitivity

During the tests on the 6-axis MPU6050 IMU equipped on the bracelet, we noticed a weird behavior in the data collected. When moving or rotating the device quickly, the values for both the gyroscope and the accelerometer were often at the edges of their scale.

In Figure 14a, it can be seen that the values of the gyroscope often reach $\pm 250 rad/s$. In Figure 14b instead, it is clear that the behavior is less frequent with the accelerometer. However, we can still notice at least two data points in the Y and Z axis in which the acceleration reaches $\pm 2g$.

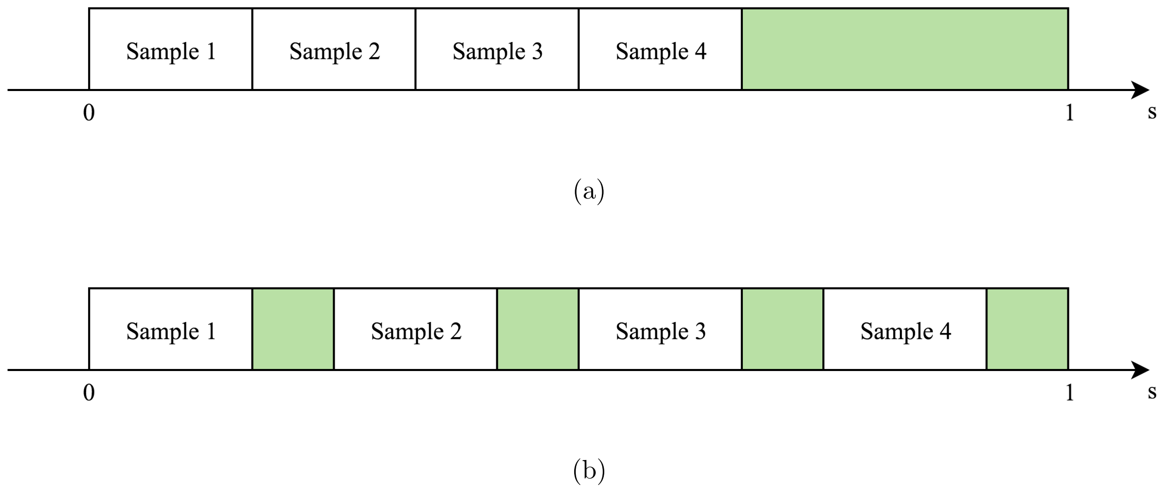
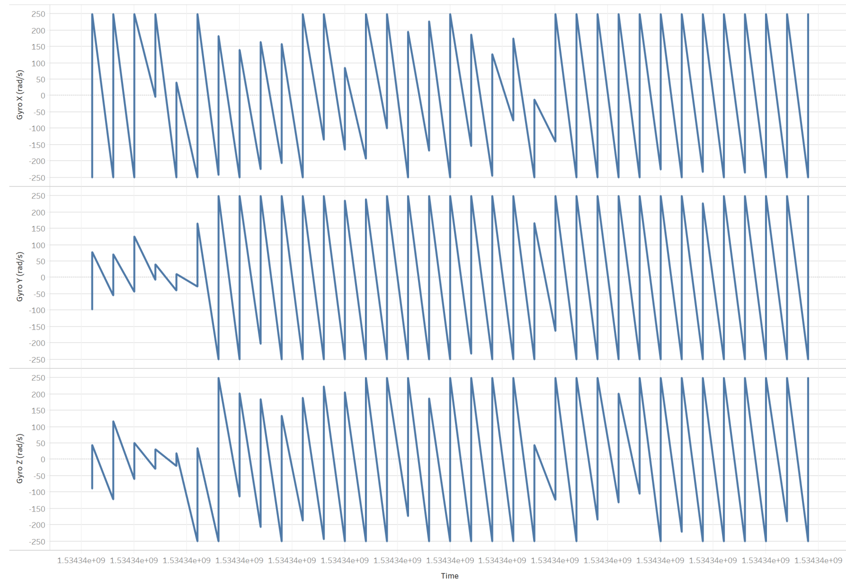


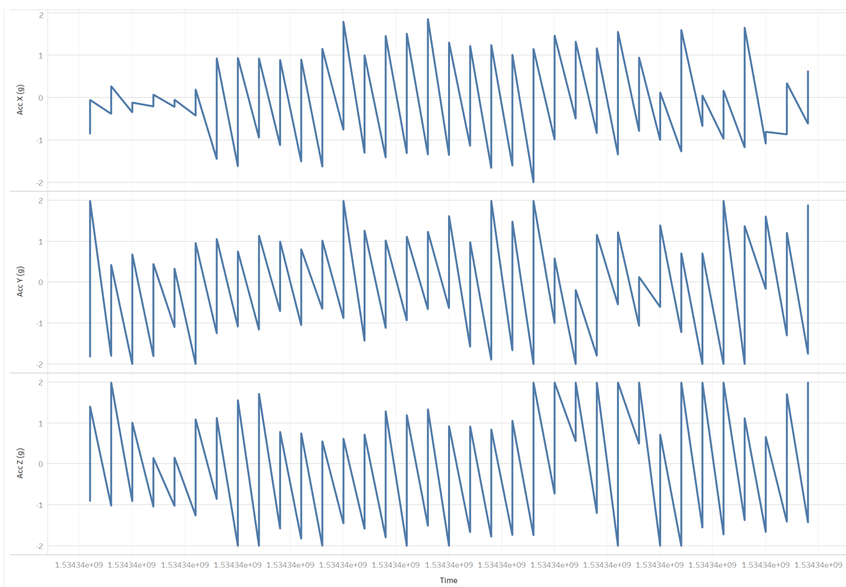
Figure 13: Figure (a) shows the situation we would face in case the samples are executed one after the other. By distributing the idle time among all the samples we can provide a true implementation of the sampling rate as it is shown in Figure (b).

The showed behavior is due to the fact that both the gyroscope and the accelerometer of the MPU6050 were set by default with the highest sensitivity possible. The sensitivity is a parameter that allows selecting a trade-off between the resolution of the sampling and the width of the range. As a matter of fact, the raw values retrieved by the sensor are converted to understandable measurements with the following formula:

$$converted\ value = \frac{raw\ value}{sensitivity} \tag{6.1}$$



(a) Gyroscope data sample



(b) Accelerometer data sample

Figure 14: Figure (a) and (b) shows that both the gyroscope and the accelerometer reaches the edges of their full scale.

