

Applying Embedded Systems and Sensor Technologies to Trampoline Gymnastics

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Abstract—At the highest level of sports, the difference between ending in first or second place can be very small. This is particularly true for the sport of Trampoline Gymnastics, where jumping a little higher and more centered on the trampoline can have a huge impact in the final score. By utilizing Sporting Technologies (STs) in training, coaches and athletes can identify hidden problems and develop new training methods, which would be impossible otherwise. In the case of Trampoline Gymnastics, two parameters were chosen to be measured: the Time of Flight (TOF) and the Horizontal Displacement (HD).

At the time that this work was started, not much research had been done in this area and most of it implicated alterations to the athlete's and/or the trampoline's behavior. Also, there were no commercial products available that measured both parameters.

The designed architecture uses a grid of infrared beams (transmitters and receivers) under the trampoline bed that wirelessly send the TOF and HD to be stored in a database. A program with a Graphical User Interface (GUI) was created to control the system and view the data. Based on this, a functioning prototype was developed and tested in a “real-world” scenario.

Experiments were conducted in Sporting Clube de Portugal, where national team level athletes and coaches tried the system. The general consensus was that the system provided enough accuracy for measuring both the TOF and HD, being a helpful tool to improve their performance.

Index Terms—Sporting Technologies, Trampoline Gymnastics, Time of Flight, Horizontal Displacement, Infrared Beam Module Transmitter, Infrared Beam Module Receiver

I. INTRODUCTION

NOWADAYS, more and more technologies are being used in the sports world. These technologies are applied in various aspects of sports: some devices are used in competition to help make judging the sport less subjective and more accurate (e.g. Hawk-Eye system in tennis [14]), and others are being used during training to help coaches and athletes achieve better results more efficiently (e.g. Babolat Play [22]). The University of Ulster defines STs as “...man-made means developed to reach human interests or goals in or relating to a particular sport ...” [26].

In general, the main purpose of STs during training is to gather data about the athletes performance. This data can then be used by the coaches to improve or develop new training methods, aiming to increase the athletes efficiency and results. In sports that use specific equipment, like cycling and tennis, this data can be analyzed and used to develop better materials or structures and improve existing instruments. Another important aspect of these technologies is that they must be “invisible” to the athletes and cannot change in any way the conditions that exist during a competition. As a paper on STs by Pervasive Computing explained, “...enhancing players so that they want to use sensors in their training, enabling unobtrusive instrumentation so that coaches can analyze the best data available ...” [6].

Trampoline Gymnastics is a competitive sport that has gained much momentum since it was introduced in the Olympic Games in Sydney, 2000. Trampoline Gymnastics competitions consist of an athlete performing two trampoline routines during the preliminaries round (where the total score is the sum of two separate scores for each routine), and one routine in the finals (one final score). Trampoline routines consist of 10 different skills/jumps performed in a sequence, one after the other. The main components of an Olympic competition trampoline are: a metallic frame structure, a set of metallic springs that are attached to the inner perimeter of the trampoline frame, and an elastic bed, as shown in Figure 1. The elastic and flexibility of the springs and bed and the rigidity of the metallic frame are the main characteristics that define how a trampoline behaves when an athlete is jumping on it. As referenced before, the properties cannot be altered in any way by any STs that want to be used.

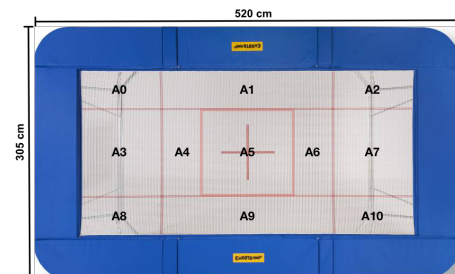


Figure 1. Trampoline bed [8], with the 11 different areas identified.

In 2010, a new rule was created adding a new variable when scoring a trampoline routine, the TOF. This new component refers to the measured time that a trampolining athlete spends in the air. This value does not count with the contact time spent on the trampoline bed. To measure the TOF, devices were created that can be attached to the trampoline and differentiate between when an athlete is in the air and when she/he touches the bed. These machines are used during competitions and in training to help athletes understand whether they should work on jumping higher or not.

Another important component of a trampoline routine is the HD. This parameter refers to the location on the bed where an athlete lands after each skill. A trampoline bed, as shown in Figure 1, has 11 areas bounded by red lines. After each jump, an HD deduction is given (0.0 for A5, 0.1 for A4 and A6, 0.2 for A1, A3, A7 and A9, and 0.3 for A0, A2, A8 and A10). Right now, during the competitions, the HD is measured by the judges using video cameras.

These two score components are very important because they can be measured in a very objective way, eliminating human

error. This makes them perfect candidates to be measured and analyzed using STs.

There is currently no machine to measure the HD of a trampoline gymnast commercially available. However, the documents and regulation needed by the Fédération Internationale de Gymnastique (FIG) are being created to allow these systems to be used in competitions. At the moment, the only STs for Trampoline Gymnastics that are commercially available are for measuring TOF. These systems have many problems that are holding back a wide spread of their usage during the training of the gymnasts. The first problem is pricing: these machines can cost between 900 euros [1] and 1400 euros [25]. Most clubs cannot afford a system at these prices because, unfortunately, Trampoline Gymnastics is not a big revenue generating sport yet. The second problem, and probably most important one, is the utility of the machine. These systems were designed mainly for the competition, so their output is merely quantitative (final score), even though the main purpose of STs is to help coaches and athletes to improve their performance in training.

The main objective of this thesis is to create a functioning prototype of a system that can accurately and precisely measure the TOF and HD of a trampoline routine, without influencing in any way the behavior of both the athlete and the trampoline.

II. THE STATE OF SENSOR TECHNOLOGIES APPLIED TO TRAMPOLINE GYMNASTICS

Because technology in Trampoline Gymnastics is a very specific topic, not many studies or systems have been developed. This also reinforces the important contribution to the area that this thesis might give.

A. Existing Products

The two main products that are being used during training and competition are: the AirTime Trampoline System (ATS) by Trampoline Timing Systems [25] and the Time Measurement Device (TMD) by AcroSport [1]. Both of these devices are very similar as they only measure the TOF of a trampoline routine.

The two systems are comprised of three pairs of Infrared (IR) beam emitters and receivers. These are attached under the trampoline bed onto the metallic frame (the receiver is attached on the opposite side of the emitter). These systems work by detecting when one of the three beams is interrupted, caused by the deformation of the trampoline bed when an athlete lands on it. By being able to detect the moments when an athlete leaves and lands on the trampoline bed, the machine can then calculate the TOF of each skill that the athlete executes. The ATS includes a GUI that displays information graphically and makes it easier for users to control the system. It also includes a database for storing the athlete's routine information so it can be consulted in the future.