The output scale (raw values) of the MPU6050 is a fixed interval that ranges between -32768 and +32768. Equation 6.1 shows that decreasing the sensitivity, makes the converted value range wider but the precision lower. By default both the sensitivities are set to their highest values and for this reason we got very precise data but with a range too narrow for our requirements. Since slightly decreasing the precision have been proven not to be an issue for the analysis phase, we opted to decrease the sensitivity and move the accelerometer range to $\pm 4g$ and the gyroscope one to $\pm 500 rad/s$.

In order to do that, we integrated a library called *I2Cdevlib* [111] that features the implementation of the configuration settings of numerous sensors, the MPU6050 among them. This library will allow us to adjust the settings of this sensor based on our requirements and other possible settings that could come up during future developments of the project.

6.1.4 Proximity Sensor

The main goal of the proximity sensor is to compensate the GPS error and therefore to provide very accurate data about the micro-location of the individual. Thus, it is important that it performs really good within the error range of the GPS module. The test we designed in order to assess its performance consisted of getting data samples at predefined increasing distances from one device at a fixed position and another one moving. Then, the RSSI values are analyzed to check if they reflect the actual distance between the two devices.

Figure 15 shows the results of the conducted test. We put a device in a fixed position and we moved another one. The results show a clear separation between the distribution peaks of $0m$ and $1m$. By going further the stability of the RSSI decreases. However, with the due data process, we expect to achieve good results. As a matter of fact, the peak of the aggregated distance of $2-3m$ is at around -68dB, while the $4-5m$ peak is at approximately $-75dB$. These results are pretty interesting since they show great performance in the very short distances that are critical to determining dyadic behaviors. These data have been collected in Kenya in an open field where the signal interference of Wi-Fi and BLE devices was negligible.

6.1.5 GPS

The GPS module performance has been evaluated with a test conducted in Kenya. We attached three collar units on the three corners of a triangle structure made of wood. The edges of the triangle have been built in order to have the three devices at an exact distance of $1.2m$ from each other. Figure 16 shows a picture taken just before conducting the test of the mentioned wood structure with the devices attached.

This test had three goals. First of all, we wanted to test the amount of time needed for the GPS module to get a fix with the satellites. Then, we wanted to measure the precision of the GPS locations by calculating the error in the GPS distance among the three devices. Finally, we wanted to check if while moving around with the devices mounted on the wood structure the relative position of each device is constantly maintained. This means that by keeping the triangle tip in the opposite direction of the movement, it would always result to be behind the other two devices. The two front devices, instead, would need to always have the same relative position.

For what concerns the GPS time to fix, we have recorded intervals between 4 and 10 minutes. We cannot say with certainty why the time needed can vary in this interval. However, the fact

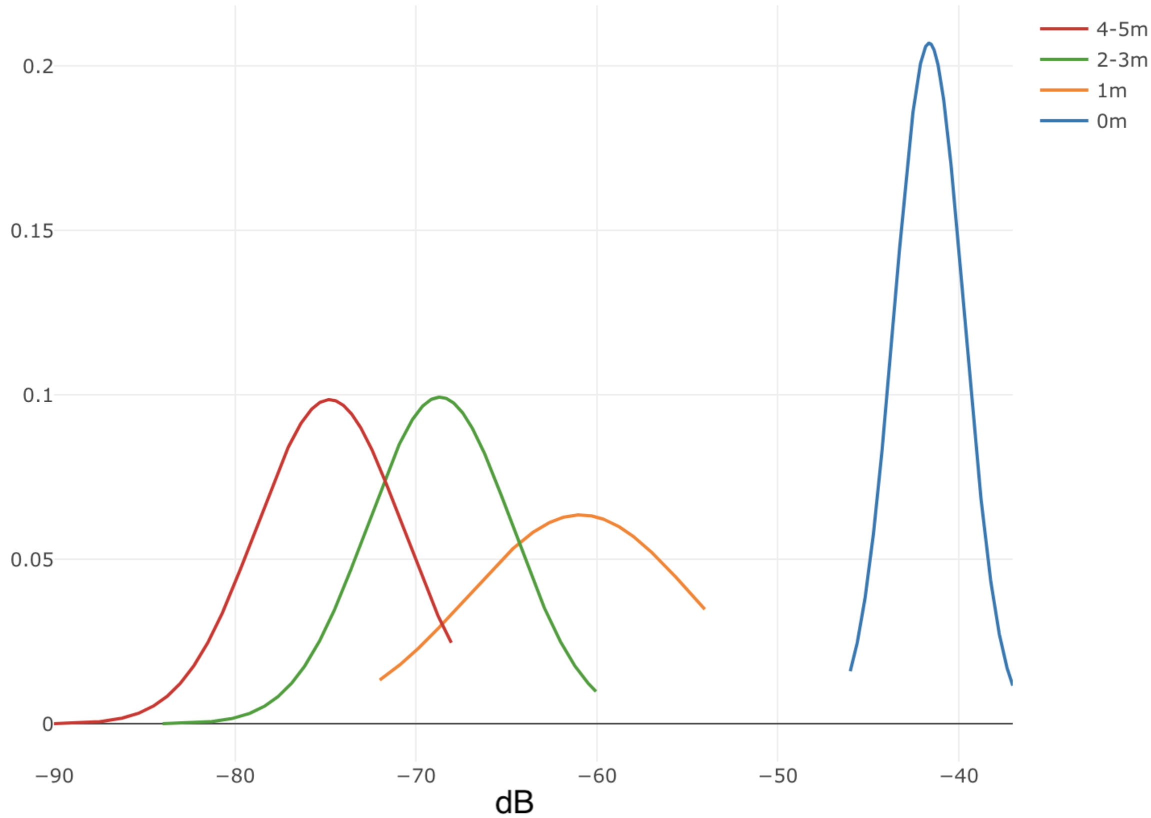


Figure 15: The graph in this figure shows the probability density functions of the proximity sensor test samples with respect to the RSSI value. The distances between $0m$ and $1m$ are pretty distinguishable. By going further the stability of the RSSI decreases. However, with the due data process, we expect to achieve good results.

that the GPS module is not equipped with an active antenna, but only with a passive one, has to be taken into account. Moreover, the GPS satellite coverage is not so dense in the area we

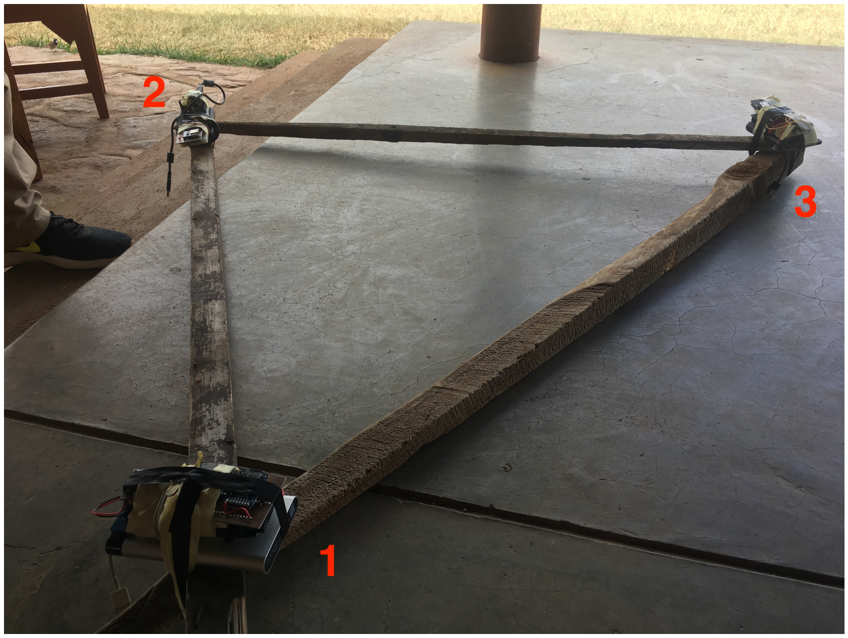


Figure 16: The picture shows the wood structure that has been built to test the GPS module. Three collar units have been attached at the three corners of the structure in order to have them at a distance of $1.2m$ from each other.

were in Kenya. Both this factor may have been responsible for longer times to fix. However, 4 to 10 minutes to get the GPS fix are acceptable if we consider that the GPS fix needs to be done only at the beginning of the data collection.

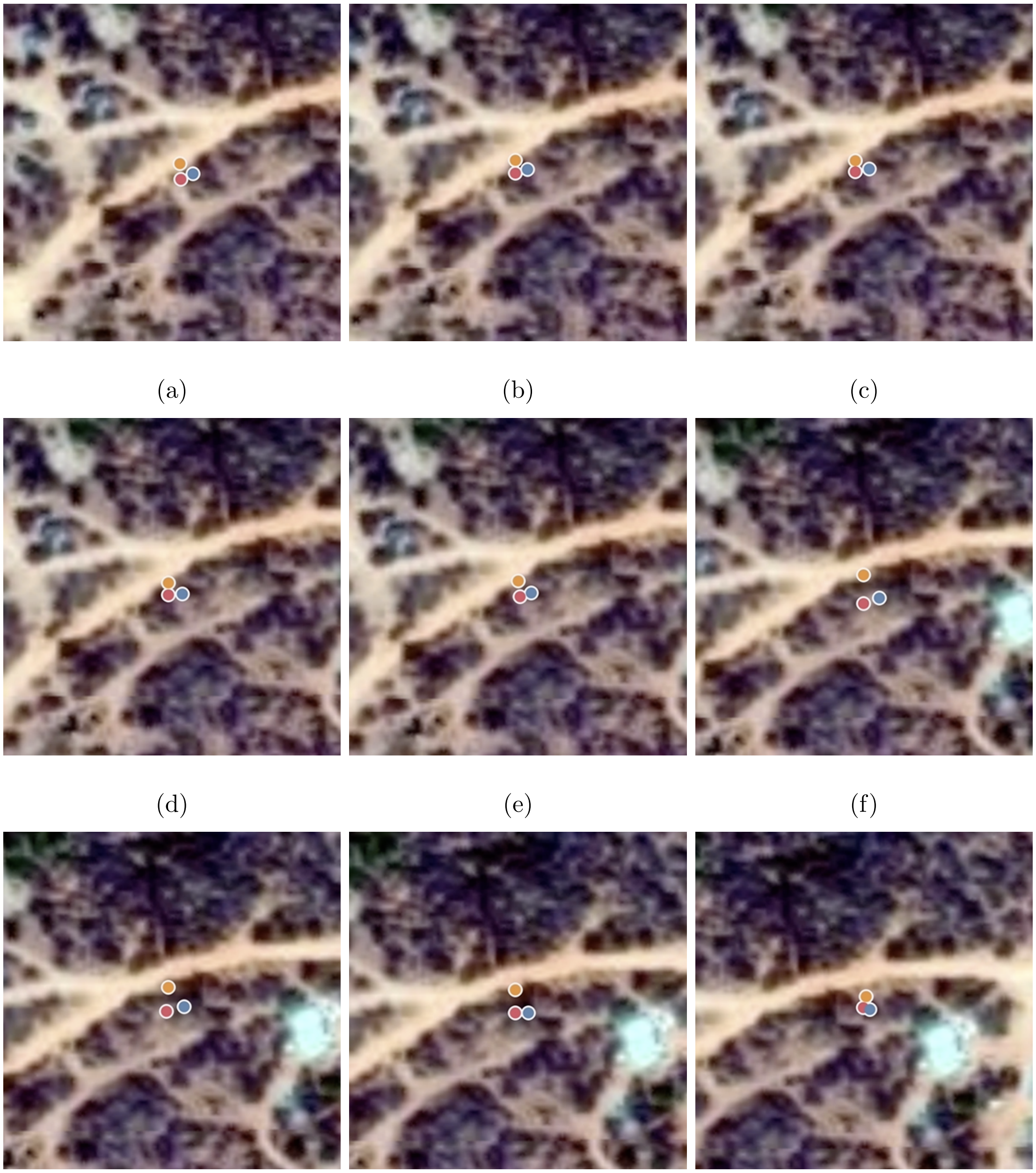
The error of the relative distance between the three devices mounted on the wood structure has been calculated to be approximately $1.2m$. In order to calculate the approximate error, we have calculated the average of the errors between each couple of devices. To calculate the error between two devices we divided by two the difference between the actual distance of the devices and the one calculated based on the GPS data. The error is divided by two because two different GPS modules contribute to it.

Figure 17 shows 12 snapshots of the data collection we have made while moving with the triangle structure. It is possible to verify that the relative positions of the three devices are always maintained. This is important as a starting point to correlate the GPS data with the one retrieved by the proximity sensor that aims to get more precise information about the micro-location of the animal, which is its relative position with the other individuals nearby.