B. Other Measuring Systems for Trampoline

A Master's Thesis submitted by Heike Brock in Saarland University [5] aimed at identifying and classifying different trampoline skills using inertial sensors (to measure, for example, acceleration or rotation). There are many different technologies to capture the human body's motion. The most used systems are: optical systems (marker-based or marker-less), mechanical systems, magnetic systems and inertial systems. An extensive comparison was made and in conclusion, given

the requirements, the study found that inertial sensors were the best candidate to successfully capture Trampoline skill motion. Ten inertial measurement units (IMUs) were attached at key points in the athletes body. Each inertial sensors contained three accelerometers, three rate gyroscopes and three magnetometers. By repeatedly testing the system and gathering large quantities of data, motion templates can be generated that are then used to infer which skills are being performed in real-time.

The main issue with this system is that it requires sensors to be attached to the bodies of athletes in order to gather the intended data. Obviously, these systems cannot be used in competitive Trampoline Gymnastics as the extra gear would limit and alter the motion of the athletes while executing very technical skills, which can compromise the jumper's safety.

There are many patents for inventions that measure some parameters of Trampoline Gymnastics, but most of them are intended for the recreational side and not for the competitive one. Most of them also alter, in some way, the trampoline's and/or the athlete's behavior. The most relevant patent found was filed by Eurotramp (German trampoline manufacturer) and describes a system that can measure the TOF and detect where an athlete lands on the trampoline bed after each skill [10]. The most important parts of this system are pressure sensors or strain gauges that are positioned underneath the four legs of the trampoline. When an athlete is jumping on a trampoline with this system, it can detect when the athlete leaves or lands on the bed by measuring the forces applied. By distinguishing these two time intervals the system can calculate the TOF of the jump. To be able to detect where the athlete has landed on the trampoline bed (which translates into HD) the system uses the difference in force applied between the four plates underneath the trampoline legs.

The main drawback of this system is that the force sensors absorb some of the force that would normally be applied on the floor where the trampoline was mounted on. This creates a dampening effect that may lower the jumping height that the athletes can achieve on that trampoline. It is also important to refer that not all the skills performed on the trampoline are perfectly vertical, which means that not all of the force is applied vertically on the force sensors. This may lead to unreliable results in terms of the HD score.

In order to create a system architecture that could achieve the desired goal, some sensor and communication technologies were analyzed. In terms of sensor technologies, the main option were Ultrasonic Sensors, Break Beam IR, Reflective IR sensors and Pyroelectric Infrared Sensors (PIR) Sensors. After analyzing all the advantages and disadvantages of each technology, the conclusion was that the most versatile option, in terms of sensing area/range, time resolution and price, was to use an array of IR beams sensors. Also, in regards to inter-sensor communication, the technology chosen was Inter-Integrated Circuit (I2C), because it was the cheapest option which would most likely meet the requirements necessary.

III. SYSTEM ARCHITECTURE

Before being able to elaborate a specific architecture, the system requirements need to be well defined. These will be divided into functional and non-functional requirements. The first type relates to the actual behavior of the components when the system is being used, while the latter defines specific criteria

that can be useful for evaluating the system's performance.

A. System Requirements

The main non-functional requirements are related to the accuracy and resolution of the trampoline sensor system. The measurement of TOF must have millisecond resolution or else it will not comply with the FIG requirements [11]. The measurement of HD must be able to differentiate with 100% accuracy in which of the areas (see Figure 1) the athlete landed on, within 10 centimeters of each side of the area lines. This requirement was defined by consulting national team level athletes and coaches. Both of these requirements are mandatory (**"Must Comply"**) in the final system. Another non-functional requirement that is important is related to the price of the machine. The goal is to make a system that is cheaper than previous similar technologies, so a requirement of being able to manufacture the machine for less than 300 euros was defined as **"Must Comply"**. This value was obtained by consulting coaches from five different national clubs to understand what would be a reasonable price for the system (not including the user terminal). The average price obtained was 600 euros. Given that in hardware products it is usual for the selling price to be double of that to produce the product, the 300 euros maximum cost to manufacture was reached. Finally, to make the system as easy to assemble and as unobstructive as possible, the connection between the user terminal and the sensor system must be wireless.

The main functional requirement has to do with the user terminal, as it is where most of the interaction with the user will take place. The User Interface (UI) should clearly display the TOF and HD of the routine in a graphical and intuitive manner. The interface must also have the functionality to manage routine information in the athletes database (Save, Delete, ...). It will also be from the terminal that the user controls the system by commanding it to start or stop the measurement of a routine. All of these requirements are defined as **"Must Comply"**.

B. Architecture

By analyzing the system requirements that needed to be met and by comparing the different sensors that are available today, an architecture was elaborated and is generally represented in Figure 2. The system can be divided into three separate main components: the Infrared Beam Grid (IR-GRID) (in red), the Access Point Server (APS) (in gray) and the User Terminal (UT) (in black).

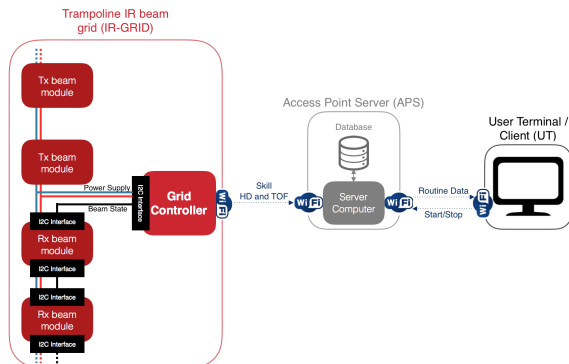


Figure 2. Diagram of the System Architecture.

The IR-GRID is comprised of a two-dimensional grid of Infrared Beam Module (IRM), containing a X-axis and Y-axis, connected to a central module called the Grid Controller (GC). Each IRM is comprised by an emitter and a receiver of IR beams. The IR-GRID will be attached, beneath and parallel to the trampoline bed, onto the metallic frame.

The idea behind the IR-GRID is that the deformation of the trampoline bed, caused when an athlete lands, will interrupt some of the IR beams. Depending on where the athlete lands on the trampoline bed, different beams will be interrupted at different moments in time. The closer the IRM is to where the athlete landed on, the sooner the deformation of the trampoline bed will interrupt its beam. This means that the first beams to be interrupted, from each one of the axis, are the ones closest to where the athlete landed. By having a 2D grid, the system can analyze the chronological order of events on the X-axis and on the Y-axis to obtain a point in 2D space that corresponds to the origin of the deformation on the trampoline bed. When the athlete is in the air, no beams are interrupted. The moment the athlete lands on the bed, the deformation will start interrupting some of the IR beams, first the ones closest, then the ones farthest. As the deformation of the bed increases (athlete falling deeper) more and more beams become interrupted, until the point of maximum deformation. At this point the highest number of beams interrupted is reached. This number can be equal to all of the IRMs or not. This process is clearly illustrated in Figure 3 and Figure 4. The progression of events seen from the Y-axis, is similar as the deformation of the trampoline bed can be approximated to a conical shape. When the athlete starts leaving the bed, the process is symmetrical. It is important to refer that the point the system is actually measuring is the lowest point of the deformation of the trampoline bed. This point is the center of pressure applied by the gymnast when impacting the trampoline bed, which should be in the middle of both feet and slightly in front of the heel.