6.1.6 Wi-Fi

The collar unit's Wi-Fi module is used to remotely download the collected data to the hub. In order to evaluate the performance of the connectivity solution, we designed a test to collect data about the signal strength with respect to the distance. The software of the collar unit has been modified for testing purposes to ping the router and record the signal strength. This allowed us to reconstruct a map of the areas we selected to conduct the test and analyze the Wi-Fi module performance.

The test has been conducted in two areas with two different settings: an urban area in Chicago and an open field in the Mpala Research Center area in Kenya. Figure 18 shows the results of the test conducted in the University of Illinois at Chicago area. This area is highly populated and for this reason, we could expect a lot of signal interference during the test. A Samsung Galaxy S9 has been used as the router endpoint. Figure 18a and Figure 18b respectively show the results obtained without and with an external antenna attached to the Wi-Fi module. The red area in the figures corresponds to data points collected with a Wi-Fi



(a) (b) (c) (d) (e) (f) (g) (h) (i)

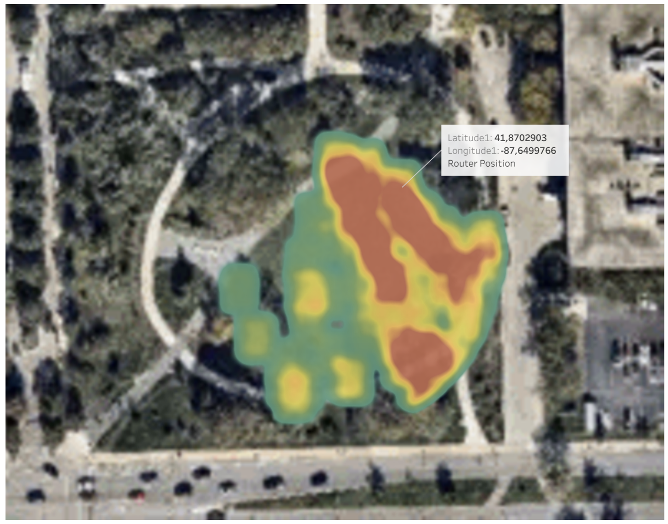
Figure 17: The figure shows the progression of the GPS data samples collected during the triangle testing. It can be seen that the orange and the blue device are always at the front left and at the front blue respectively. The red one instead is always in the middle behind the other two.

signal strength greater or equal to $-60dB$. The yellow area, instead, shows data points where the signal strength was between $-60dB$ and $-80dB$, while below $-80dB$ in the green area. We have been able to achieve an average increase in the signal strength of $15dB$ with the external antenna. Theoretically, a Wi-Fi signal strength greater or equal to $-80dB$ is enough to establish and maintain a stable connection. The furthest data points in the figures were approximately $70m$ apart from the router position.

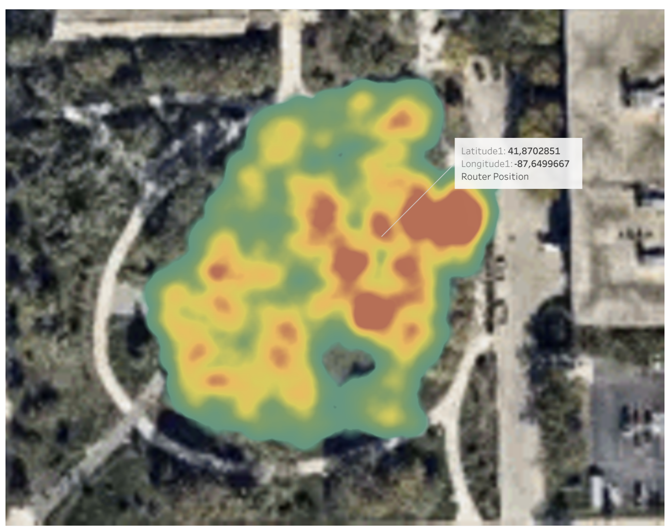
The results obtained from this test are pretty satisfying for several reasons. First of all, it is usually not a problem for biologists in the field to get within a $70m$ radius from the baboons' group. This means that the hub could be manually brought into the area each time a remote download is wanted. Then, both the fact that we conducted this test in an urban area and that we used a smartphone as router are factors that could bring to an underestimation of the performance of the solution. As a matter of fact, the targeted deployment area in Kenya is free of any signal interference and the spaces are usually free of obstacles.

The same test has been conducted also in Kenya in the same areas in which the baboons usually hang around. To conduct this test we used an adapted version of the collar unit with the same components and the same software used to conduct the test described above. However, we used an Asus RT-AC88U router which provides a higher theoretical range than the Samsung Galaxy S9 [106].

The results we obtained through these tests confirmed our expectations. We were able to reach a distance of approximately $100m$ with a signal strength of $-69dB$. A visual representation of this test results is available in Figure 19.



(a) Wi-Fi range test without external antenna



(b) Wi-Fi range test with external antenna

Figure 18: Figure (a) and (b) shows the Wi-Fi range test without and with an external antenna attached to the module. The test has been conducted in the University of Illinois at Chicago area. The red area corresponds to a signal strength greater or equal to $-60dB$, in the yellow area between $-60dB$ and $-80dB$, while in the green area below $-80dB$.