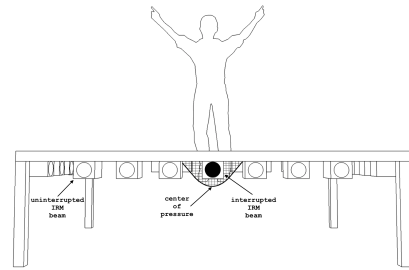


Figure 3. Minimum bed deformation with one IR beam interrupted, viewed from the X-axis side.

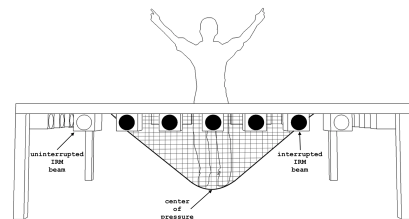


Figure 4. Maximum bed deformation with five IR beam interrupted, viewed from the X-axis side.

The IR-GRID is also able to calculate the TOF of each skill by measuring the time between when the first beam of any IRM is interrupted (athlete landed) and when all the beams in the IR-GRID stop being interrupted (athlete in the air).

The resolution of the IR-GRID for detecting where an athlete lands on the trampoline bed is directly proportional to the number of IRMs on each axis. It is similar to a touch screen, where the higher the number of pixels, the higher the resolution. Although the system needs to have good resolution, in practical terms, what is actually needed is only to detect in which of the bed areas the athlete lands on. Given this optimization, the minimum number of IRMs is 10, as shown in Figure 5 (six IRMs in the X-axis and four in the Y-axis).

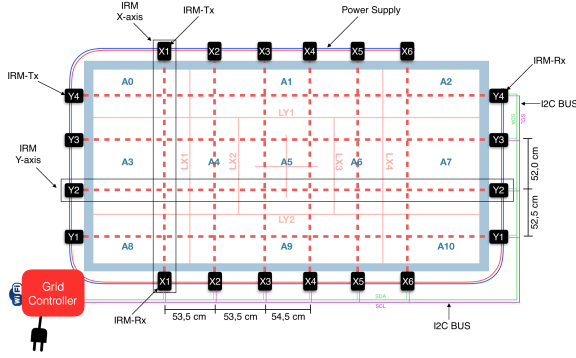


Figure 5. IR-GRID configuration.

The IRMs are the basic building blocks of the IR-GRID. Each one is responsible for producing an IR beam and detecting whether it is interrupted or not by the trampoline bed. They are comprised of two sub-modules called IRM-Tx and IRM-Rx.

IRM-Tx must emit a narrow beam of IR light (so it does not interfere with its neighboring IRM-Rx modules) with enough power to be detected on the other side of the trampoline, which has 520 centimeters on the X-axis and 305 centimeters on the Y-axis. The IR beam produced must also be pulsed for it to be distinguished from natural IR sources like the sun.

The IRM-Rx must be able to detect the pulsed IR beam and differentiate it from other IR sources. It will sense if the beam is broken or not (athlete on or off the bed). This module must have an I2C interface to send data, relative to the state of the IR beam, through the I2C bus to the GC.

The GC is the main component in the IR-GRID and connects it to the rest of the system. It must have a I2C interface to gather the data from the sensors in the Infrared Beam Module Receiver (IRM-Rx), related to the state of the IR beams. This information is processed by a processing unit that will output the TOF and the trampoline area where the athlete landed on (which translates into a certain HD value) after every jump that is performed on the trampoline. The GC must also have a wireless module to send data to the APS. The GC will send the HD and TOF data of every skill that is performed on the trampoline to the APS, but only the most recent jump is stored at any given time.

The APS is the “middle man” between the user and the IR-GRID. It must have a wireless module to communicate between the GC and the UT. The main idea is to configure the APS as an Access Point (AP) so that both the IR-GRID and UT can connect to it, creating a small Local Area Network

(LAN). The APS will also have a web server with a Web Application (WebApp) installed. The front-end will provide an UI to display and manage the data stored on the databases in the back-end.

The UT represents a “window” into the entire system. As referred above, it will serve as a Web Client to the WebApp implemented in the APS and as the GUI for the user. This means that it will send requests for information to the APS. The main function of the UT is to display the data stored in the APS in a simple and graphical manner and to send the user’s commands of START and STOP of the routine. The most important data displayed in the UT is the TOF and HD information of the most recent skill. Secondly, it will also serve as a way for the users to manage the coach/athlete/routine database.

The connection between the GC and the IRM-Rx uses the I2C protocol to communicate. The GC sends a request for data to each IRM-Rx. One at a time, each IRM-Rx responds with a message containing the state (interrupted or not) of its corresponding IR beam.

The GC, the APS and the UT communicate via Wi-Fi with each other. The GC sends the final information about each jump to the APS. This data contains the TOF value and the HD area (one of the 11 represented in Figure 5) from the most recent skill. The APS sends data related to the HD and TOF of the most recent skill, previously stored routine data and athlete profile data. The UT will issue the START and STOP commands to the APS and will be used to manage the databases, in terms of deleting or editing existing profiles. The UT also sends information of new coach or athlete profiles to be stored in the APS.

IV. HARDWARE AND SOFTWARE DESIGN AND IMPLEMENTATION

After defining the general architecture of the system, both the hardware and software were designed and implemented. There will also be reference to some initial tests that were done in order to validate and help to decide about certain design choices. The specific electrical components and software frameworks were chosen based on the requirements that needed to be met: price, availability, documentation, laboratory resources and prior knowledge on the subject.

A. IRM-Tx Design and Implementation

In terms of hardware, what is needed is (1) a circuit to produce a pulsed signal, (2) an IR led with a relatively small emission angle, (3) a lens to focus the IR light even more and (4) a box that can correctly encapsulate the entire module.

To implement this, an **ATTiny85** [4] microcontroller was used to create a 38kHz signal to pulse the **TSAL6100** [27] IR LED. In the case of the TSAL6100, this angle is 10 degrees to each side, meaning that at 520 centimeters the beam formed by the IR light would have a diameter of about 183.4 centimeters and at 305 centimeters in would have a diameter of 107.6 centimeters. Given the configuration illustrated in Figure 5, these numbers are not acceptable, as the IR light from one IRM-Tx would affect the IR receivers neighboring its corresponding IRM-Rx. To solve this problem, a focusing lens was used to decrease the emitting angle of the IRM-Tx. Based on the availability, price and dimension requirements, the best option

found was to use the same **asymmetric double-convex lenses** that are used in the Google Cardboard Virtual Reality project [12]. After analyzing all of the main components needed for the IRM-Tx, the electric circuit, illustrated in Figure 6, was designed.