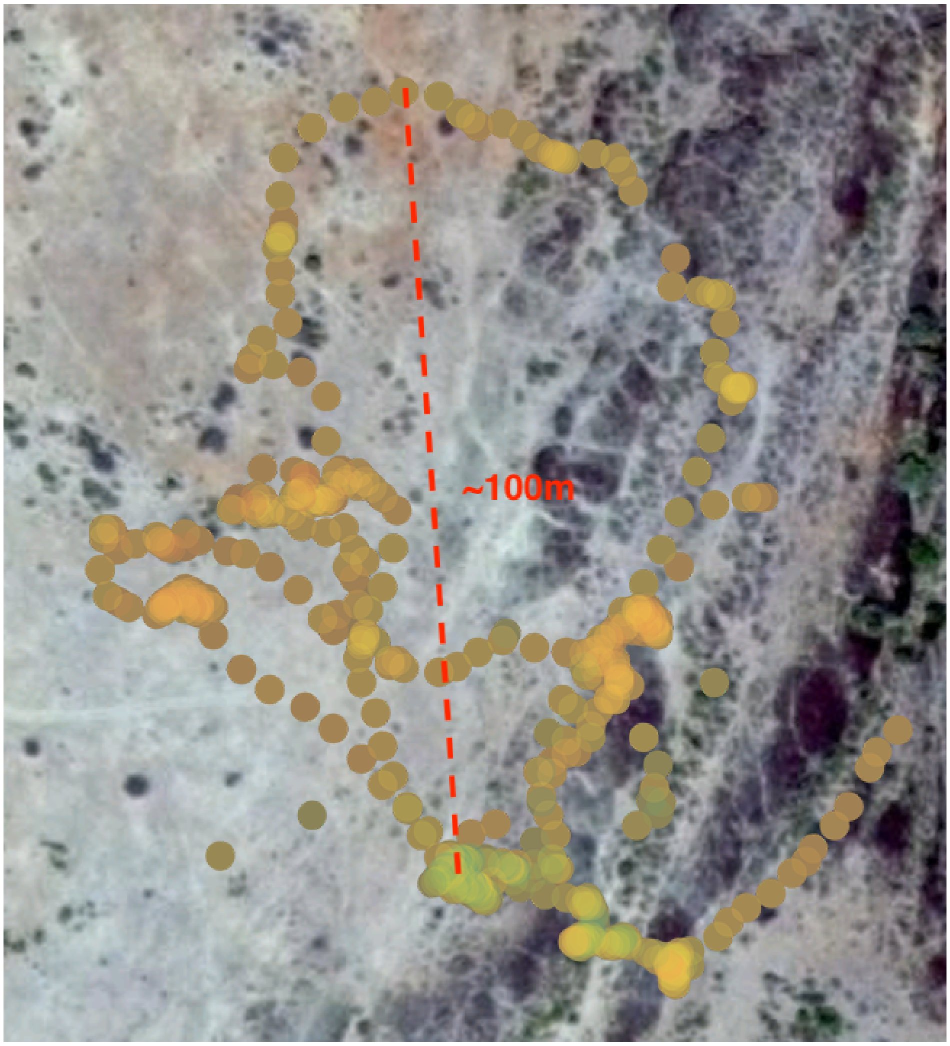


Figure 19: The figure shows the Wi-Fi range test conducted in Kenya. The greenish points at the bottom of the image correspond to the router location. The router and the furthest position we were able to reach were approximately $100m$ apart. We were able to reach a signal strength of $-69dB$ at that location. There are a couple of brighter orange spots in which the signal strength recorded went slightly below $-80dB$ because of some natural obstacles that were present in the area.

6.1.7 Battery Lifetime

In order to evaluate the energy efficiency of our implementation, we measured the instantaneous current absorbed by both the collar and the bracelet unit. We measured this value for each significant operational state of the devices.

To conduct this test, we powered both the collar and the bracelet unit with fully charged $500mAh$ $3.7V$ LiPo battery [112]. We used the same operational parameters that we would have used in a deployment condition in order to obtain results as much reliable as possible. An exception has been made for the collar duty cycle that has been reduced to 2 minutes of collection and 2 minutes of Wi-Fi state.

6.1.7.1 Collar

In Figure 20, the instantaneous current absorbed by the collar in its stages is provided. During the collection phases (first and third segment of the graph), we achieved an average instantaneous current of $99.51mA$.

During the first Wi-Fi stage (second segment of the graph), we did not switch on the router, hence the target Wi-Fi network was not available. In this case, the collar unit tries to establish a connection every $\sim 10s$. During this phase, the instantaneous current shows peaks of $\sim 140mA$ preceded by drops to $\sim 75mA$. This behavior is due to the activations of the Wi-Fi antenna and the related Wi-Fi networks scans.

During the second Wi-Fi stage (fourth segment of the graph), the target Wi-Fi network was available. For this reason, the device was able to establish a connection at first try. The instantaneous current, in this case, was pretty stable at $\sim 130mA$.

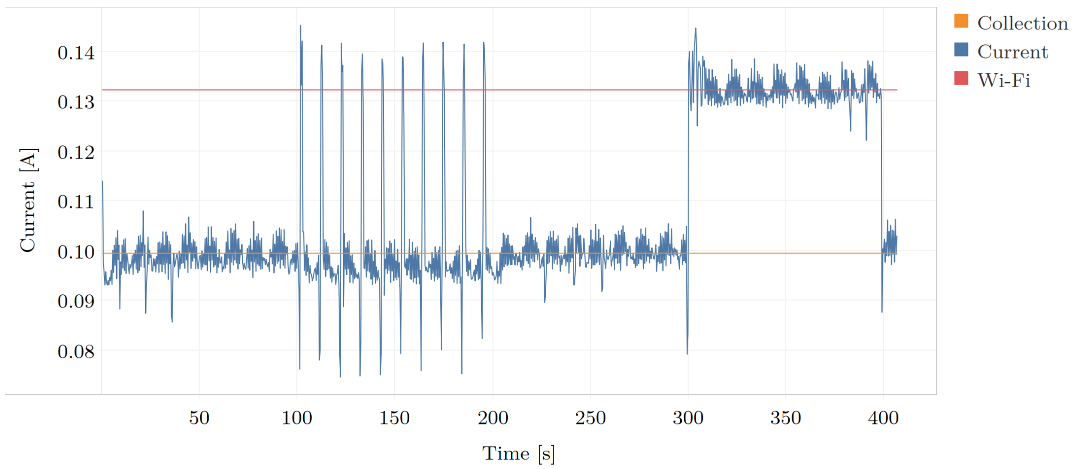


Figure 20: This graph shows the collar unit battery instantaneous current. There are four distinguishable segments in the graph. The first and the third one represents collection stages. The second one represents a Wi-Fi stage with no network available, while the fourth one is another Wi-Fi stage in which the device manages to connect to the target Wi-Fi network.

The lifetime estimation for the collar is strictly dependent on the type of batteries used. Unlike the bracelet unit, the collar unit case design allows several configurations in terms of batteries used. Once the configuration will be selected, the data provided will allow making an estimate of the number of operational hours available.

6.1.7.2 Bracelet

After the bootstrapping phase, the bracelet stays in the same operational setting until it is turned off or the battery is completely discharged. We measured an instantaneous current absorbed of $\sim 12mA$.

The targeted battery for the bracelet unit is the same we used for this test ($500mAh$ $3.7V$ LiPo battery [112]). This particular battery has been chosen for its reliability and small size. With this power consumption, we can expect a lifetime of ~ 42 hours.