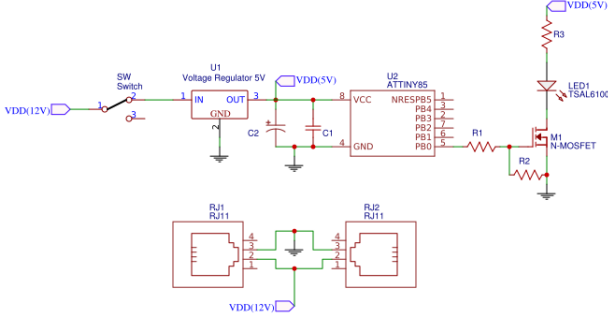


Figure 6. Schematic of the electrical circuit implementation for the IRM-Tx.

In the top left corner of Figure 6 is the voltage regulating part of the circuit. It uses a **linear voltage regulator** to convert the higher voltage that is fed into the IRM-Tx to a more usable 5V. Moreover, there are two **decoupling capacitors (C1 and C2)** connected to the VCC pin of the ATtiny85 that are used to suppress noise in the power supply lines. Typically, there is a ceramic capacitor (C1) with a small value between $0.01\mu\text{F}$ and $0.1\mu\text{F}$ to short high frequency noise away from the microcontroller and a electrolytic capacitor (C2) with a higher value between $10\mu\text{F}$ and $100\mu\text{F}$ to smooth out lower frequency oscillations in the power lines [2]. There is also a **switch** to turn on or off the power supply to the IRM-Tx. The LED power circuit is in the top right corner of Figure 6. This circuit uses a **N-Channel Metal Oxide Semiconductor Field Effect Transistor (MOSFET)** to supply current to the TSAL6100 LED. A transistor is used because the ATtiny85 cannot safely supply enough current to the TSAL6100 LED for the IR beam to reach a distance of 520 centimeters. Testing showed that the necessary current for the IR beam to reach 520 centimeters with enough power was 160mA at a 50% duty cycle. The **R1 resistor** is used to reduce the current surge when the microcontroller drives the MOSFET from “off” to “on”. The **R2 resistor** is a “pull-down” resistor used to ensure the MOSFET is “off” when the PB0 pin’s logic level is not defined (floating) and to discharge the accumulated charge caused by the capacitance between the Gate and the Source of the MOSFET. The **R3 resistor** is used to limit the amount of current needed for the TSAL6100 LED. In the bottom part of Figure 6 are the **RJ11 female connectors**, used to receive and relay the power supply signals from and to the neighboring IRM-Tx.

In terms of software, a simple program was developed that switched the logic value of the PB0 pin between “high” and “low” every $13.15\mu\text{s}$ (half a period for a frequency of 38kHz). This is accomplished using the Timer0 in Clear Timer on Compare Match Mode (CTC Mode).

Based on the schematic in Figure 6 and on the tests, a Printed Circuit Board (PCB) layout was developed. To encapsulate the IRM-Tx PCB, a box was designed and 3D printed using Polylactic Acid (PLA) material. Figure 7 shows the final IRM-Tx PCB with all components soldered inside the lower half of

the PLA box. The total cost of the materials for each IRM-Tx is **5.20 euros**.

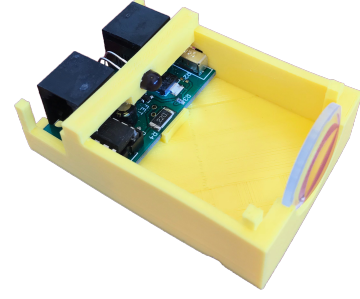
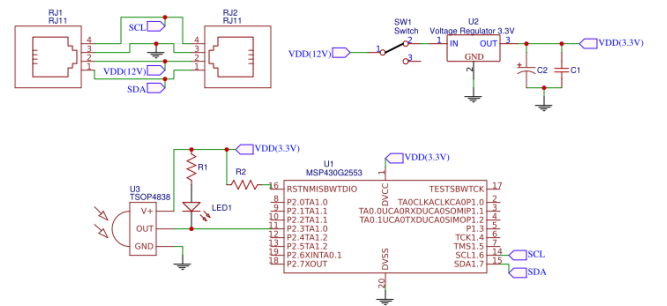


Figure 7. IRM-Tx PCB inside the bottom part of the PLA box with the lens.

B. IRM-Rx Design and Implementation

In terms of hardware, what is needed is (1) a 38kHz IR sensor, (2) a microcontroller with I2C compatibility to send information to the GC, (3) a LED that indicates whether the IRM-Rx is aligned or not and (4) a box to encapsulate de electronics.

To implement this, a **TSOP4838** [28] connected to a **MSP430G2553** [24] microcontroller. The TSOP4838 works as a binary digital sensor in the sense that it can only output two values, either “high” when it is not receiving a 38kHz IR signal, or “low” when it is. The MSP430G2553 has an Universal Serial Communication Interface (USCI) module that has a full I2C protocol implementation compliant with the I2C specification [16]. After analyzing all of the main components needed for the IRM-Rx, the electric circuit, illustrated in Figure 8, was designed.



RJ11 female connectors, used to receive and relay the power supply signals and the SCL and SDA lines from and to the neighboring IRM-Rx. The SCL and SDA lines are connected to pins 1.6 and 1.7 of the MSP430G2553, respectively.

In terms of software, what is needed is a program that reads the binary digital value in pin 2.3 and sends it via I2C to the GC. Based on the architecture defined, the IRM-Rx is used as a slave in the I2C bus that only sends one byte of data when the master (GC) requests it. Based on examples provided by Texas Instruments on how to use the USCI module as I2C, program was developed.

The program starts by calibrating the CPU clock to 16MHz, setting pin 2.3 as an input, setting pins 1.6 and 1.7 to their I2C functions as SCL and SDA, respectively, and configuring the MSP430's USCI_B module in slave mode with a unique address (each IRM-Rx will be programmed with a different I2C address). Most of the time the MSP430 is in Low Power Mode (LPM) with the system interrupts enabled. When the master wants to read the value of the TSOP sensor, it initiates an I2C transaction with the desired IRM-Rx slave. An Interrupt Service Routine (ISR) is performed where the the program reads the logic value in pin 2.3 and sends it to the master. Several tests in breadboard versions of the IRM-Rx were performed in order to verify if this design could work with ten IRM-Rx.