The energy consumption of the bracelet still needs to be improved to get to the target battery lifetime. First of all, one parameter that will need to be tuned is the transmission power of the BLE module. During the test we have just described, the RF power was at its maximum value. However, we believe that there is a large margin of improvement in terms of energy consumption if we decrease the BLE module RF power. As a matter of fact, we do not expect the bracelet unit to be further than $1m$ from the collar unit and the transmission range of our BLE module with the maximum RF power can reach more than $10m$. Moreover, we expect the energy consumption to decrease once the board will be industrially manufactured since the prototype we used for the test was made by connecting the sensors breakout board in a compact solution.

6.2 Uninstrumented Environment

In this section, the test deployment we have conducted in Kenya during August 2018 are described. The first part describes the setup of the deployment, while the second one presents the results of the deployment with the machine learning measures obtained.

6.2.1 Setup

The trip to Kenya was planned to conduct a test deployment with five individuals of the targeted baboons' troop. Unfortunately, a couple of days prior to our arrival, an unexpected moratorium on wild animal sedation was issued by the Kenyan government. For this reason, we had to change the target of our deployment from baboons to sheep.

Although the moratorium did not allow us to test the device on our target species, we have been able to reproduce the same environmental setting with another species that presents similar characteristics to baboons. Indeed, the dimension of an adult sheep is comparable to the size of the previously targeted baboons. The size of the neck and the arm are similar too, so we could easily reuse the collar and bracelet attachments thought for the baboons. Finally, the relative distance of the bracelet and the collar are also comparable to what it would be with baboons. The relative distance of the devices from the ground was also realistic. This allowed us to have useful insights related to Wi-Fi connectivity. In Figure 21 it is possible to see one of the tracked sheep instrumented with our collar and bracelet units.

We conducted two experiments in the early morning of August 13 and August 16 at a local farm close to the Mpala Research Center. In the following section, the results of the two experiments are reported.

6.2.2 Results

We deployed three units during the first test and two units during the second. We collected more than two hours of data in total. During the first test, one of the three collar units deployed stopped working. We analyzed the devices log and we were able to understand that the issue was related to the power source. We reported the issue to the electronic engineers that provided us the prototype boards who are currently investigating what could have caused the problem. Based on our limited knowledge of the electronic aspects of the board, we were able to

Figure 21: The sheep in this figure is one of the tracked ones instrumented with our collar and bracelet units.

understand that the maximum current output of the selected battery was not enough to support the device most consuming operation. We partially solved the issue before the second test by connecting two batteries in parallel to the collar unit in order to provide a higher maximum current output.

During the experiments, we experienced some problems to keep a stable Wi-Fi connection between the hub and the collar units. We are currently investigating the factors that could have caused this issues and the preliminary results that we had indicated that the possible interferences caused by the collar enclosure and in general by the animal body have been underestimated.

Even though the data analysis showed some collection intervals in which the devices experienced data losses of the data coming from the bracelet units, the machine learning framework has been able to classify six activities with an accuracy of 92% and an F1-score of 90%. The models were trained based on labels that the biologist team reported during the two experiments. The framework used to conduct the data analysis is part of the master thesis research of Guido Muscioni [105].

In Section 8.1 and 8.3, we discuss the directions we are pursuing to improve the devices based on the issues that we experienced during this test phase.

6.3 Summary

In this chapter, we described a series of instrumented test that has been conducted to assess the quality of the proposed implementation. We discussed how we determined the correct sample rate for the collar and bracelet units' IMUs. The process used to balance the sampling cycles within a second has been described too. We provided a brief description of the concept of sensitivity and how it can be viewed as a trade-off between data resolution and scale range. Then, we presented the results we have obtained by testing our implementation of the proximity sensor, the GPS and the Wi-Fi module. Preliminary results about the expected battery lifetime were also provided.

Then, we described the setting and the results of the first deployment test that we have conducted during Summer 2018 in Kenya. Thanks to this test, we had the possibility to highlight the potential of our solution as well as the limitations. We are currently analyzing the results we have extracted about the issues that we have experienced and working on providing improvements for the future deployments.

In the next two chapters, a series of possible research directions that can be pursued based on what we did until now is presented. Then, we will recap the whole project in the conclusion chapter.

CHAPTER 7

CONCLUSIONS

The aim of this research project was to design and develop a new reliable and fault tolerant sensor system for tracking individual and social behavior of animals in the wild.

Based on the literature and on the conversation we had with the team of biologists from UC Davis that we are collaborating with, we came up with two innovative additions that improved the already available solutions. The first one is the design of a proximity sensor to improve the accuracy of the animal micro-location, which is directly related to the relative position of the animal with respect to the other individuals nearby. The second one is the design of a peripheral unit in order to have multiple data source points on the animal body, rather than a single data source from the collar-like solutions.

Ultimately, we have been able to provide a viable solution that includes both of the mentioned new features. We developed a system composed of three elements: a bracelet unit, a collar unit, and a hub. The bracelet is the realization of the peripheral unit we envisioned while redacting the requirements of the project. Thanks to this unit we are able to reconstruct the movement of the arm of the individual. This is leading to a significant expansion of the individual behavior set that we will be able to identify. The collar unit is the most critical element of the whole system. It is equipped with a comprehensive set of sensors to collect a large amount of data about the baboons macro and micro movements. As a matter of fact, the collar unit implements the proximity sensor exploiting the BLE technologies. Lastly, the hub is the element designed to remotely retrieve all the data collected by the deployed devices.

We designed and conducted a test set to evaluate our implementation. Based on the result we have obtained, we were able to define precise specifications of our system. This allowed us to have prototypes board of our units, thanks to the work done at NECSTLab - Politecnico di Milano, and to bring our system in Kenya to conduct a preliminary field test. The field test highlighted both the potential and limitations of our solution.

The results we have obtained tell us that we are pursuing the right direction in the development of a production-ready system. However, we have already planned a series of feasibility studies and corrections to improve the quality of the data collected and the reliability of the whole system. All this work will be done with the goal of conduct another field test during Spring 2019. The results that we will obtain will allow us to plan accordingly a full deployment of the system on an entire troop of baboons. We expect this deployment to happen within the end of 2019.