Based on the schematic in Figure 8 and on the tests, a PCB layout was developed. To encapsulate the IRM-Rx PCB, a box was designed and 3D printed using PLA material. Figure 9 shows the final IRM-Rx PCB with all components soldered inside the lower half of the PLA box. The total cost of the materials for each IRM-Rx is **5.12 euros**.



Figure 9. IRM-Rx PCB inside the bottom part of the PLA box.

C. GC Design and Implementation

In terms of hardware, what is needed is (1) a microcontroller with I2C compatibility to receive information from the IRM-Rx, (2) a LED that indicates whether the system is working correctly or not, (3) a Wi-Fi module connected to the microcontroller to send the HD data and TOF score to the APS and (4) a box to encapsulate the electronics.

To implement this, a **MSP430G2553** [24] connected to a **ESP-12E** [21], which is based on the ESP8266EX System on Chip (SoC) [7] and integrated in the NodeMCU Development Kit V1.0 [31] (Wi-Fi module). After analyzing all of the main components needed for the GC, the electric circuit, illustrated in Figure 10, was designed.

The voltage regulating part of the circuit is similar to that of the IRM-Rx. In the bottom part of Figure 10 is the MSP430G2553 microcontroller. Connected to pin 1.0 is a **LED** with a current limiting **R1 resistor**. This LED was used

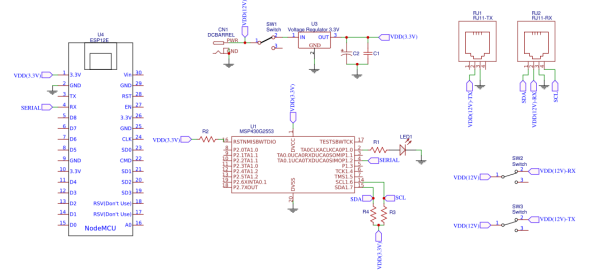


Figure 10. Schematic of the electrical circuit implementation for the GC.

for debugging during development and, in the future, for the user to know if the system is working correctly or not. The **R2 resistor** serves as a “pull-up” in order to maintain the RST pin “high” and avoid the microcontroller from hardware restarting. Connected to pins 1.6 and 1.7 (SCL and SDA lines) are **resistors R3 and R4**, respectively. These resistors serve as a “pull-up” for the I2C lines, as both SCL and SDA are open-drain, which means that they need to be externally pulled “high” when a digital “1” needs to be transmitted. In the left part of the circuit is the NodeMCU, which is connected to the MSP430's TX pin 1.2 via the RX pin 4 (they communicate via Serial). In the top right part of Figure 10 are the **RJ11 female connectors**. One is used to connect the power lines to the IRM-Tx and the other is to connect power and I2C lines to the IRM-Rx. In the bottom right part of Figure 10 are **switches 2 and 3** that turn on or off the IRM-Rx and IRM-Tx, respectively.

In terms of software, what is needed is a program that constantly reads the state of the IRM-Rx sensors and depending on how those values change over time (while the athlete is jumping), can calculate the TOF and HD data for each jump performed. There will also need to be a program that defines the GC as a Wi-Fi client and sends the relevant jump data to the APS. The first part of the software needed was implemented on the MSP430 and the second part on the ESP module.

Before developing the final software for the GC, some tests were performed using a breadboard-version of the GC connected to all ten IRM-Tx and IRM-Rx mounted on the trampoline. These experiments gathered data on how the IR beams behaved when an athlete was jumping on the trampoline. Various charts similar to that shown in Figure 11.

These tests showed that the behavior of the trampoline bed is as follows: (1) all the sensors start with a value of zero which means the athlete is in the air; (2) when the athlete lands on the trampoline bed the beams start to become interrupted by a certain order, depending on where the athlete landed on; (3) while the athlete is on the bed, some of the IR beams alternate between uninterrupted and interrupted; and (4) when the athlete leaves the trampoline bed all the beams become uninterrupted in the inverse order from when they became interrupted initially. The IR beams in the Y-axis behave in the same way. It was also verified that the system had a resolution of the system (i.e. the time interval to read all 10 IRM-Rx sensors) was 600 microseconds.

Given these results, a program for the MSP430 was developed. Most of the time the program is polling all the IRM-Rx sensors waiting for the first beam, in each axis, to become interrupted. When this happens it means that the athlete has landed on the trampoline and so the program sends the

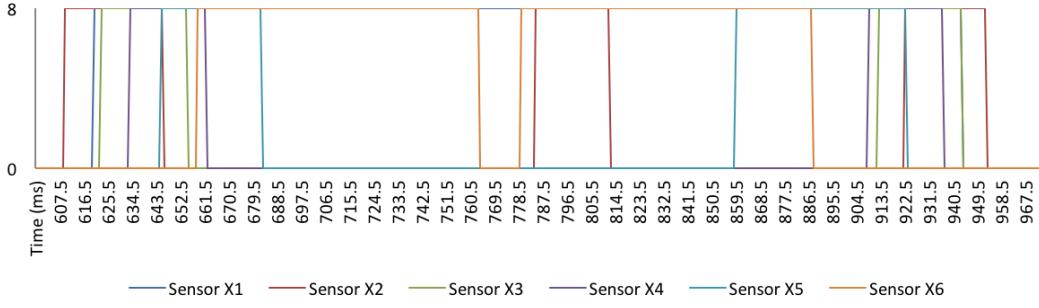


Figure 11. Line charts of the X-axis IRM-Rx sensor values during one jump (landing on area A4). Each sensor has a value of “8” when its IR beam is interrupted and “0” when its IR beam is uninterrupted.

determined TOF and HD data to the ESP module. After that a function called `pollForTakeOff()` starts, and tries to detect when the athlete left the bed to perform a new jump. The algorithm was made in a way that only when the IR beams are uninterrupted for more than 400 milliseconds, can the program be sure that the athlete left the bed. When this happens the timer starts to count the TOF and the same process is repeated again.

In terms of the ESP module, the code developed is fairly simple as it is based on two pre-made libraries for the ESP8266 family, the ESP8266WiFi and ESP8266HTTPClient libraries. The program starts by opening a serial communication at 115200 baud rate and connecting to the Wi-Fi network “Pi_AP” created by the APS. When it receives the TOF and HD data from the MSP430, it sends a message (POST request) with the following format: “area-Code/TOF(seconds)/jumpTmpID/trampID”.

Based on the schematic in Figure 10 and on the tests, a PCB layout was developed. To encapsulate the GC PCB, a box was designed and 3D printed using PLA material. Figure 12 shows the final GC PCB with all components soldered inside the lower half of the PLA box. The total cost of the materials for each GC is **9.73 euros**.

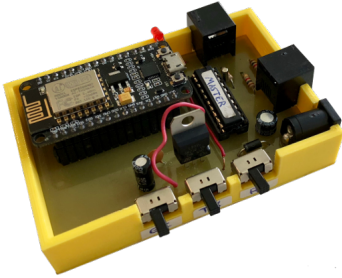


Figure 12. GC PCB inside the bottom part of the PLA box.

D. APS Design and Implementation

The hardware chosen for the APS is the **Raspberry Pi (RPI) 3 Model B** [19][20]. In terms of the software, the back-end programming language chosen was **Python** [18] and the web framework chosen was **Flask** [17][13]. The front-end languages used were **Hypertext Markup Language (HTML) 5** [30], **Cascading Style Sheets (CSS) 3** [29] and **JavaScript** [15]. An Structured Query Language (SQL) database based on the relational model was chosen. The database abstraction

layer chosen for this application was **SQLAlchemy** [23], which was adapted for Flask in the extension **Flask-SQLAlchemy** [3].

In this database there is a table called “Coach” which has the user’s data to log into the application. Each coach may have several athlete profiles, with information such as name, date of birth and level, stored in a table called “Athlete Profile”. Each athlete has up to three routines stored in the “Routine” table. When theGC sends the corresponding HD and TOF data to the APS, it stores them in the “JumpData” table. When the user wishes to save the routine information with the total TOF and HD, it is stored in a table called “ScoredRoutine”.

Flask defines *routes* (the association between an URL and a function to handle it) as *view functions*. These functions process the necessary data for the client’s request and return a response that usually is an HTML file to be displayed in the client’s browser.

In this application there are seven main *view functions*. The `login()` *view function* has to do with displaying the login page and validating the credentials that are submitted by the user to login. It returns the ‘login.html’ file. The `appPage()` *view function* is related with displaying main application, which has the controls to start/stop displaying the jump TOF and HD data to the user, save the routine data, create a new profile, ... It returns the ‘gui.html’ file. The `getScore()` *view function* has the objective of getting the most recent skill data from the “JumpData” table and sending it back to the client browser to be displayed in the GUI. This transaction is done using JavaScript, particularly Asynchronous JavaScript And XML (AJAX), which is a way to partially update web pages asynchronously, by exchanging data with a web server “behind the scenes”, i.e. without reloading the whole page. This *view function* returns a *Dictionary* data type that contains all the TOF and HD data for the most recent jump performed. The `postSensorJumpData()` has to do with sending the TOF and HD data of the last jump performed from the GC to the APS and storing it in the “JumpData” table. It returns a simple *String* so that the GC can confirm that the data was received by the APS. In the `saveRoutine()` *view function*, the TOF and HD data from the whole routine can be saved when the user presses the SAVE button in the main application page. This data is stored in the “ScoredRoutine” table along with a timestamp from the client browser. This transaction is also done via AJAX and it returns a simple JSON text for the client browser to know that the data was successfully received. The `profilePage()` *view function* is used for

displaying the athlete's profile page with the data that is stored in the "AthleteProfile" table. It returns the 'profile.html' file. Finally, the `profileHistoryPage()` view function is related with displaying, organizing and filtering all of the routine history of a specific athlete, which means displaying all of the records stored in the "ScoredRoutine" table of that athlete, under the current coach login session. It returns the 'profileHistory.html' file.

In terms of the server used, Flask comes with an in-house development web server for prototyping, which was capable enough for the desired application.

To encapsulate the RPi, a box was 3D printed using a design available online in PLA material. In terms of cost the total is **36.62 euros**.

E. Final System Design and Implementation

One last important problem needed to be solved to finalize the design of the whole system: where and how to attach the IR-GRID to the trampoline in an universal (i.e. one fit for most Olympic sized trampolines) and non-invasive way? The only structure where the IR-GRID could be placed without changing the elastic/bouncing properties of the trampoline is the metallic ring frame that goes around the trampoline and holds the springs and bed in place.

In terms of how to attach the IR-GRID modules, many options were considered. The main requirements were that modules needed to be fixed in all three dimensions, as vibrations could cause them to misalign, and to be able to attach on any brand of Olympic sized trampolines. Three options were considered: mechanically attaching the modules with clamps, using magnets and using velcro. The chosen one was the last as the modules could be freely positioned in any location of the metallic ring frame without any limitations, it is independent of the dimensions of the ring frame shape (universal between trampoline brands) and offers enough fixing strength across all three dimensions.

The main downside of this solution is that the velcro must be glued on the ring frame by hand without any physical guide to help the user know precisely where to position it. Also, the IR-GRID modules are aligned and attached to the ring frame manually which can cause some difficulties during this process. After testing this attachment method, it was found that the manual alignment of the IR-GRID modules was not complicated, as it took about seven minutes to mount the entire system. This is aided by the wide diameter of the IR beam which does not mandate the IRM-Tx to be perfectly aligned with the IRM-Rx. Figure 13 shows a picture of how the IR-GRID modules are attached to the metallic ring frame.

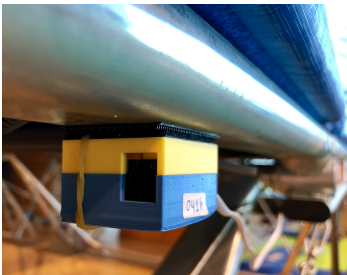


Figure 13. Image of how the IR-GRID modules are attached to the metallic ring frame.

To finalize the system design, the last hardware needed were the **RJ11 cables** to connect all the IR-GRID modules with the power and I2C bus lines, the **RJ11 male connectors** and the **AC to DC 12V power supply**. The final cost for the hardware of the entire system at **178.76 euros**. Figure 14 shows an image of the complete hardware implementation of the designed system.



Figure 14. Picture of the hardware implementation for the complete system.

V. TESTING AND RESULTS

The main goal of the following tests was to check whether the system was working correctly, in a "real world" environment, and if it met all the requirements proposed. It was also important to characterize how the trampoline behaves when an athlete is jumping, which variables influence that behavior and how that limits the capabilities of the system. These experiments were mostly conducted to understand the system's capability of measuring the HD, as the TOF was a easier problem to solve and validate. All the tests were conducted in the Sporting Clube de Portugal Trampoline Gymnasium using an Olympic size trampoline, with the help of national team level athletes and coaches, in order to get valuable feedback from them.