The research in animal tracking and behavior tracking solutions is more active than ever. New technologies are being introduced at an impressive rate. Biologists are optimistic about the fact that such solutions could bring breakthrough tools for their research and be a valuable asset in the conservation field. We have put the basis for the development of an integrated solution that allows collecting a comprehensive set of data. Data analytics, machine learning, and artificial intelligence methods have obtained really interesting results starting from the data we provided, proving the viability and the potential of our proposed solution.

CHAPTER 8

FUTURE WORK

In this chapter, a series of interesting direction that could be pursued to improve the quality of the work already done will be discussed. First, we will start with a couple of improvements that could be brought to the system. Already viable features could be enabled by modifying the existing software, such as the microphone installed on the collar unit board, while newer and more powerful upgrades could be also brought to the units in terms of used components. Then, we will discuss possible alternatives to improve the connectivity between the devices and the hub in order to have stabler solutions to remotely download the data. Lastly, we will present a whole new feature that could be added to the system by introducing an additional element in the architecture.

8.1 Main Unit Controller

The main reason that led us to opt for having two separate controllers on the collar unit is the complexity due to the simultaneous execution of the sensor data collection and the BLE callbacks triggered on packets reception. As a matter of fact, the collar unit continuously collects data from all the sensors installed on the board (i.e. accelerometer, gyroscope, magnetometer, GPS and microphone), while in the meantime, every time a BLE packet is received, an asynchronous callback is executed. Having these two operations running simultaneously on the single core of the RedBear Duo did not allow to provide a precise sample rate and to guarantee that all the received packets are handled and the related data stored. Indeed, the number of BLE packets received by each collar unit can quickly increase a lot since, besides the bracelet unit packets to transmit the accelerometer and gyroscope data, the collar is in charge of handling all the BLE packets sent by the proximity sensor. This could lead to a continuous interruption of the main collection routine.

For this reason, we added a RedBear Nano V2 as secondary controller of the collar unit. The goal was to let the RedBear Nano handle all the interrupts raised by the BLE packets and then send the data to the RedBear Duo in a synchronous way through a serial channel. The RedBear Nano could not store directly the data retrieved to the SD card because no support is provided in terms of APIs to allow the RedBead Nano to send data to the SD card module.

However, the code to handle the double controller solution had become really complex especially because of all the details needed to correctly synchronize the activities of the two controllers. In particular, as it has been mentioned in Section 6.2.2, we have experienced some data losses of the bracelet unit data due to synchronization issues of the serial bus.

To solve these issues we plan to change the controller of the collar unit with a more powerful one. The Espressif ESP32 is a really interesting option since it provides an SoC solution with a dual-core processor and BLE + Wi-Fi connectivity [113]. Having the possibility to divide the computation between the two core provided would allow us to have less complex management of all the operations that need to be executed and increasing the performance at the same time. A study to compare the energy consumption of the current solution and the ESP32 one will need to be conducted. Though, we are pretty positive that this option would be a great trade-off between performance and energy consumption.

Better management of the BLE callbacks would allow the possibility of handling multiple peripherals. This aspect is subjected to high expectations by biologists. Having the possibility to deploy multiple peripheral units and therefore covering all the limbs of the individual and possibly the head would bring a significant improvement of the data analysis phase.

8.2 Microphone

The current collar unit prototype board is also equipped with a microphone as described in Section 5.2.1. However, the current implementation of the collar unit does not handle it. Integrating the microphone in the overall procedure has not been possible due to time constraints. Indeed, the microphone PDM microphone interface needs to be studied in order to correctly add the related sampling in the current implementation. However, the microphone component has been introduced correctly in the schematics of the device, so it will be only a matter of software integration in order to make it work.

The importance of a microphone and the effectiveness of the information that could be retrieved from it have confirmations in the literature, as mentioned in 2.2. For this reason, we are planning to enable the microphone in the next future since the data we would be able to retrieve from it could improve the performance of the data analysis and further extend the set of behaviors recognized. As a matter of fact, biologists have a clear understanding of the meaning of the sounds emitted especially by primates. This information could be used both to further confirm an already detected activity or even to find an explanation to certain group dynamics that could come up during the experiment.

8.3 Wi-Fi Alternatives

Remote data extraction has proved to be one of the most valuable features of this kind of solutions. As described in Section 3.3.3 and 3.3.4, it is critical for biologists to get the most out of every single deployment. Indeed, going out in the field is extremely costly and resource consuming. Moreover, since every time a deployment is made it is unclear whether it will be possible or not to retrieve the device and in particular the SD cards with all the data collection stored, it is important to have a way to remotely get at least a part of the data collection.

In addition to the data retrieval aspect, having a reliable way to connect to the deployed devices become even more interesting with the possibility to change the operational parameters of the devices during the deployment itself. This would allow conducting even more valuable experiments. As a matter of fact, one use case could be that the data retrieved are analyzed overnight and at the moment of the next connection with the device, the software could be updated to perform better based on the obtained results.

Our Wi-Fi solution performed really well in the preliminary tests executed before deploying our solution (Section 6.1.6). However, at deployment-time, we experienced issues to establish a connection also at reduced distances and even to keep the connection stable once it was established. We are currently working on this issue to determine what factors contributed the most in causing the issue.

In the meantime, we also want to evaluate alternatives to Wi-Fi connectivity. An interesting option could be the LoRa technology [114]. LoRa stands for *Low Range* since it allows to reach a range of more than $10km$ exploiting sub-GHz frequencies. However, this implies lower bandwidths. Before choosing to adopt LoRa or a similar solution, an accurate feasibility study needs to be conducted since the technology is pretty recent and not really mature yet. However, such technologies are being increasingly adopted and they could open interesting possibilities in the field of animal tracking.

8.4 Sleep Sites

The conversations with the biologist team highlighted a series of questions that are currently of high interest for them. Studying the group dynamics of baboons related to sleep times is one of the research directions that they would like to pursue. Why the group chooses a sleep site rather than another one? Is there a well-defined process that describes how the group approaches the sleep site? Are the elders that first choose a spot in the designated area? Is the whole positioning process defined by some rules? Do the individuals move during the night? These questions are some examples of what biologists are interested in.

In the previous experiment, it has not been possible to study these processes because it had been necessary to turn off the devices in order to save batteries. A possible solution could be to get a GPS location with more sparse sampling. Baboons do not move a lot during the night, so having a position for each individual every 15 or 30 minutes could be enough for this type of studies. However, this solution could bring some issues with it. First of all, getting a GPS position more rarely could be as energy expensive as a continuous sampling (e.g. $1Hz$). This is because if the GPS module is turned off, before being able to get a new position, it has to require the fix with the satellites. Getting the satellite fix is the most expensive process for the GPS module in terms of energy consumption.