A. Trampoline Bed Behavior Characterization

The main variables that may influence the behavior of the trampoline and therefore the output of the system were the jumping height, the location where the athlete lands on the bed, the athlete's weight and the trampoline model. Theoretically the jumping height is the variable that influences the most the way the trampoline bed deforms when an athlete is jumping on it, so two intervals that can be easily controlled by the athlete were considered: less than two meters and more than two meters, which will later be referred to as "low" and "high", respectively. In terms of the location where the athlete lands on, given that the trampoline is symmetrical, only areas A0, A1, A3, A4 and A5 were tested (see Figure 5). Even though, the athlete weight should not influence too much the behavior of the trampoline bed, it was always the same athlete (male), with approximately 67 kilograms, to perform the experiments. The trampoline model used was also always the same, an Eurotramp Ultimate 4x4 Trampoline [9], which is the latest model to be used in the Olympic Games. In order to validate the data read by the IR-GRID sensors, during all tests, a fish-eye camera (GoPro) was positioned below the trampoline so that it could capture all of the bed areas.

The IR-GRID was mounted on the trampoline frame (see Figure 5) and the IRM-Rx sensor values were read by the GC and sent to a computer via USB. In this test, the resolution

of the system was 900 microseconds (instead of the 600 microseconds) due to the extra data that needs to be sent after each reading. The athlete was asked to jump ten times on areas A3, A4 and A5, at both the “high” and “low” heights. In areas A0 and A1, the athlete was only asked to jump at less than two meters, as it can be very dangerous to jump higher on those areas.

Based on the data, what was previously theorized, in terms of how the bed behaves, was validated. This is evident by the order in which the IR beams are interrupted, the first ones being those closest to the center of pressure of where the athlete lands on the trampoline bed. After analyzing the data from all 80 jumps, one can conclude that this behavior appears to be the same in all bed areas, in both the X and Y axis and at both jumping heights. Regarding the jumping height, it was observed that the higher an athlete jumps, the less time she/he actually spends on the trampoline bed. An example of this is in area A4, where when the athlete was jumping low (with a TOF of 666.9 milliseconds), the Time on Bed (TOB) was 420.0 milliseconds, and when the athlete was jumping high (TOF of 1171.8 milliseconds), the TOB was 340.0 milliseconds. The relation between the TOF and the TOB can be observed more explicitly in Figure 15, where a linear relationship between the two can be inferred. In area A5 this relation was also verified but in area A3 it was not so obvious.

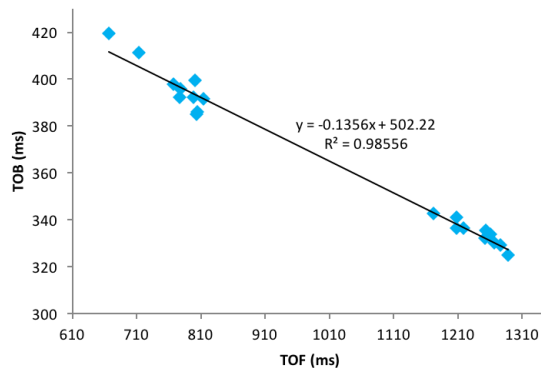


Figure 15. Chart showing the relationship between TOF and TOB values in area A4 at the heights of less and more than two meters. The data was organized in scatter charts and a linear regression was done in each one.

What is most important to understand for this application is that, as an athlete jumps higher, the TOB becomes lower, and therefore the time interval between consecutive IR beams becoming interrupted also becomes lower. This is critical, as the maximum resolution of the system is 0.6 milliseconds, which means that if two consecutive IR beams become interrupted in less than that time, the system cannot differentiate between those two events. In average, the TOF when the athlete was jumping “low” in area A4 was 772.29 milliseconds, and the difference between the first and second IR beam becoming interrupted (in the X-axis) was 12.15 milliseconds. In contrast, when the athlete was jumping “high” in area A4, the average TOF was 1240.47 milliseconds, and the difference between the first and second IR beam becoming interrupted (in the X-axis) was in average 8.28 milliseconds. This means that an increase of 468.18 milliseconds in the TOF resulted in a decrease of 3.87 milliseconds in the time interval between the first and second

X-axis IR beams becoming interrupted. An over-simplistic way to interpret these results is to assume that this relationship is linear. Thus, it would be easy to calculate that for a TOF of 2100 milliseconds (one of the highest single jump TOF that can be performed in a routine), the time interval between the first and second X-axis IR beams becoming interrupted would be 1.18 milliseconds, meaning that the system would always be able to measure the HD when an athlete landed in area A4. Unfortunately, this cannot be concluded as there are many other variables that influence the trampoline bed’s behavior.

Another important characteristic in the trampoline bed’s behavior is that inside the same area, the difference in time intervals between when each IR beam is interrupted may also vary. For example, if an athlete lands on top of line LX1 (see Figure 5), the time interval between when IR beams X1 and X2 become interrupted is almost zero. This makes it very hard for the system to correctly determine the correct HD score when the athlete lands very close to the lines. Given that there are no FIG guidelines describing the resolution, accuracy and precision of an HD measuring machine, a 10 centimeter “gray area” to each side of the trampoline lines was defined. When the athlete lands on this region (their feet are already touching the lines), it is not demanded that the system correctly determine in which trampoline area the athlete actually is on.

B. “Real World” Testing

In this test the entire system, including the IR-GRID, APS and a laptop computer as the UT, were setup in an Ultimate 4x4 Eurotramp Trampoline [9] at the Sporting Clube de Portugal gymnasium. The APS was positioned at a distance of approximately 16 meters from the IR-GRID. A GoPro camera was also positioned under the trampoline bed in order to capture all bed areas and validate the HD results given by the system. This experiment was conducted during a real Trampoline Gymnastics training session, gathering a total of 80 jumps/skills, ranging in TOF from 1.247 to 1.814 seconds. Jumps from four different athletes were measured, who ranged in weight from 44 to 75 kilograms. The system, in particular the UT, was used by two national team level coaches from Sporting Clube de Portugal.

Each jump performed was divided into two groups: those where the athlete landed with his center of pressure more than 10 centimeters away from any area line (outside the “gray area”) and those where the athlete landed less than 10 centimeters of any area line (inside the “gray area”). The athlete’s center of pressure was outside the “gray area” in 60 jumps, and the system correctly identified the HD area every time (accuracy of 100%). Also, the athlete landed 20 times inside the “gray area”, where in 16 of those jumps the HD area was correctly identified, in 2 jumps it was wrongly identified and in 2 other jumps the results were inconclusive (the human eye was not able to discern in which was the correct HD area).

VI. CONCLUSIONS AND FUTURE WORK

Most of the data gathered was used to help better understand how the trampoline bed behaves as an athlete jumps, in order to improve the systems performance. Several athletes and coaches from Sporting Clube de Portugal used the system and the recurrent opinion was that it could be a very helpful tool to improve their performance. The application’s UI was

also praised as it was very intuitive and displayed all the relevant data in a way that made it easy for coaches to gain important insights about an athlete's performance. By being able to store a history of the routines performed by each athlete, the coaches can find patterns in the athlete's jumping behavior that otherwise would be impossible. The fact that the interface between the user and the trampoline IR grid is wireless improved the usability of the system, as it avoids the use of fixed long cables. A big concern was put into developing an attachment method for the system that would be non-invasive for both the trampoline and the athlete and would be compatible with most Olympic format trampoline models. This was also achieved by utilizing velcro positioned in key places around the trampoline's metallic ring frame. In terms of TOF resolution and HD accuracy, the developed system met both requirements as it was able to detect TOF differences with 600 microseconds and during testing, it correctly detected the HD area of each jump 100% of the time, within 10 centimeters of each area line. Finally, the cost of making the hardware was kept as low as possible, and if commercially produced would likely be sold at an affordable price for the clubs.

On the down side, the users felt that setting up the system for the first time was a bit confusing and time consuming, as all the velcro strips needed to be attached to the trampoline frame by hand. Despite this, after some explanation and trials the users were able to mount or dismount the system in less than 10 minutes. Another difficulty felt during this project was trying to test the system in a controlled environment. Given the resources available and the nature of the sport, it was very difficult to replicate experiments several times while controlling all the involved variables.

A. Future Work

In order to improve the system's capabilities, more work needs to be done in terms of testing in controlled environments. For example, the trampoline bed reacts differently when the athlete is closer to the edges where the springs are. This work assumed that the bed behaved the same everywhere which is a good approximation but is not exactly true.

An example of a future improvement to the system is a different software implementation that could help improve the HD resolution dramatically. In this scenario the individual IRM-Rx would locally measure the TOB during each jump and after, send those values to the GC to be analyzed and determine the correct HD and TOF values. Here the resolution of the system is only limited by the timer's capabilities in each IRM-Rx and not by the speed at which the GC can communicate with them. Instead of hundreds of microseconds it would be dozens of microseconds, i.e. one order of magnitude lower.

In time and with more clubs using this system, more optimizations, in hardware and software, will surely be made to improve the system's performance and help more athletes and coaches achieve higher goals.

REFERENCES

- [1] Acrosport (russian) (2017) Innovative technologies / systems testing. http://www.acrosport.ru/catalogue/innovatsionnye_tekhnologii/sistemy_testirovaniya/sinkhronnyy_apparat_s_3_mya_datchikami/
- [2] Analog Devices (2009) Decoupling Techniques. <http://www.analog.com/media/en/training-seminars/tutorials/MT-101.pdf>
- [3] Armin Ronacher (2017) Flask-SQLAlchemy. <http://flask-sqlalchemy.pocoo.org/2.3/>
- [4] Atmel (2013) Atmel 8-bit AVR Microcontroller with 2/4/8K Bytes In-System Programmable Flash
- [5] Brock H (2010) Department of Computer Science Automated Classification of Trampoline Motions Based on Inertial Sensor Input. Master's thesis, Faculty of Natural Sciences and Technology I, Department of Computer Science, Saarland University
- [6] Chi EH, Borriello G, Hunt G, Davies N (2005) Guest Editors' Introduction: Pervasive Computing in Sports Technologies. *Pervasive Computing, IEEE (Volume:4, Issue:3)* pp 22–25
- [7] Espressif (2018) ESP8266EX Datasheet. https://www.espressif.com/sites/default/files/documentation/0a-esp8266ex_datasheet_en.pdf
- [8] Eurotramp (2017) Eurotramp Trampoline bed. <https://www.eurotramp.com/us-en/products/large-trampolines/premium/>
- [9] Eurotramp (2017) Eurotramp Trampoline frame. <https://www.eurotramp.com/us-en/products/large-trampolines/ultimate/>
- [10] Eurotramp Trampoline - Kurt Hack (2017) United states patent publication trampoline no.:us2017/0157444a1
- [11] Fédération Internationale De Gymnastique (2017) 2017 – 2020 code of points, trampoline gymnastics. http://www.fig-gymnastics.com/publicdir/rules/files/tra/TRA-CoP_2017-2020-e.pdf
- [12] Google (2017) Google Cardboard. <https://vr.google.com/cardboard/>
- [13] Grinberg M (2014) Flask Web Development - Developing Web Applications With Python. O'Reilly Media
- [14] Hawk-Eye Innovations (2017) Hawk-Eye in Tennis. <http://www.hawkeyeinnovations.co.uk/sports/tennis>
- [15] Mozilla, MDN and other contributors (2018) JavaScript reference. <https://developer.mozilla.org/en-US/docs/Web/JavaScript/Reference>
- [16] NXP Semiconductors (2014) I2C-bus specification and user manual. <http://www.nxp.com/docs/en/user-guide/UM10204.pdf>
- [17] Pallets (2010) Welcome to Flask. <http://flask.pocoo.org/docs/1.0/>
- [18] Python Software Foundation (2018) Python 2.7.15 documentation. <https://docs.python.org/2/>
- [19] Raspberry Pi Foundation (2018) Raspberry Pi 3 Model B. <https://www.raspberrypi.org/products/raspberry-pi-3-model-b/>
- [20] Raspberry Pi Foundation (2018) Raspberry Pi Documentation. <https://www.raspberrypi.org/documentation/>
- [21] Shenzhen Anxinke Technology (2015) ESP-12E WiFi Module. <http://www.kloppenborg.net/images/blog/esp8266/esp8266-esp12e-specs.pdf>
- [22] SportTechie - Sports Technology News (2015) Babolat Play Connected Tennis Racket is the Future of Tennis. <http://www.sporttechie.com/2015/01/29/babolat-play-connected-tennis-racket-is-the-future-of-tennis/>
- [23] SQLAlchemy and other contributors (2018) SQLAlchemy 1.2 Documentation. <http://docs.sqlalchemy.org/en/latest/>
- [24] Texas Instruments (2013) MIXED SIGNAL MICROCONTROLLER. <http://www.ti.com/lit/ds/symlink/msp430g2353.pdf>
- [25] Trampoline Timing Systems (2017) AirTime Trampoline System. <http://www.trampolinetimingsystems.com/products.htm?submenuheader=0>
- [26] University of Ulster (2015) The Role of Technology in Sport. <http://www.ulster.ac.uk/scienceinsociety/technologyinsport.html>
- [27] Vishay (2014) High Power Infrared Emitting Diode, 940 nm, GaAlAs, MQW
- [28] Vishay (2016) IR Receiver Modules for Remote Control Systems. <https://www.vishay.com/docs/82459/tsop48.pdf>
- [29] World Wide Web Consortium (W3C) and other contributors (2017) CSS Snapshot 2017. <https://www.w3.org/TR/2017/NOTE-css-2017-20170131/>
- [30] World Wide Web Consortium (W3C) and other contributors (2017) HTML 5.2. <https://www.w3.org/TR/html5/>
- [31] zeroday GitHub repository (2015) nodemcu-devkit-v1.0. <https://github.com/nodemcu/nodemcu-devkit-v1.0>