Another problem is the configuration of the sleep site. Baboons' sleep sites are usually steep rocks and trees and these conditions are among the trickiest ones for GPSs. Rocks could reduce the signal precisions due to the configuration of the rock surface while getting a precise position in a tree could not be trivial since the third dimension related to the height has to be introduced in the model.

For these reasons, we have designed a solution, which has not been implemented yet, to answer these questions. Based on the same concepts of our proximity sensor, the idea is to place a set of BLE beacons across the sleep site and reconstruct a map of the sleep site by keeping track of the position of the devices. Then, the individuals will be placed on the reconstructed map by triangulating their location using the RSSI of the nearest beacons. The proposed solution does not require major modification of the current system architecture. As a matter of fact, the collar units will receive BLE packets both from the nearby units and from the beacons. One interesting option for the beacons are the *Estimote Proximity Beacons* [115]. These beacons provide between 2 and 3 years of battery life and they are light-weight and robust at the same time. We have been in contact with the company that confirmed the feasibility of the proposed solution.

Figure 22 provides a possible use case for the proposed solution. The picture has been shot in August 2018 during the field testing of the devices conducted in Laikipia County, Kenya.

The tree in the picture was chosen by the baboons' troop we were observing as their sleep site for the night. In the purple square is it possible to see three adults individuals who had already taken place. The red dots represent the possible positions to deploy the BLE beacons. We would use those dots to recreate the map of the three and then map (possibly in 3D) the position of the animal with respect to the beacons.

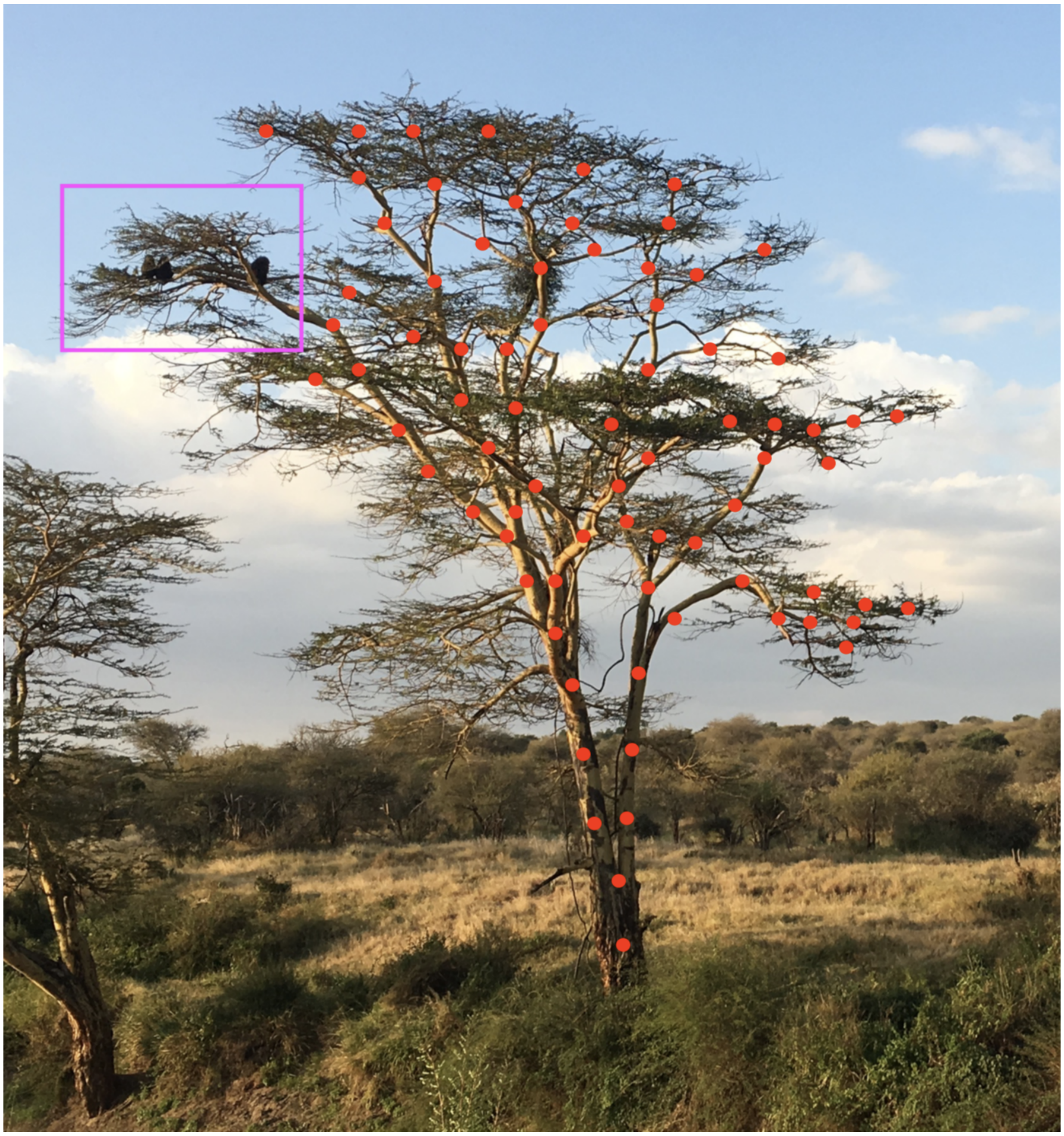


Figure 22: The picture shows a possible use case of individuals tracking in sleep sites. The red dots correspond to the possible positioning of the beacons on the tree branches. In the purple square, it is possible to see three adult baboons. The picture was shot in August 2018 during the field testing of the devices conducted in Laikipia County, Kenya.

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VITA

NAME:	RICCARDO PRESSIANI
EDUCATION:	Master of Science, Computer Science, University of Illinois at Chicago, Chicago, Illinois, 2017 - Present.
	Master of Science, Computer Science and Engineering, Politecnico di Milano, Milano, Italy, 2016 - Present.
	Bachelor of Science, Engineering of Computing Systems, Politecnico di Milano, Milano, Italy, 2016.
ACADEMIC EXPERIENCE:	Graduate Research Assistant, Computational Population Biology Lab, Department of Computer Science, University of Illinois at Chicago, 2018.
	Computer Lab Assistant, Politecnico di Milano, 2017: