POLITECNICO DI MILANO
Master degree in Biomedical Engineering
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An Advanced Interactive Rhythmic Exercising Dancing Machine to address physical inactivity: AIR ExDaMa.

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Abstract

This thesis pertains the field of computer and electronics applied to healthcare and, more specifically, this work proposes a new device to address the physical inactivity issue that is currently afflicting many countries worldwide. In this work a fully working interactive fitness machine was designed, built and extensively tested; complementary software for the automatic generation of new content for it was also developed.

Sommario

Questa tesi appartiene al settore dell'informatica ed elettronica applicate al settore medicale e, più specificatamente, questo lavoro propone un nuovo dispositivo per far fronte al problema dell'assenza di attività fisica che attualmente sta affliggendo diverse nazioni. In questo lavoro è stato progettato, costruito e ampliamente testato un dispositivo di fitness interattivo. Questo dispositivo è stato inoltre dotato di software ausiliare per la creazione automatica di nuovi contenuti.

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Chapter 1

Introduction

1.1 General overview

1.1.1 Introduction to the problem

"Sitting is the new smoking". While this sentence has been object of controversies for its inaccuracy [139] the evidence of the numerous beneficial effects that physical activity (PA) has on our body is undiscussed [138]. According to the World Health Organization (WHO) PA is defined as "any bodily movement produced by skeletal muscles that requires energy expenditure. Physical activity refers to all movement including during leisure time, for transport to get to and from places, or as part of a person's work. Both moderate and vigorous-intensity physical activity improve health". The risks associated with insufficient PA are several and include higher all-cause, cardiovascular disease, and cancer mortality in addition to higher incidence of cardiovascular diseases, cancer, type-2 diabetes and overall lower quality of life.

More than a quarter of the world's adult population (1.4 billion) are insufficiently active and the problem is only getting worse. The number of people not performing enough PA increased by 5% (from 31.6% to 36.8%) in high-income countries between 2001 and 2016. "Increased levels of physical inactivity have negative impacts on health systems, the environment, economic development, community well-being and quality of life" and "The drop in physical activity is partly due to inaction during leisure time and sedentary behaviour on the job and at home. Likewise, an increase in the use of "passive" modes of transportation also contributes to insufficient physical activity" keeps reporting the WHO [60].

1.1.2 Approached solutions

Many ways to increase PA have been designed and tested; they are differing from each other in the organization through which the promotion is done (e.g. public sanity, workplace, schools), the medium used to achieve the goal (e.g apps, phone calls, green prescriptions), and the way it is used. Research though, is still green and results are mixed so that no clear dominating approaches are determined yet.

One of the used mediums to improve PA is interactive fitness (IF) gear. IF is a union between fitness gear and interactive software. While, strictly speaking, the term refers to a device that is able to establish some sort of communication with the user (e.g. a game), it is also often used to indicate purely reactive machines that simply respond to the user input (e.g score trackers, virtual bikes).

> " The idea behind a reactive experience is to distract you during your workout, making it easier to get through the exercise. While it usually carries some significant early appeal, the experience of these platforms remains the same with each use and for each user. The goal of an interactive product is to fully immerse you in the experience of the workout. With an interactive product, you must steer, shift, punch, kick, or raise your competitive level to achieve the goal the product hangs in front of you. Your success is truly dependent on the path you choose. The experience between you and the product is truly unique..."[32]

these are the words used by Advantage Sport & Fitness (a major fitness gear seller) while describing this category of products. While those are obviously words directed to a potential customer and thus, posed as to make their products as desirable as possible, they can still capture the main advantages of IF devices: every time you use them you are faced with a different experience and goals whose achievement only depend on you, you can also keep track of your improvement, scores and compare them with your buddies. These kind of characteristic have been shown to be strong factors affecting the motivation of an individual in undertaking a behaviour in several psychological theories like STD (see section 2.2 for more details).

Having only recently gotten popular IF, the variety of products is quite limited and no specific trend can be identified. It has been noticed that there was an absence of a device focused on the upper body training that made use of an highly interactive and addictive interface (like a game). The goal of this thesis is thus the development of an IF device focused on the movement of the upper body that has the potential to retain its user base over long periods of time and that is usable and likable by the largest possible age range. The device was decided to be a highly customizable rhythm game to which an AI for the automatic generation of playable content added.

1.2 Brief description of the work

1.2.1 Current status of the research

The last few decades we assisted to an astonishing technological evolution. Devices that only one hundred years ago people couldn't phantom are now an everyday reality for developed countries, making life easier and more enjoyable but this didn't come without a price. Due to changes in work typologies (shifting toward less physically demanding jobs) and habits, people have started to move less and less. Result of this is the spreading of physical inactivity (PI) to the point where it was defined as a pandemic by the The Lancet in 2012 [109] [138]. The risks associated with PI are numerous and are reported in A.1 and A.2 (taken from Thompson et al. 2020 [138]). As if the resulting lower quality of life wasn't enough, lower PA is also associated to higher medical costs and loss of productivity due to illnesses and other factors. While today the economic impact of this sedentary behaviour is yet to be gauged with precision due the relative low amount of studies, their heterogeneity in population (different countries) and estimation methods (and, in addition, its strong variability among countries), its impact on the healthcare budget is undiscussed ranging from one to over ten percentage points [86]. Given the increasing size and severity of the problem governments and organizations started promoting PA trough every possible means: workplace, schools, communities everything that hinted the ability to address the issue was used. Meanwhile research also started activating itself in understanding which interventions were more effective and why in order to design evidence-based interventions trying to maximize the efficiency as much as possible.

Illustrated below 1.1 is the number of results for "physical inactivity" on PubMed. It's easily noticeable how the amount of publications rapidly increased in the last twenty years.

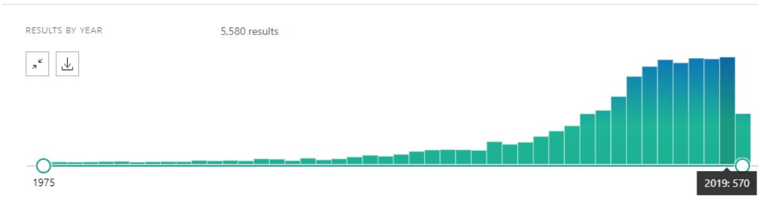


Figure 1.1: Results over the years for "physical inactivity" trough PubMed

Despite this evidence, cost-effectiveness of methods of interventions from both the point of view of employers [112] and the public sector [115] is yet to be assessed. The low amount of studies, test subjects and, mostly, the huge heterogeneity in the way the experiments were performed and validated, provides little to no evidence to the matter so that a push for stronger guidelines is required [83].

Nowadays the fitness (gyms) sector is steadily increasing its share. While the total annual revenue is closing on the 100 billions, numerous new centers are being built around the world, going from 165.000 in 2014 to 210.000 in 2018 [57]. This big increase in numbers (that is mirrored by an increase in the number of subscribed memberships) is due to several factors. First of all the increased awareness of the population about the issue that, as consequence, resolves itself to train. Secondly, the increase in the amount some people (especially millennials) are willing to pay for their well-being. This had as consequence an increase in membership costs as well as the birth of fitness boutiques, small places where the training is either done one to one or in small groups with a professional instructor.

While this is a good sign that shows people's awareness of the problem, it doesn't mean that the issue is gonna fix itself with time. If we look into more statistic data [43], it is possible to observe that the retention rate for new gym members is about 50% in six months and 30% over one year. It has also been recorded that a significant number of people use the gym to hang out and, out of those, some don't even break a sweat while there.

1.2.2 Interactive fitness

In order to get people to perform more PA, external interventions are needed. Intervention plans usually target a group of people that can be reached trough a particular institution (e.g healthcare system, workplace, schools) using a medium (e.g. phone apps, green prescription, incentives) in a certain way (e.g. referencing to behaviour change psychological theories). Out of the mediums, a relatively popular one are *exergames*. With this term people indicates games that require the user to perform PA in order to be played. By unifying fun with exercise, manufacturers aimed to introduce computer games fans to the fitness industry and fitness people to games [56].

Despite the efforts of several companies, products like exerbikes and balance boards never really took off till the recent period when they realized that selling a product as either fitness instrument and game was actually counterproductive since both the target customers were totally uninterested in one side of it. Because of this, the broader term of "Interactive Fitness" (IF) was created. With this term companies aimed to sell their products as fitness instruments that were, as bonus, more fun to use with respect to their competitors. At the same time, proper games that had fitness as bonus were either sold as exergames or as IF products depending on the customer type.

IF can be defined as

> "An "interactive" piece of fitness equipment implies there is input from a user that is reciprocated through the machine's response. In other words, it's a two-way street. Not only will the machine respond to your input, but will reciprocate with input of its own. Whether it changes the resistance, changes the visual path, or awards you "points" during a game, the machine is changing your experience based on your input. It sounds pretty straight forward, but confusion arises when we try to differentiate between a platform that is interactive and a platform that is strictly reactive. A reactive process stops after the input of a user. You may be able to change your resistance, but the machine simply responds to this command, and does not reciprocate with any input back to you. These platforms typically involve a screen in front of the user guiding them through virtual landscapes or allowing them to watch television and browse the web" [31].

While the IF market is rapidly growing in size [58], accompanied by the so called "smart fitness" device market (that is roughly comprised of the smart wearable devices) [45], the exergame market is today nowhere to be found. One of the reasons for this is the failure of the main mediums that made exergames possible in the past: consoles and arcade machines.

Consoles have been the first method trough which exergames were introduced to the public, with Atari's exerbike "Puffer" in the 80'. Following that almost every successful exergame has been published for console, from the DDR in 2000 (first successful exergame) to other games produced for Sony's Eyetoy, Nintendo's Wii and Microsoft's Kinect. Unfortunately all three of those peripherals failed due to marketing mistakes and unfortunate political accidents.

Similar situation affected the arcade sector. After the end of the last century boom owners have been unable to adapt to the new situation and competitors, ultimately losing the trust of their customers. As a result, arcades are today almost dead with the exception of Japan (where they are part of the culture), some American/international companies like D&B and Round1 and few other exceptions.

While it doesn't seem like exergames will be able to rise again anytime soon, it doesn't mean they are dead. Luckily innovation never stop and new mediums are today available, namely, smartphones and immersive virtual reality. Many augmented reality games like Ingress or Pokemon Go (whose cumulative earning reached 4 billions in 2020) [37] have been extremely successful in increasing the population's PA.

On the other hand, immersive virtual reality, despite producing some extremely successful titles like Beat Saber, is still lagging behind due to the immaturity of the technology that can often induce symptoms like nausea and dizziness in the user, especially if used for prolonged periods of time [93].

1.2.3 Current direction of the research

Finally, numerous papers and products [62] [67] [65]are released every year about the potential use of virtual and augmented reality in the field of rehabilitation [66]. The research is particularly focused in its use in the fields of neurodegenerative diseases (like Alzheimer), strokes and general therapy. The use of this particular approach hold several advantages. First of all it has been found that gamification of the exercises significantly motivate patients [97] [94]. Secondly, especially in the case of a stroke patient, every second after the accident is important. In many cases people have to wait a long time before they can start exercising in the hospital/clinic, the gear is often inappropriate and due the high number of patients, inadequate time is allocated to the performance. As if that wasn't enough, people often get discouraged from the lack of results and stop exercising after the discharge, when they are not being monitored anymore [63] [64]. The possibility to provide a low-cost enjoyable personal training device is seen as a top priority for these patients. Finally, having an internet-connected interactive device taking over part of the rehabilitative process, would allow for remote supervision and longer follow up for patients.

Unfortunately, published papers about the issue are not only extremely heterogeneous in methods and results, but also suffer from low number of involved subjects. Because of these issues, that are not helped by the widespread use of a young and still defective technology as is immersive virtual reality, it's still hard to tell whether it will be possible to achieve the set goal even tough past studies seems to suggest so. [104] [100] [101]

In the IF field, instead, it is simply a race to dominate the market. A trending line is that of home fitness, that is, the development of smart modular gears that can provide the benefits of a gym in an relative compact device. Home fitness has seen a large increase in the pandemic situation.

1.2.4 From the problem to our work

This thesis' idea stems from multiple observations:

- Many interactive fitness devices are more like score trackers than actual games. While this is still in line with their goal, these devices lack the potential to hook the users for long periods of time due to their monotony and lack of competition.
- Despite the huge success of Konami's DDR, no one ever made a version that would exercise the upper part of the body
- Many devices (especially exergames) are not friendly towards people with limited physical ability and reflexes and are too complicated for what is the taste of some people (mainly older adults that prefer simpler frameworks).

The goal of the thesis was the development of an interactive fitness device (later called AIR ExDaMa) mainly focused on exercising the upper part of the body. The produced device must be suitable for any age, body size and physical prowess and, at the same time, being enjoyable, competitive and capable to motivate people in its use for long periods of time.

1.3 Thesis' structure

This thesis is structured as follow:

- In chapter 1 the problem, the current status of the art and the thesis's goal are briefly explained.
- In chapter 2 the state of the art is presented in detail. It starts with the broader filed of physical activity nudging and then gets more specific when talking about interactive fitness and exergames.
- In chapter 3 the design and working principles of the proposed solution will be shown.
- In chapter 4 the user test with its results will be commented.
- In chapter 5 the conclusions will be reported.
- Appendix A reports the used tables.
- Appendix B reports with a certain degree of detail the crafting and assembling process.
- Appendix C reports the history of the project, better highlighting the reason for which some components and solutions have been chosen.
- Appendix D reports the user manual.
- Appendix E reports the playing instructions.
- Appendix F contains the necessary data-sheets.

Chapter 2

State of the art

2.1 Methods for physical activity promotion

The physical inactivity issue has been widely addressed in the past couple of decades. Research on the topic has been divided by target in order to increase the quality of the evidence. Namely, these groups are children, adolescents, adults, older adults, ill people (classified by illness type) and pregnant women [60]. Trough the use of every exploitable organization (e.g. workplaces, healthcare systems, schools) various types of interventions have been implemented [114] [60]. All these solutions make use of a medium, that is, an object and/or a service that is supposed to, in some way, increase people's tendency toward PA.

The institutions trough which people have been tried to reach are listed here below.

2.1.1 Schools

The main advantage of using schools as intermediary is that a deep underlying link between a significant part of the population and the institution already exist. School-oriented PA interventions fall into five different categories that are often combined: physical education curriculum, breaks (mainly recess), school commuting, extracurricular activities and playground design (e.g., [90] [98]).

Only moderate quality of evidence about the effectiveness of these methods has been obtained till now. Despite that there seem to be a positive effect that is more accentuated when the various methods are combined [87] [129] [121] [142]. Finally, according to the estimations made by the Washington state (still based, tough, on literature up to 2015 [3]), the chance of cost-effectiveness for school based intervention is about 66%.

While all the previously mentioned methods are being tested to promote physical activity, out of school interventions are the most promising ones. The reason is that working on the activities made at school can only marginally contribute to the cause since it does not address how children and adolescent spend their leisure time at home [107].

Of particular interest is a report from 2018 by the WHO [95] that, other than giving an overview about how physical activity is addressed in the EU, reports numerous examples about how several member states successfully applied school-based solutions to increase PA in youngsters: "The most common were improving the quality or increasing the quantity of physical education lessons and promoting active travel to school. Some of the examples consisted of after-school programs, and only a few were for active school breaks and active breaks during school lessons" observe the document. The report also suggests to use this ideas as framework to either implement new solutions or shape future research.

2.1.2 Workplaces

Workplaces can be considered the equivalent of school for adults. Since the health of the employees and, as consequence, their productivity is at stake, detailed research was done in this field and extensive documentation on how to implement solutions and which are the best practices is available online. In 2020 two massive literature reviews got published about this issue by Pronk et al. [130] and Zhu et al. [146]. These papers thoroughly highlight various theoretical fundamentals for intervention planning and the best practices in the field, together with the various advantages that companies would obtain from them. Some of the most common ones regard sit-up desks, work commutation, incentives, gym memberships, PA introduction in the work routine or staircase usage. While single plans, if correctly tailored for the company, can already give results, the usage of multiscale plans that synergyically act on different aspects of the working experience are what seems to give the better results and are, thus, the focus of the research.

2.1.3 Urbanistic

While encouraging people to practice physical activity is definitely important, making sure that there are no barriers keeping people away from it is not to be neglected. Most of the industrialized population lives in cities that, as everyone knows, are affected by problems like pollution, traffic or criminality. These problems can prevent people from performing PA since the risk or uncomfortableness they would incur to end up outweighing any possible perceived gain. It's in this situation that urbanistic come into play acting on the city itself.

Evidence of effectiveness of urban interventions through various means is already present in literature [106]. The most intuitive one is the construction of walk/cycling roads since they allow people to travel in security and, following that, we have the presence of parks or recreation environments (e.g., skate parks). The accessibility and quality of these elements has been reported to significantly increase PA levels [133].

While designing the urban environment is also of utmost importance to take in consideration the population subgroups that would use the area, their tastes, and economical status. For example low income population, which, besides everything, has been reported to be statistically more susceptible to lack of PA, has been observed to frequent public parks less often that richer or higher educated people [133]. Following this reasoning, in some countries like the United States the importance of the neighbourhood has taken the spotlight, since it has been seen that interventions at this level tend to be particularly effective [127].

2.1.4 Communities

Research for the health of community-dwellers have also been performed. Starting from the known premise that PA is beneficial for everyone and since they live in a controlled environment in which they can be thoroughly checked and, to a certain extent, forced to exercise, the studies focused on which strategies seem to be more effective in making patients more willing to move. Zubala et al., 2017 [147] reported that cognitive approaches (e.g., based on information) were less effective than other, more intimate ones, involving social support or enjoyment.

2.1.5 Family

Trying to get to the children through their parents has been a topic of interest in literature. Various studies found positive effect when adding the family into a physical intervention for children [140], [99]; some authors even affirmed that "without the involvement of family members, it is unlikely that long-term change in children's physical activity levels is possible" and moved the research topic further, analyzing which are the most effective intervention with this approach [79].

2.1.6 Ethnic subgroups

Another factor to be taken in consideration (although this is often a variable instead than an institution) is ethnicity that, in some cases, is also associated with different economical situations. Effects of culture, socio-economical and seasonal barriers have been widely reported in literature [132] [92] [105] [137] making it necessary to take in consideration the population subgroup when designing a trial or proposing an intervention. Significant differences to be taken into account have also been reported between rural and city areas [143].

2.1.7 Healthcare

In the past decades, the focus of public health has expanded to include injuries and chronic diseases prevention, health-promoting policies and support for behavioural changes [73]. While evidence of the efficacy of PA promotion in the healthcare system has been shown in several occasions, the main factors that impact on its efficacy are yet to be determined [70]. Unfortunately, despite the evidence hinting towards its usefulness, healthcare personnel often fail to appropriately promote physical activity (through counseling, prescription or third party referral) [141] [111]. The reasons why, despite its recognized importance in the medical sector, PA is not advertised as it should, are various and were investigated in numerous studies. These reported as main factors the lack of knowledge and confidence on the effective strategies for promoting PA, lack of skills, limited time, reimbursements, workload, and practice barriers [70].

In order to face these problems, several formative initiatives for healthcare personnel, but also medicine students are being done while, in the research field, clinical protocols for the correct handling of the situation are being published, e.g., [102].

2.1.8 Media coverage

Before even trying about convincing people to exercise more, raising their awareness of the problem is fundamental. The use of TV, newspapers, social media, ads, and websites can allow for a wider (and correct) information diffusion. Unfortunately, regarding the use of mass media campaigns, despite managing raises awareness and produces changes in people's behaviour, the evidence for lasting effects is lacking [108]. Thanks to, instead, the increasing use of internet, the possibility of using a web based approach seems to be more appealing. This kind of methods are cheap and able to reach a significant number of people. According to Rose et al. [131], this approach seems to be effective but, due to the heterogeneity of the studies, a generalization results difficult. Cost effectiveness analysis and the use of other media should also be considered in future studies.

2.1.9 Multiple behaviour changes

Hoping for the possibility of a synergic effect, experiments were conducted by integrating physical activity interventions into other behaviour correction programs (e.g., diets, smoke quitting). Unfortunately, evidence showed that single focus activities provided better results [135] so nowadays solutions of this type are extremely uncommon.

2.1.10 Home

While promoting physical activity is also of fundamental importance to take in consideration the limitations people may encounter. For this reason most of the studies that were done in a home setting referred to older adults and/or ill/recovering people. Although results seem to suggest that this type of intervention is feasible, safe and effective [85], strong evidence of efficacy is yet to be provided (most of the studies with this setting were often multi-behavioural and, as such, didn't have PA as main goal, thus the data quality about it is lacking) [81]. This type of intervention is often associated to the healthcare setting and focused on the use of state-of-the-art knowledge about effective exercises that require minimum amount of risk, gear cost and space requirement. They also exploit systems like phone calls and home visits to increase adherence [84]. As one might guess, adherence is a critical factor in these approaches so the development of methods for its maximization and estimation [91] is crucial.

2.2 Theoretical basis

In the last couple of decades, the use of psychology for the design of new intervention plans for PA promotion has been undertaken. By adding some "evidence based instructions" to the way mediums are used to increase PA research aimed to maximize the interventions efficacy while also reducing the risk of wasting time and resources on frameworks with no chance to work. Today, more and more authors either use or push for the use a rigorous psychological framework as basis for new trials. For this purpose several psychological theories and human behaviours have been exploited. Most of the theories are about behaviour change in humans, but others, like behavioural economics, are not ignored. Given the vastity of the topic only a few commonly used ones will be briefly presented here.

2.2.1 Self-determination theory

The self-determination theory (STD) aims to predict the human behaviour by distinguishing motivation in two types: internal and external. Internal motivation is about doing something for the sake and enjoyment of it while the external is doing something because we want to achieve a certain goal. Motivation is, in turn, function of three basic needs that are autonomy (will to be the cause one's own life's events), competence (tendency to seek mastery) and relatedness (will to be connected with other people). The theory also distinguishes several types of external motivation, classified by the degree to which the results that want to be achieved are valued and internalized by the person. STD considers many other things like individual differences that will not be reported here.

This theoretical framework is used by either setting up an intervention to maximize the quality of external motivation or/and by performing internalization that is, "the active attempt to transform an extrinsic motive into personally endorsed values and thus assimilate behavioral regulations that were originally external" [21]. As of today the effect of STD based interventions are still unclear, tough it seems hinting to short term "modest but significant" improvements [123].

2.2.2 Theory of planned behaviour

The theory of planned behaviour explains physical activity as function of intention that is, in turn, function of attitude (inclination toward the behavior due to enjoyment or goals), subjective norms (how people important for the subject think of the behaviour) and perceived behavioural control (frequency of factors that could facilitate/impede aid behaviour) [122].

2.2.3 Social cognitive theory

The social cognitive theory (SCT) affirms that people learn from others. By seeing how a person in a certain environment and way achieved a particular result people expect a similar outcome given similar conditions. A study conducted in 2015 that aimed at the discovery of the biggest impact factors in SCT-based interventions reported that high correlation was found between self-efficacy and PA [145]. Self-efficacy is defined as the extent an individual can master a particular skill. This can be improved with experience, social modelling (examples of people who achieved said goal), verbal persuasion and psycho-physical state improvement (ensuring to be rested and relaxed before engaging in a new behaviour) [22].

2.2.4 Behavioural economics

Behavioural economics (BE) is a branch of economics that takes into account that people are not completely rational beings and, thus, their judgement isn't always correct when maximizing cost-benefits. The use of this field's knowledge would give practical guidelines for intervention designs. Unfortunately, the use of these methods is scarcely reported [78].

2.2.5 Social ecological model

The Social Ecological Models "take a broader approach in that they propose that behaviour is the result of interactions between individual characteristics (e.g., age, gender, Body Mass Index, employment status), the social environment (e.g., family or peer social support, social norms), the physical environment (e.g., weather, attributes of the physical environment such as green space, safety) and aspects of the macro-environment, in particular policy (e.g., urban planning policies, workplace policies, active transport policies)." These models take into account that despite an individual being motivated and inclined towards physical activity, external factors that operate against it (like price for gyms or crime for running) end up preventing the execution of the behaviour [122].

2.2.6 Affective-reflective theory

The affective-reflective theory (ART) affirms that behaviour is a consequence of a reminder (like an advertisement or an alarm) that elicits an affective reaction in the person that is in turn mediated by the previous experience with the behaviour and his rational judgement of it. This theory is new and, as opposed to others, is manly used in trying to describe the reasons for not being physical active [77].

2.2.7 Energetic cost minimization

The energetic cost minimization theory is based on the the observation that living beings have the tendency to optimize energy expenditure and, same as ART, is used to describe physical inactivity in terms of barriers and effort optimization [77].

2.3 MEDIA

2.3.1 Incentives

Economical incentives are the most intuitive medium to motivate people in doing more physical activity but, do they really work? Are they sustainable over time? Numerous trials analyzed how different types of incentives influenced people's behaviour. It has been found that the use of conditional incentives (that are given only if a condition is met) are more effective than granted ones and that when rewarding the effort, giving a prize for reaching a certain goal is more effective than doing it for attendance [72]. A study from Patel et al. in 2016 [125] reported that the use of the so called "loss aversion", a phenomena for which people give more importance to avoiding losses than to obtain gains, provided significantly better results than fixed or lottery based incentives and, in an other study by the same author [124], it was found that rewarding a group for achieving a collective goal (everyone in the group had to reach it) yielded better results than giving it out to singular individuals. This last result can probably be explained by assuming that people that aimed at the reward pressured the others in completing their task and by the very fact that, as it known that social interactions promote retention. Finally it has also been found that the use of training goals that update automatically based on people's improvements yield significantly better result in term of fitness [75].

In general, as said in Carrera et al. [82] "simply timing an incentive program to coincide with endogenous attempts at habit formation is likely to be insufficient on its own to help people reach their health goals". This means that research should take in high regard and thoroughly investigate how different models affect people's response. Some guidelines for that were given by Brower et al. [78] that found that the value of the incentive is way less significant than other factors like how and when is given and that future studies should take inspiration from behavioural economics studies in order to maximise the effect of incentives. In conclusion we can say that while sustainability, long term efficacy and cost-effectiveness of incentive plans are yet to find evidence, significant effects can be obtained in short term ones [118] [136] [96].

2.3.2 M-health

With the ever increasing use of mobile phones, the possibility to exploit them as a cheap medium for treatment is alluring. Out of many papers published in the field of mobile health, many are related to emerging countries for this very motive. Several reviews were done recently and, while it seems that m-health is a viable and feasible solution, methodological heterogeneity, small sample sizes and different populations makes results not too reliable. There is also a lack of understanding of long terms effect and the difference of effect between various methodology of interventions is yet to be found. [144] [119] [71] [103] [80] [120] Future research in this field will most likely be more oriented toward the use of mobile apps and tracking devices (instead of SMS, that have been dominant until now, especially in low income countries). The use of AI to increase efficacy also seems promising[69].

2.3.3 Interactive fitness and smart fitness

IF is such recently created term that, despite its success, a Wikipedia page for it does not even exist. That said it is a widely used term in the industry and, according to Advantage Sport & Fitness, a well established fitness equipment provider, IF is defined as "An "interactive" piece of fitness equipment implies there is input from a user that is reciprocated through the machine's response. In other words, it's a two-way street. Not only will the machine respond to your input, but will reciprocate with input of its own. Whether it changes the resistance, changes the visual path, or awards you "points" during a game, the machine is changing your experience based on your input. It sounds pretty straightforward, but confusion arises when we try to differentiate between a platform that is interactive and a platform that is strictly reactive.

A reactive process stops after the input of a user. You may be able to change your resistance, but the machine simply responds to this command, and does not reciprocate with any input back to you. These platforms typically involve a screen in front of the users guiding them through virtual landscapes or allowing them to watch television and browse the web. The idea behind a reactive experience is to distract you during your workout, making it easier to get through the exercise. While it usually carries some significant early appeal, the experience of these platforms remains the same with each use and for each user. The goal of an interactive product is to fully immerse you in the experience of the workout." [32]

IF gear is often paired with the so called smart fitness (SM) equipment. This is another newly formed term that that still lacks an official definition and is normally used to define smart wearable sensors. The SM market is usually divided in these groups: smartwatches, wristbands, mmart clothes, smart shoes, bike computers, and "others", with smartwatches taking up a significant part of the market share [46].

Both IF and smart fitness are sectors in rapid growth. Not much public information for IF is available but, knowing that it has an estimated CGAR of 6% and a growth in five years (from 2019 to 2024) of 5 Billions, it is possible to compute an approximate market size of 15 and 20 Billions for respectively 2019 and 2024 (15=5/((1.06$\hat{5}$)-1)) [53]. This yet extremely approximated value will probably be slightly higher than what previously computed, according to a report from 2020 [38].

SF is instead expected to grow much more going from the 6 billion $ in 2016 to 30 billion by the end of 2025 [46] [44] [55] [47]. Another rapidly growing market that partially overlaps with that of interactive fitness is the online/virtual fitness that is expected to increase from its 6 billions in 2019 to 60 in 2027 [33].

At the roots of the concept of IF lies that of exergame. As will be successively explained IF was given birth due to marketing reasons but, despite everything, it can be considered a generalization of the exergame concept in which the interactive part is not required to be a game. That said in order to understand what IF is today an overview of what is and was exergaming is necessary.

2.4 History of the exergames

2.4.1 The early years

The puffer

The "Puffer" (see figure 2.1) from Atari is considered the first attempt at exergames. Unfortunately, the company was sold due to an industry crash in 1984 and the product was never released. "Puffer" was supposed to be a bike that could act as a controller for an Atari console and, by varying the pedaling speed and pressing some buttons on the handles, it was possible to control the in-game character. The rationale behind it has been leaked from a document and revealed what subsequently said: "There is a whole generation of kids (and adults) out there who aren't into sports and/or don't get enough exercise. At the same time there is a huge fitness market ... we are going to hook up an exercise bike to a video game, where the bike is the controller ... we can make fitness freaks out of the kids and game players out of the keep fitters." [56]

Figure 2.1: Puffer [56]

The first exergames

The actual first exerbike to make it to the market was the HighCycle (see figure 2.2)in 1983 by Autodesk. This device made use of projections on walls to increase the level of immersion of the user [25].

Figure 2.2: Highcycle [25]

Other products from the 80's were the Joyboard from Atari that was, in essence, a balance board [18] and Virtual racquetball from Autodesk, that made use of tracking devices and an head mounted visor to detect motion [29].

Several games got released in the following 20 years with an increasing interest toward the immersive/semi-immersive virtual reality attached to high end gym equipment. Unfortunately "Three issues combined to ensure the failure of these systems in the marketplace. First, they were significantly more expensive than the equivalent models that did not have all the additional electronics. Second, they were harder to maintain, and were often left broken. Lastly the additional expertise required to operate the software was often intimidating to the users, who shied away from the machines out of fear that they would look foolish while trying to master the machine.” [13]

2.4.2 The rise of dance games

DDR and PIU

In the end no exergame achieved success till 1998 when Dance Dance Revolution (DDR) got released by Konami (see figure 2.3). The objective of the game was to press four different panels on a dance pad according to some visual cues while following the music’s rhythm. The game was initially released as arcade game but had its huge success only when it got ported to PlayStation in 2000 and became available to a significantly higher number of users worldwide.

Figure 2.3: Dance Dance Revolution [30]

A similar game was released in 1999: the Pump it Up (PIU) by Andamiro (see figure 2.4). Gameplay wise, the only difference between the two games were the position of the panels and their size. While DDR had the sensors over the four cardinal directions (up, down, right and left) the PIU had them along their bisectors (up/right, up/left, down/left, down/right, middle).

Figure 2.4: Pump It Up [68]

These two games are still alive today and newer versions are constantly being released for the arcade market.

2.4.3 Fighting mania

During the 2000 a fighting game and its sequel were also released by Konami: Fighting mania 1 and 2 (see figure 2.5). The game required the player push rubber panels that would pop out in patterns from a frontally positioned machine. Failing to hit them the very moment they were fully extended, would result in a penalty that varied based on the error. Despite being a fighting game and thus lacking in the musical compartment, the game can be considered a DDR for the upper limbs, due to its focus on speed, patterns and timing.[14]

Figure 2.5: Fighting Mania [14]

2.4.4 Dancemaniax

In the same year another relatively successful game, Dancemaniax (see figure 2.6) got released. The game can be considered an hybrid between the DDR and fighting mania and consisted in a rhythm game where the four sensors where placed on relatively wide plane and the user had to "press" (it used infrared technology) the proper one at the right time. The game also required to differentiate between the upper or the lower group of sensors, where the latter could also be triggered using legs, although it seems like it was more of a freestyle method than an actual strategy. No info was found about its lack of longevity, but, by consulting an expert in the field, it seems likely that the ridiculous appearance of the player during the game was a critical factor. In addition in that period music games were being released in mass so that some people refer to it as the "golden age" [4] for the genre and the dancemaniax didn't hold to the competition, especially that of the two main protagonist in the scene: the DDR as main dance game and the Beatmania as hands based rhythm game (this last game is played with a controller so it is not discussed as not related to exercise).

Figure 2.6: Dancemaniax [61]

2.4.5 Stepmania

In 2001 an emulator for rhythm games (games in which the user had to press keys following the music's rhythm) was released. Stepmania is a cross-platform, open source software that allows to emulate several music games, allowing anyone to play custom songs on PC as long a they can use a controller or, at least, a keyboard. [23]

2.4.6 ITG

In 2004 ROXOR Games released "In the Groove" (ITG) a game that, even more than the PIU, resembled the DDR since it used the same type of sensors positioning. Because of this, Konami filed for a patent infringement (also due the fact that ITG software was installed to some DDR cabinets) and ultimately won, acquiring all the right to the ITG and shutting down ROXOR. Luckily this didn't happen before June 2005 when the ITG2 was released [17]. ITG2 had USB slots to save players scores, play custom songs and make updates,too; with the software update "r21", it became possible to upload songs to the machine [16]. The possibility to play custom songs was a massive advancement but, between copyright issues and the Konami determined to eradicate the game, nowadays only a handful of private cabs of which most are running Stepmania (thus emulating the game) exist.

2.4.7 The rise and fall of console controllers

After DDR, the next groundbreaking technologies in the field were the Eyetoy by Sony, Nintendo's Wii and Microsoft's Kinect.

Eyetoy

Sony's Eyetoy was a PlayStation peripheral that made use of a camera and a microphone to detect the user's gestures. Unfortunately, the performance wasn't particularly good and almost all games for it were casual/family oriented, that is, a genre not much appealing to that of the hardcore gamers that were the typical users of the console, leading to the discontinuation of the peripheral [39].

Wii and full body movement games

The Wii is a console released by Nintendo in 2006. Its revolutionary aspect consisted in being able to play the game by performing actual movements: while the Eyetoy was just an optional peripheral, here the concept of movement was integrated in the very core of the console. Because of its user friendliness and the simplicity of several of its games, it had a huge success with the public [24], but, for reasons concerning Nintendo's business model, the console and its successor, the WiiU, ended up dying only a few years after the release [42]. Nowadays the console has been discontinued; due to this, it is only barely seen (e.g Santos et al. [134]) in research.

Despite the dying console some developer kept making some game. One case is Ubisoft that continued till 2020 to release newer version of what was one of the Wii's best selling titles: Just dance. An arcade version of the game was released in 2015 but didn't have much success. Two similar games, Danz Base and Dance Evolution were released respectively in 2015 and 2012, the second being a port of the the Xbox version (2010) [15] [12]. This type of game is historically important since it was the first exergame that required full body movements.

Kinect

The Kinect was an accessory for Xbox released in 2010. Just like the Eyetoy, it allowed players to play without even needing a controller trough the use of a series of sensors whose data would successively get elaborated by an AI in order to detect the movement [19]. Despite its huge success, wrong marketing choices and an unfortunate political event brought it to its demise a few years after the new Xbox model got released [26] [49]. Nowadays the Kinect production for Xbox is discontinued and its only used in research for its use in rehabilitation and computer vision.

2.4.8 Recent years

Mobile games and augmented reality

While all the major game console companies failed with their respective motion tracking devices, another type of exergames was rising. Due to higher availability of internet connection on smartphones and their increased use by the population, games like Zombies, Run (2012), Ingress (2013) and Pokemon go (2016) had a huge success. These mobile phone apps made use of augmented reality to set up the game in the real world. In order to play the game the user had to physically travel around cities and meet other people.

Switch

In the recent years, most of the exergame focus has been oriented towards the use of immersive virtual reality. That said, those are not the only ones worth mentioning. Through the use of its latest console, the Switch, Nintendo has launched some exergames on the market like Fitness boxing and Ring fit adventure. While this is not the main focus for the console, some of these games, especially the last mentioned, had incredible success [20].

New arcade games

In the arcade sector, aside from new versions of DDR and PIU, games like the Dancerush (see figure 2.7) by Konami (2018) and Kung Fu Panda (2014) (see figure 2.8) were released. In Dancerush the user interacts with a dance pad working like a touch screen and able to detect the position of the feet. Commands are given on screen following the music like every other rhythm game and are expressed in terms of foot to be used (right or left) and position on the plane parallel to the screen. Kung Fu Panda, instead, was released as a redemption (ticket) game. Because of this, despite having a strong potential as exergame (it could be considered an improvement of the Fighting mania, from the structural point of view) it cannot really be considered as such.

Figure 2.7: Dancerush [50]

Figure 2.8: Kung fu panda arcade [41]

Immersive virtual reality

As stated before, most of the recent exergames are published for VR. Holodance (2016) was the first rhythm game released for it and consists in an emulator of the popular free to play game OSU. Unfortunately, it never really gained any popularity. Another interesting game that was really never used, was an indie emulator of the DDR [51].

Beatsaber

The first rhythm game to really take off was Beatsaber (see figure 2.9) in 2019. Produced by Beat Games, it quickly gained popularity on the Steam platform becoming a well established title, to the point where even games that were older and decently rated like Audioshield are now often considered its copies. In Beatsaber the user has to slice red and blue cubes with a saber of the corresponding color; the movements, naturally, should follow the music [10].

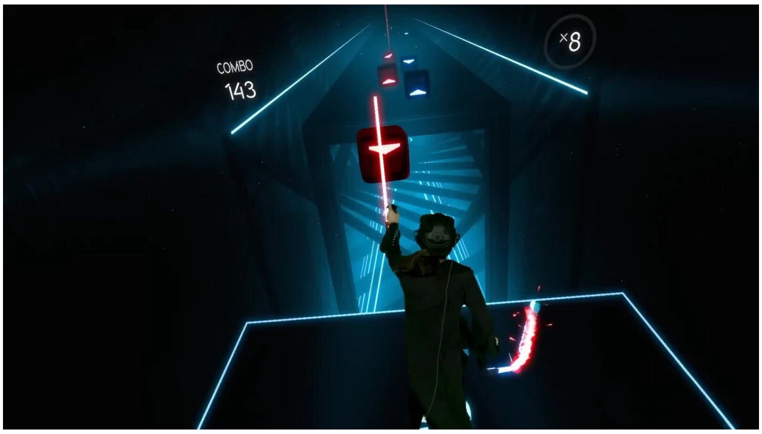


Figure 2.9: Beatsaber [8]

Harmonix

Another game worth of mention is Dance Central. This one is a VR version of the same game series published by Harmonix (developers of the famous Guitar Hero) and, just like Just Dance, requires the user to perform full body movements to play [11].

Other games

While music games are certainly a way to make the user move, this doesn't mean that other more direct approaches weren't used. Since the VR controller requires the user to perform movements in any game it allows, in theory, for at least low intensity PA regardless of the game. Also, following what was one the biggest hits for previous exergaming consoles, several sport and fitness games got released (e.g., Ohshape, 2019).

Rhythm horizon

Lastly it is worth mentioning the existence of Rhythm Horizon. The game can be considered as a 9 arrows variant of the DDR and gets most of its fame due to the Impulse Pad, a supposedly amazing dance pad whose release has been continually postponed till it's official abortion in 2020. This said, this game, together with OSU, can be considered as a precedent for the use of custom songs without incurring in copyright infringement.

2.4.9 Interactive fitness

So now, what happened to the old exerbikes? Adding games to fitness product and calling them exergames did not yield the desired effect of alluring fitness minded people. Because of this in the recent years a new term "interactive fitness" was formed to avoid the negative connotation that the word game had. Embedded exergames are nowadays a subcategory of the interactive fitness and the use in marketing of one or the other other term strongly depend on their sales target.

By analyzing the major players [59] in the IF industry, we can categorize its products in several categories based on their appearance and functionality.

Gym equipment

This kind of devices are the simplest and consist in normal cardio training equipment that uses the user performance as input to run either a game or a virtual simulation (e.g. you would see on screen yourself on a boat sailing along the river while using a rower (see figure 2.10 for an example)).

Figure 2.10: Hydrow rower [34]

Game walls, floors, rooms

These devices make use of the existing infrastructure and make it interactive. They can either project image on the desired surface or be mounted on it and require the user to perform actions reacting to visual and sound cues. Some examples are reported in figures 2.11 and 2.12.

Figure 2.11: Cardiowall Pro X [9]

Figure 2.12: T-wall 64 [36]

Boxing

Speciality of Nexersys, this method uses interactive boxing dummies to entertain and train the user. They can come in different shapes and structures (e.g. figure 2.13).

Figure 2.13: Nexersys Pro [48]

Brain + fitness formula

Produced by BrainFit, these devices cannot be considered original in their shapes or function but the fact that the user is supposed to use his brain (e.g. solving arithmetic problems) to play makes it an interesting product for children and elderly.

Climbing devices

There are many variants of climbing devices, ranging from customizable types that though the use of a treadmill or rotations allows for a "limitless" exercise (tough these can hardly be called "interactive") to more sophisticated ones that make use of lights to indicate a path. One example product can be found in figure 2.14.

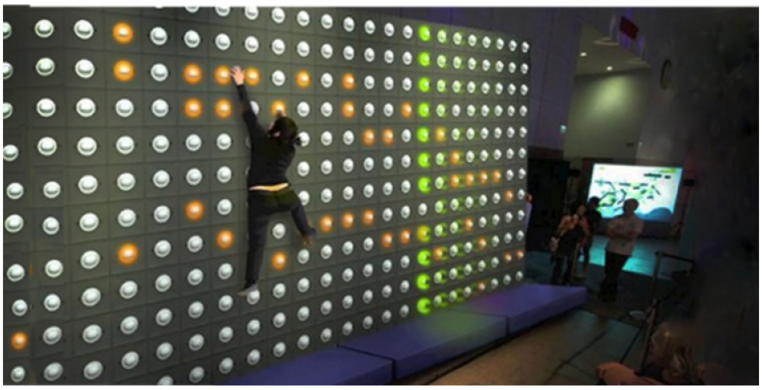


Figure 2.14: An example of interactive climbing wall [6]

Dance games

In order to approach a wider market games like Idance2 and StepmaniaX are sold as interactive fitness. Idance2 can be considered the same as DDR gameplay-wise, but it allows up to 32 user to play the same song at the same time trough the use of wireless dance mats making it extremely useful for collective exercise. StepmaniaX (see figure 2.15)add the middle panel as a command with respect to DDR and had its share of success in the community thanks to its high quality plug and play pads; before its release, most good home pads for DDR players were simply old, modified and fixed DDR arcade pads.

Figure 2.15: Stepmaniax [52]

Home gyms

Having a gym at home allows people to train whenever they want, save the bothersome travel to the gym ease up on the fear of the annual subscription commitment and avoid the judgment of their peers. Because of these reasons and their ability to keep the user in shape home gym gear saw an incredible increase in price and demand during the Covid-19 pandemic [5]. These devices range from normal gym equipment that is simply sold to privates (often as a cheaper, less professional version) to specialized and modular devices like Tonal. Tonal (see figure 2.16) is an AI powered IF device that has to be put on a wall. It offers various services like interactive lessons and different time of scored exercises for every part of the body[54].

Figure 2.16: Tonal [40])

Others

Devices than cannot be categorized in any of the above. Out of those most of them are fitness gear like weights or core training devices [35].

Important is to take into account that most of these devices can be interfaced with their specific fitness app.

2.5 Rehabilitation

An interesting application for VR exergames is rehabilitation (see figure 2.17 for an example). The use of this technology holds several advantages such as allowing patients to execute actions they would not be able to perform in real life due to their disabilities, providing immediate and clearer feedback and results and enhancing a patient motivation trough a fun activity. It can also be used in the emerging field of telerehabiltation to better monitor the activities.

Unfortunately virtual reality is still in its early stages in this field and many thing are still unclear like the presence of minimum requirement for the user to meet in order to take advantage of the technology and eventual differences in outcomes between semi-immersive and immersive VR [28].

The diseases for which VR is currently used are mainly Parkinson disease, multiple sclerosis, acute and chronic post-stroke, traumatic brain injury, and cerebral palsy [128]. The quality of the evidence about their effectiveness is still low [88], but the results are hinting toward positive results [28]. Also, a recent study about the difference between specific and non-specific VR rehabilitation for stroke patients revealed specific rehabilitation to perform better than common therapy and the last being better than the non-specific [113]. Unfortunately due the nature of the stroke, the same result is not guaranteed, at least with the same magnitude, for other diseases.

Figure 2.17: Example of immersive VR rehabilitation device [27]

Chapter 3

Materials and methods

The goal of this thesis was the development of an interactive fitness device focused on exercising the upper part of the body. The produced device had to be suitable for any age, body size, physical prowess and, at the same time, being enjoyable, stimulate the competition and capable of inducing people into its regular use.

3.1 Produced solution

Figure 3.1: Image of AIR ExDaMa.

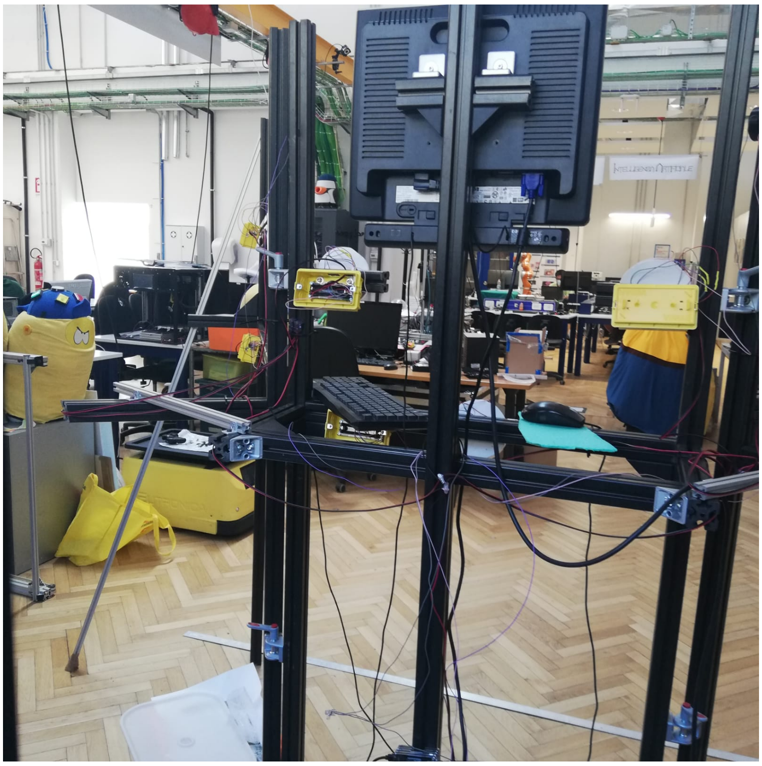


Figure 3.2: Image of the back of AIR ExDaMa.

AIR ExDaMa (Figures 3.1–3.2) is a rhythm game in which the user has to press seven different sensors according to visual cues that go along the played music and presents itself as a wide beam-based structure of human-sized height. Thanks to the sliding connections, every component can be freely moved, placed and removed. This grants the system the ability to adapt to most needs and makes the dismantlement for storage or transportation purposes easier. In addition, the angle between the two side wings is modifiable in order to adapt to the user's needs.

It's also important to notice that this type of design also allows for structures with shapes that are significantly different from the original one, thus making possible to play games that are extremely different from the original one. Thanks to this, several game modes can be implemented. For example, widening the aperture angle of the lateral sides and increasing the distance between sensors it's possible to force the user to execute wide movements while, by doing the opposite, fast but short movements would be required. The dual power supply (mains and battery) allows the sensors to be used even in remote positions w.r.t. the main controller, thus widening the application scope even more. The sensor's ability to gauge an hand's distance/applied pressure could also be exploited, if desired, in addition, LEDs are also present in every sensor in order to distinguish them, to make the game better looking and to use as troubleshooting tool.

The software necessary for playing is launched at boot so there is no need for inexperienced users to know about the underling drivers. That said, minimal knowledge about the system is necessary to manage and customize the game. Some of the most important features are the ability to add playable songs to the game, to change the sensors' calibration parameters and to access the raw sensors' readings. While it is possible to play without keyboard and mouse, they are necessary for every other task.

In order not to limit the users' musical choices, a software able to generate playable content from any audio file was created. The tool create five different difficulties for any given song and, for each of them, a level indicative of the expected challenge degree is assigned. In addition, another software able to convert four-sensors based Stepmania (.sm) files into N-sensors ones was created in order to let the user experience higher quality charts (the automated ones, aside from not being perfectly musically accurate, don't make use of the numerous supported special steps (e.g holding, avoiding, double pressing...) and timing variation (stops, speed changes)).

The reason why the four-sensors based files were used as source is because a significant amount of them are available online. In addition, content in other formats (e.g. from other games like OSU) or with different sensor count can easily be converted in the here required one trough already existing programs.

The reason, instead, for which the target sensor number can be defined trough a constant is to keep it flexible since, despite the fact that the original game has sevens of them, there is no constraint on that number.

Finally, the used game framework, Stepmania, is a highly customizable program. By simply adding a file in the correct folder, any part of the UI can be modified to better suit the user needs. In addition, the game offers many kinds of special notes and modifiers (they change the way notes behave on the screen) together with a significant amount of game options ranging from coin use (for arcade purposes) to the accuracy judgment window size, to basic sensor management and much more. Noteworthy, there are also the so called "Gimmick songs". These charts massively modify the way arrows appear on screen (normally in a funny/cool way) to increase the reading difficulty. In several cases the interface is also completely changed and the user is basically asked to play another game (e.g. avoiding cars on a three lanes highway). Everything always follows the music's rhythm.

3.2 Breakdown of the machine

3.2.1 Frame

The frame (Figures 3.1–3.2) is a 190 cm tall structure with variable width and height. It presents itself as a naked bars cluster of trapezoidal shape to make the sensors easier to press during the play. Every bar can host sliders on all sides, allowing every component to move with respect to each other, thus granting a high degree of flexibility. The variable angular connections are instead placed between the pairs of vertical bars at the monitor's sides, two for each one. The used material was a mix of plastic and bamboo fibers in order to avoid any possible interference with the capacitive sensors. Unfortunately, its resistance to deformations ended up being too low, as such, several reinforcement bars were added to reduce the movements that resulted from the interaction with the users.

3.2.2 Sensors

Figure 3.3: Image of a lighted sensor.

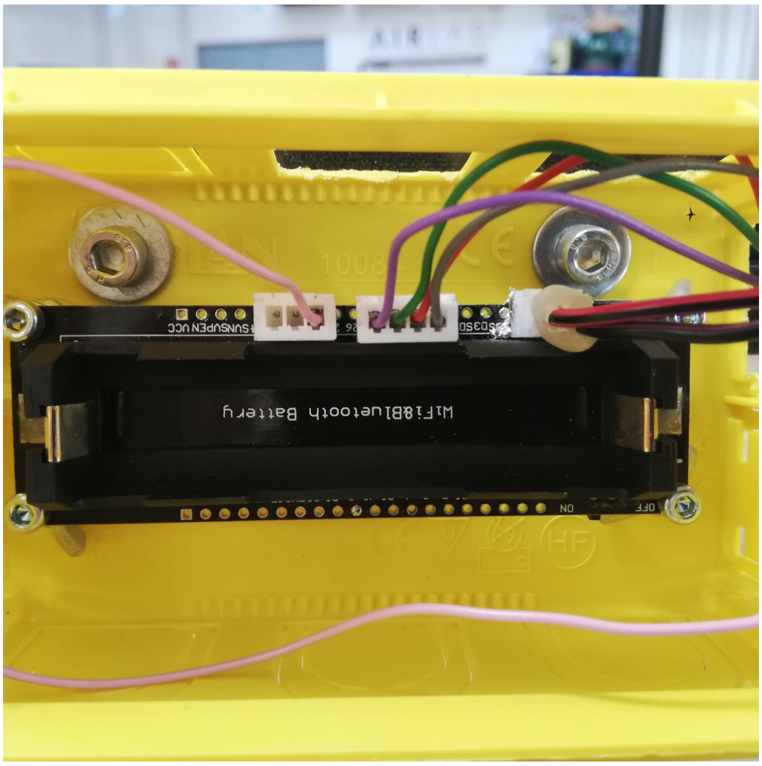


Figure 3.4: Image of an ESP inside its junction box.

Sensors

The sensors (Figure 3.3) are silicon discs with a metal wire woven inside. This structure grants them a capacitive property that is measured by a microcontroller. They can be freely placed on AIR ExDaMA's bars through the use of sliders.

Back covers

A circular sheet of material, with properties in between plastic and cardboard, was placed between the sensors and the bars in order to grant structural resistance to the silicon that is not in contact with the frame. The material and shape was chosen to minimize the risk of injury.

LEDs

Every sensor has a LED inside it. The LEDs not only makes AIR ExDaMa better looking, but also, serves as a troubleshooting tool since, based on their behaviours, an experienced user is able quickly notice if an issue arose and where.

ESP32s

Every sensor/LED pair is managed by a microcontroller which also has the duty of communicating with the main server (RPi). For such tasks a special ESP32 board was chosen (Figure 3.4). ESP32 chips have an integrated Wi-Fi function, dedicated pins for capacitive reading and cheap price making them the ideal solution for the project. In addition, the chosen board (on which the chip is mounted) comes with a LI-PO battery slot integrated. While this function isn't used for the current application, since the ESPs are powered trough the mains, it has been regarded as necessary in order to grant the possibility of using the sensors for other purposes (e.g. treasure hunt).

Case

In order to fix the ESPs to the frame, junction boxes (Figure 3.4) have been used.

3.2.3 Buttons

Figure 3.5: Image of a button inside its case.

To navigate inside the game menu, the ”Enter” and ”Escape” commands are necessary. Unfortunately, it was impossible to assign those keys to the sensors as they were used to play. To solve the issue, two appropriately encased push buttons (Figure 3.5) (managed by the Raspberry) were added.

3.2.4 Raspberry

In order to run the game and manage the sensors’ data coming through Wi-Fi, a mini-computer was needed. In addition, since Stepmania had already been identified as a possible choice to avoid making a game from scratch, a device able to run it was suitable. The Raspberry Pi 4 was found to be the cheapest solution that met the requirements.

3.2.5 Monitor

In order to communicate with the user, a monitor to display the game was needed. As a consequence, one was attached at a reasonable height to the middle bar of the frame. In addition, since the monitor came with integrated speakers, the need for an audio device was also fulfilled. Unfortunately, the volume coming from a 3.3V jack port was too low so an USB-jack converter to send signals from the RPi to the speakers was added.

3.2.6 Markers

In order to quickly notice if a sensor is out of position and to easily mount them back if detached, white tape (Figure 3.3) was added to mark the correct positions of the sensors. This was needed since, in order to keep the results comparable, a standard set up was required.

3.2.7 Stepmania

For the game, many options were taken in consideration. The final choice fell upon the rhythm game genre due to the high scalability of the difficulty level. While making a brand new game was a possibility, using an already done framework was certainly a better solution. As such Stepmania, a famous emulator for rhythm games, was used. Stepmania is known for being extremely customizable. This property was exploited to change the UI theme, note skins, score calculation and other parameters to suit the device.

3.3 Power supply diagram

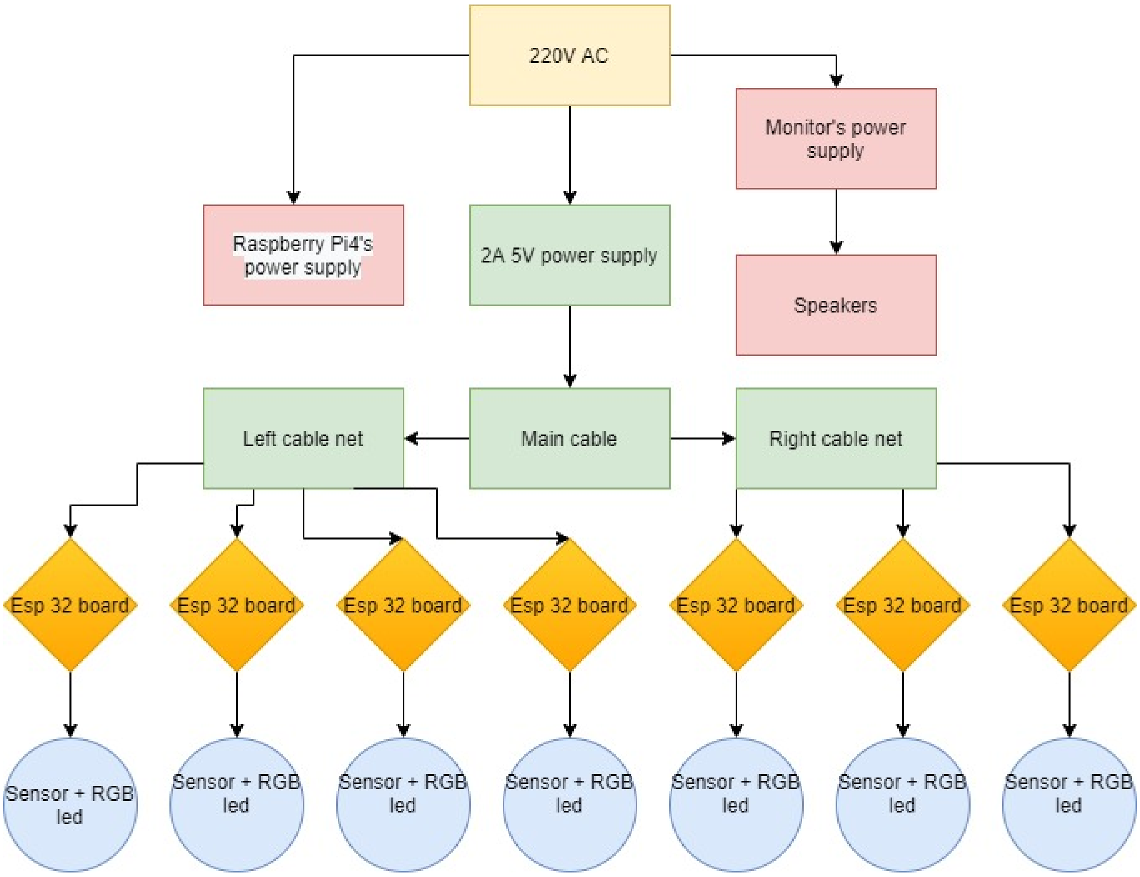


Figure 3.6: Diagram showing how every component is powered up.

Starting from a multiple socket with three slots, the RPi, monitor and ESP boards are each powered with their respective power supply systems (see Figure 3.6). In order to reduce the amount of cables used, a net was created to efficiently connect the ESPs with the power supply. These boards can also be integrated with a battery that is recharged when connected to the main power supply. Regarding the peripherals, an RGB LED and a capacitive sensor are powered by each ESP while the RPi takes care of two push buttons. The speakers are integrated with the monitor.

3.4 Software architecture

The software necessary to run AIR ExDaMa can be divided into four different categories: client, server, game and auxiliary tools

3.4.1 Client

The client code is run on the ESP32 modules. Right after booting, the microcontrollers fetch the calibration parameters from the EEPROM and wait till they can connect to the RPi's Wi-Fi network. Once the the link is established the sensors' calibration is performed. The used method compute the rounded average of the mode over five batches of twenty readings and consider such value as the expected reading if no user is interacting. The reason why the mode is used is due to the presence of random outliers that can assume any value lower than the real one at a given time. While all the initialization processes take place the LEDs are lighted up.

After the booting is done, the ESPs keep reading their sensor's capacitance (measured in symbolic units). In this phase the sensor has two states: pressed and released. In order to pass from a state to the other, two consecutive readings under (for pressing) or over (for releasing) the respective state threshold must be read. Those values are computed as "environmental capacitance value - user defined calibration parameter". When the sensor is "pressed" the LEDs are lighted up. Whenever a state change happens the ESP sends a message to the raspberry trough UDP containing an integer number. The number is the sensor ID (starting from 0) plus the total number of existing ID's (defined as constant) in case the sensor is getting released. This way the RPi is able to understand which sensor got triggered and in which way while keeping the data transfer to a minimum. While the UDP is known for not being reliable, a test on 100k packets in rapid succession revealed a success rate of 100%, as consequence, the risk of losing information was deemed negligible. Finally, between every read of the sensor, the ESP checks if there are messages for him from the RPi. If there are, the reading of the sensor is halted and the new request is processed. While the operation takes place the LEDs are lighted. The operation implemented thus way are:

- Modify the calibration parameters (either temporarily or permanently)
- Change the calibration mode (in addition to the described way to compute thresholds, the system allows for absolute values to be used instead, tough it's not recommended).

- Recalibration (compute again the environmental capacitance).
- Enter diagnostic mode (the ESP start sending unfiltered sensor readings to the RPi).

3.4.2 Server

The server code is located on the RPi. The program is launched at boot and keep checking for data from the ESPs. If a packet is found, its message is decoded to obtain the sensor ID and new status. Then, a command to emulate the press (hold)/release of the alphabet letter corresponding to the obtained ID (starting from "a"=0) is given. In the same way, in case of a detected potential change on the button pins, an interrupt is triggered that emulates the "Esc" and "Enter" buttons. Finally, some special commands were added. If the "Esc" button is pressed while the "Enter" one is held down, a recalibration request is sent to all sensors. If, instead, some defined sensors (2 and 4) are pressed while the "Enter" button is held down, a double arrow up/down is emulated. This last command was necessary due to a bug for the used Stepmania's game mode.

3.4.3 Game

As previously stated, Stepmania is used a game and it's configured to be executed at boot. Another software, OutFox, has also been installed on the RPi. OutFox is a Stepmania's github branch focused on the engine optimization. This program is not only compatible with most Stepmania's skins but is also still being actively developed and maintained on several operative systems and devices.

3.4.4 Utility tools

In order to improve the overall experience and to make the system more user friendly, several QOL tools were added to the RPi.

Calibration script

The calibration script can be used to modify the calibration parameters and modality of each individual ESP. Provided with a simple GUI trough the use of the guizero [1] library, the software not only keeps track of the current state of the parameters for all sensors, but it also allows to choose between testing or saving any made change. A small drawback is that no confirmation message is sent back by the ESPs but even in the case of the unlikely failure, it's easy to notice the fault due to a sensor's LED not lighting up. Important is the presence of a file where the sensor colors, in order by ID, are listed. Those data are used by the GUI to allow the user to identify the correct sensors even when they are not placed in order on the frame.

Diagnostic script

In order to properly analyze oddly behaving sensors, a dedicated software was added. The tool simply sends a message to all sensors requesting them to enter the diagnostic mode. While in that status, all the reading of the sensors are sent almost unfiltered. Only exceptions are:

- Library error -1: 253 is sent
- Library error -2: 254 is sent
- Any value ¡ -2 and ¿ 252: 255 is sent

All the readings are then printed on screen. Due to the working methodology of this script only one ESP can be on at a given time to get a meaningful reading. Finally, no exit condition is provided for this mode so restarting the ESP is necessary or it to work properly again.

Quick-launch scripts

In order to allow the user to use utilities without having to navigate in the RPi folders or use the command line, quick-launch shell scripts were added to the desktop. In addition, the first letter of their name has been set up to be a letter between "a" and "g" (the letters emulated by the "server" code) so that it's possible to launch them without a keyboard. Same thing goes for the shutdown script, thus preventing the user from having to take out the power from the RPi to switch it off in absence of keyboard.

3.4.5 AI

One the main objectives for AIR ExDamA was to be customizable and we wanted to remain true to this even regarding the game's content. Since Stepmania doesn't come with default playable songs (aside from three test tracks), it's up to the user to add them. Unfortunately, creating a new chart from an audio file is a hard and time consuming experience and, in addition, there could be issues regarding copyrights if shared since, in order for it to be legal, both parties have to own the right to that specific audio file (and not the song). In order to address the issue, the creation of a program to execute such task automatically was decided.

First of all, the existing software for such task was tested but none of them produced musically accurate results (notes placement was seemingly random) or was able to work on modern systems due to being too old.

Neural networks

The then first thought approach were neural networks due to their grey box modelling nature. A research in literature showed how the problem in question (obtaining the user perceived beats, scaled by different difficulty, from an audio file) was something in between the musical onset detection and the automatic music transcription, with the added condition of perceived (and not real) notes and presence of different rhythm interpretations (difficulties). To be more precise, in an ideal way, the program had to be able, given an audio file, to identify at any instant all the different rhythms and choose the one that better fits the current difficulty, returning a list on the time stamps of the chosen notes.

Further research brought to light three papers that performed the same or similar tasks [116] [110] [126]. After a careful reading two of them were discarded while keeping only the general concepts in mind. This was due fact that the amount of information reported wasn't nowhere near enough to produce a similar model while the third [116], despite some ambiguities, was found to be a good starting point. The data preprocessing and the model were coded as closely as possible to how was done in the paper, unfortunately, no result of acceptable quality was found. Successively, many modifications were done, from hyper-parameters tuning to adding new gimmicks that showed good results for similar tasks (and that were published after the paper) or that were tough necessary to get an improved state of the art. Unfortunately time went by and no satisfactory result was obtained.

Onset detection functions

Since time was ticking and results were necessary, alternative methods were investigated. In the end, a program able to exploit the onset detection functions present in the Essentia [76] and Librosa [117] libraries to produce playable songs with different difficulties was created. After careful evaluation of the results, an even mix of the probability distribution generated trough Essentia's ”complex” [74] and ”melflux” [89] methods was used to obtain the musical onsets. The various difficulties are then obtained from the successively predicted onset list. From the highest to the lowest:

- Expert: The unfiltered predicted onset are coupled 1:1 with a note in the game.
- Hard: Note sequences with constant time interval are individuated and one every two of them is removed. This method reduce the difficulty while leaving the rhythm almost unchanged.
- Medium: One note every two is removed. In this case the rhythm starts to get affected. The reason why this approach was used is that the "Expert" prediction is already incorrect and can often mix several instruments rhythms (since all of them can be independently recognised as onsets). As consequence, generating difficulties from such data trough reduction won't, in any case, give excessively good results, especially if the cut has to be significant (like for lower difficulties). In conclusion, since the expected results were not that good in any case, a simpler filter was adopted.
- Easy: One note every four is kept.
- Beginner: one note every eight is kept.

As one could expect, the predicted average onset density significantly varies between songs. As such, the used notion of difficulty was not enough to properly communicate the degree of challenge. This issue is resolved by Stepmania trough the use of an integer number called "level", which is positively correlated with the difficulty.

This value, is normally given by experienced players after a careful analysis of the song. Unfortunately, since the game type is new and there is no expert player for it, precisely and automatically determining the level was a difficult if not impossible task. For such reasons, the level was decided to be computed trough a non-linear function with the average number of steps as only variable. The used formula tries to approximate the output level with the one that would normally be given for an ITG (most used Stepmania mode) song. After computing the average number of onset per second for a selected difficulty, the level is assigned trough a threshold approach according to the numerical series: X2=X1*(B1+1) and B2=B1*K. The values for X1, B1 and K were empirically determined in order to meet the following requirements as closely as possible.

- Songs one level apart are more than twice as hard (like is it for four-sensors songs). In order to satisfy such condition, the increase of the average number of steps per second has to decrease over time (as such

K¡1). This is due the fact that speed is something that gets increasingly hard to improve.

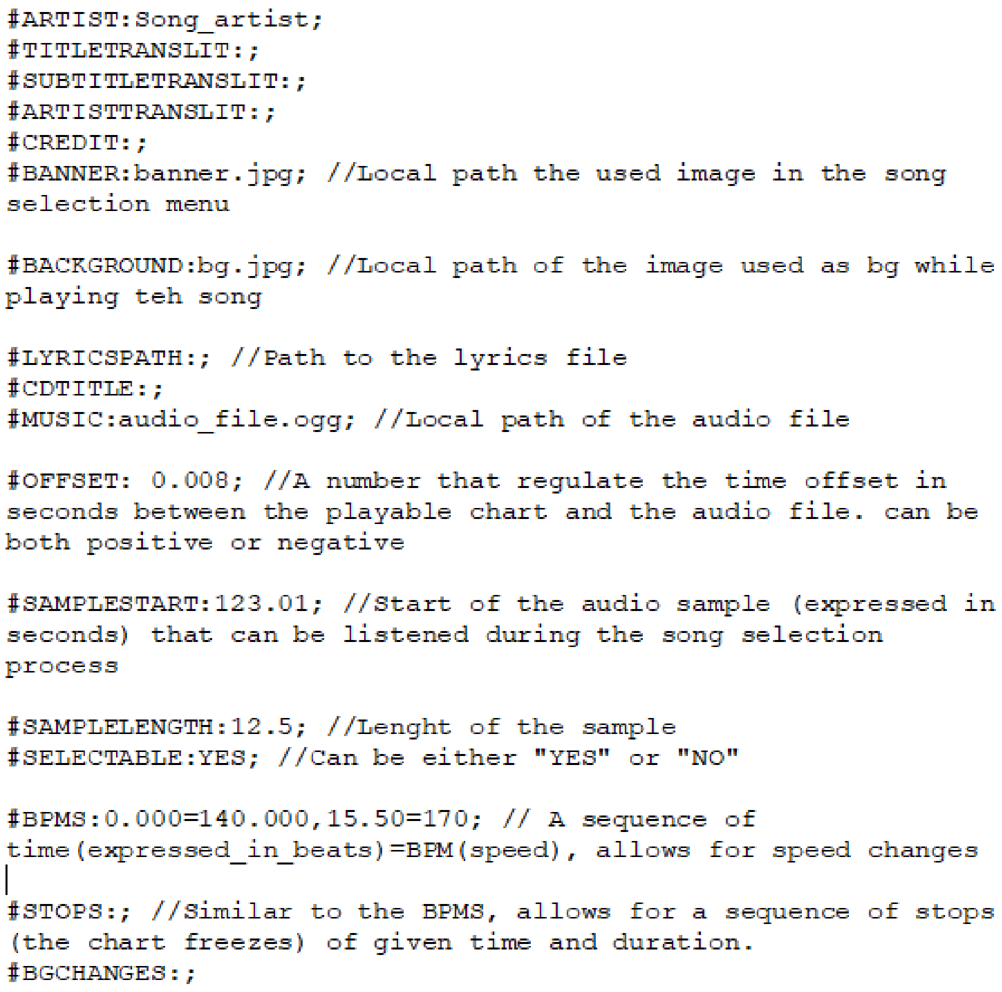
- Values inside the chosen output level range (1-12, all harder other songs are rated as 13) must be always growing, with a given initial (1/3) and final (6, approximated) value.

After everything is computed, the output files are written out in the .sm (Stepmania's format) extension with the arrows' positions (which sensor is to be pressed at a certain time) randomized. In addition, to simplify the game for beginners, the lower the difficulty is, the more it has a skewed probability distribution that prioritize the inner sensors. Hard and Expert difficulties have uniform probability. The final result is a folder with all the output songs already organized so that that it can be simply copypasted into the appropriate Stepmania directory for the use.

Song converter

As previously mentioned, a software able to convert four arrow songs into N ones was added. The process of the program is simple: it replace all the .sm files in the input directory with a new version with same header but different charts (four arrow ones are converted while all the others are discarded). The charts are faithfully converted from a format to another without any changes in timing and note type (tough their position are randomized since no meaningful relation can be inferred in that sense). Only exceptions are "hands". "Hands" is a term used to indicate when three or more arrows are supposed to be pressed at the same time. Due the nature of the game, such task is impossible so a filter that removes commands based on their type (following some custom settings of importance) was added to guarantee the charts' playability.

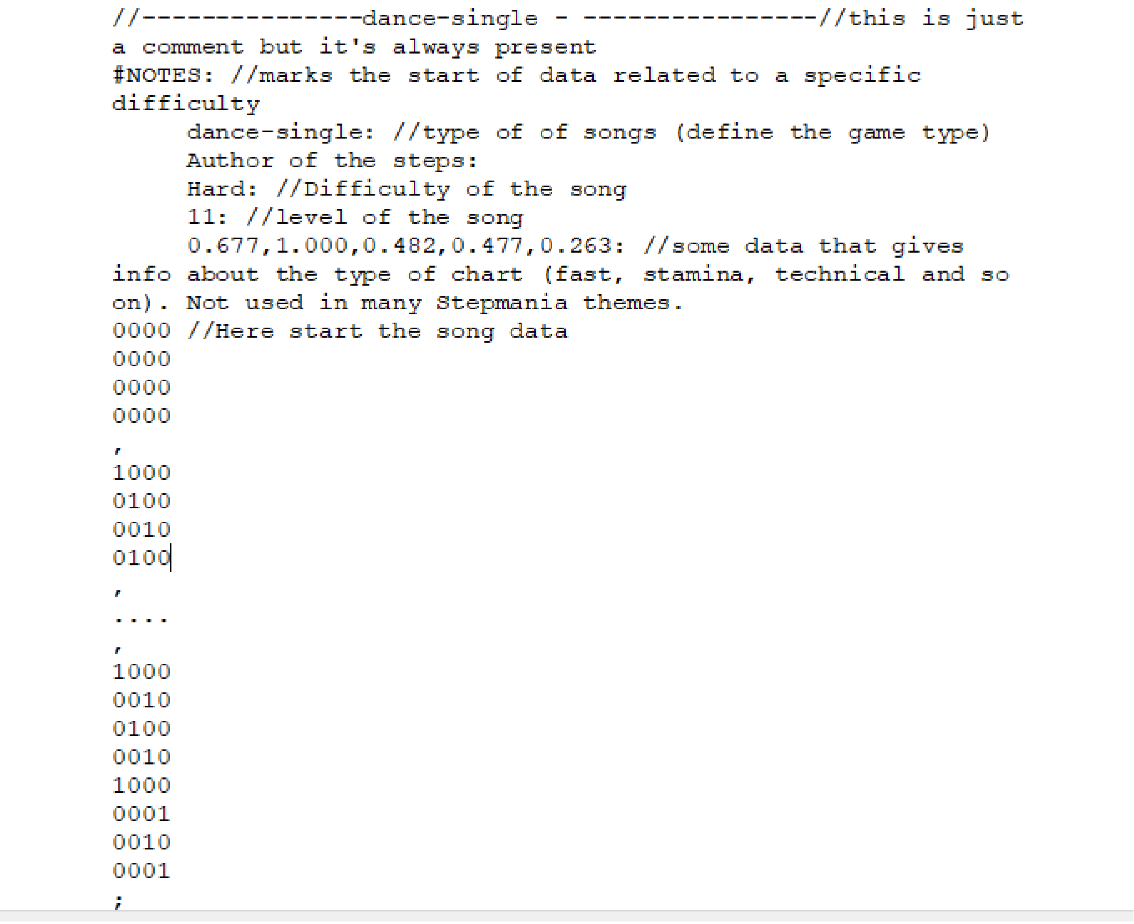
In order to understand how the filter works, it's necessary to know how the .sm files (Stepmania's data files for songs) are structured (one file one song, many difficulties).



```
#ARTIST:Song_artist;
#TITLETRANSLIT:;
#SUBTITLETRANSLIT:;
#ARTISTTRANSLIT:;
#CREDIT:;
#BANNER:banner.jpg; //Local path the used image in the song
selection menu

#BACKGROUND:bg.jpg; //Local path of the image used as bg while
playing teh song

#LYRICSPATH:; //Path to the lyrics file
#CDTITLE:;
#MUSIC:audio_file.ogg; //Local path of the audio file

#OFFSET: 0.008; //A number that regulate the time offset in
seconds between the playable chart and the audio file. can be
both positive or negative

#SAMPLESTART:123.01; //Start of the audio sample (expressed in
seconds) that can be listened during the song selection
process

#SAMPLELENGTH:12.5; //Lenght of the sample
#SELECTABLE:YES; //Can be either "YES" or "NO"

#BPMS:0.000=140.000,15.50=170; // A sequence of
time(expressed_in_beats)=BPM(speed), allows for speed changes

#STOPS:; //Similar to the BPMS, allows for a sequence of stops
(the chart freezes) of given time and duration.
#BGCHANGES:;
```

Figure 3.7: Header of a .sm file

In Figure 3.7 a typical .sm header is shown with added comments to explain what the various voices are used for. Most of the hashtags are optional and several are sometimes not even present. The goal of this file section is to provide information about the song (that is then available to the player during the game), add some graphic elements (e.g. background) and set the timing relations between the encoded steps and the audio file (e.g. offset).



```
//---------------dance-single - ----------------//this is just
a comment but it's always present
#NOTES: //marks the start of data related to a specific
difficulty
     dance-single: //type of of songs (define the game type)
     Author of the steps:
     Hard: //Difficulty of the song
     11: //level of the song
     0.677,1.000,0.482,0.477,0.263: //some data that gives
info about the type of chart (fast, stamina, technical and so
on). Not used in many Stepmania themes.
0000 //Here start the song data
0000
0000
0000
,
1000
0100
0010
0100
,
....
,
1000
0010
0100
0010
1000
0001
0010
0001
;
```

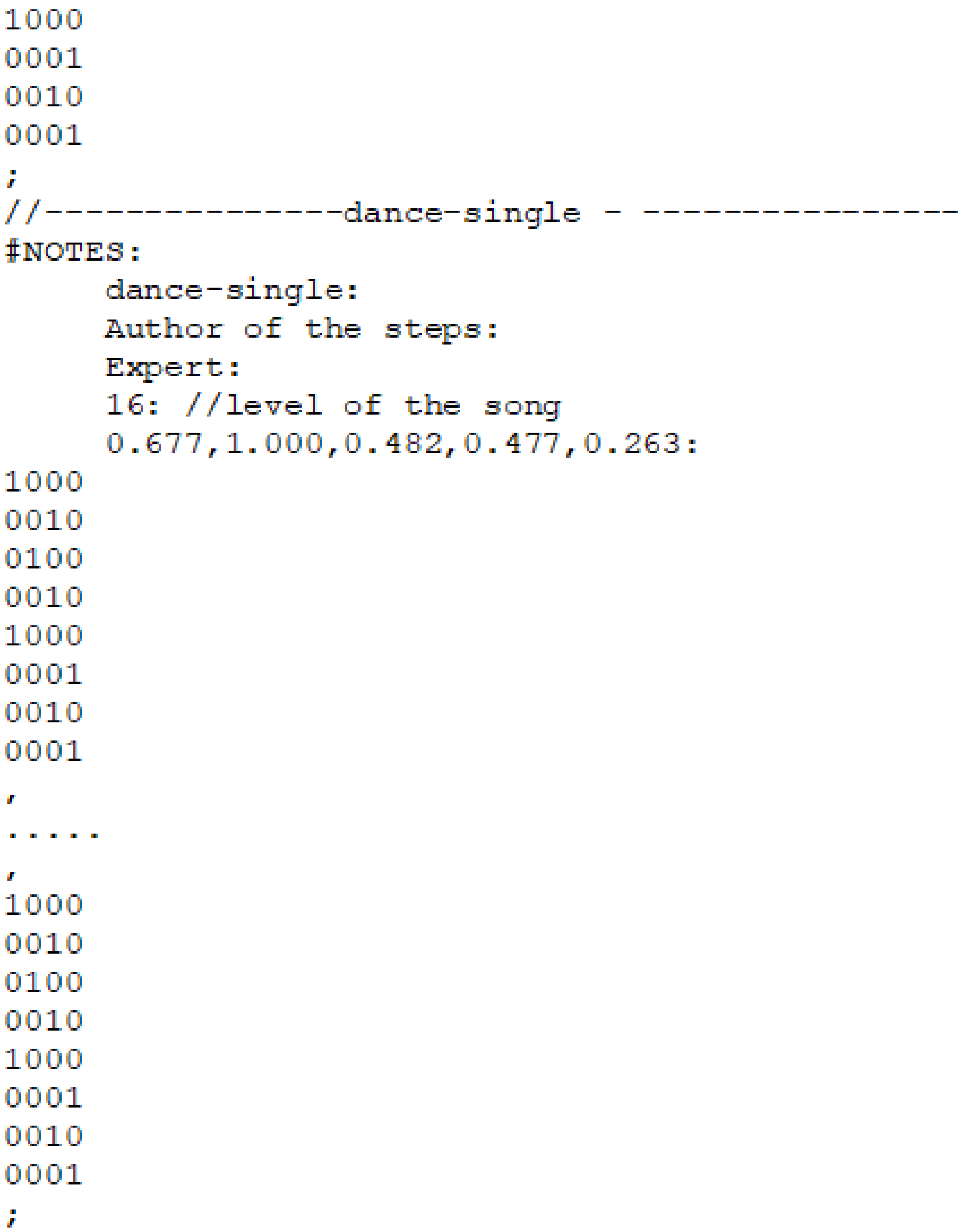
Figure 3.8: Example of an encoded chart.

In Figure 3.8 is shown how, after the header, the various song's difficulties are encoded. After a comment line indicating the type of game the following encoded chart is for, the "#NOTES:" line marks the start of the data. Some information regarding the chart is then convened to the game over the span of five lines before getting to the actual steps encoding. The encoding is divided in musical measures (separated by a comma) and the end is marked by a semicolon. Every measure is represented by a sequence of lines of N characters, where N is the number of different inputs for the selected game mode (e.g. N=7 for AIR ExDaMa standard setting). Every measure is divided in quantized and equispaced time intervals (lines). That means that a measure might be either represented (for example) by sixteen lines (each covering one sixteenth of it) or by twelve, depending on the needs of the maker to better fit the audio rhythm. While the number of lines can be chosen at will, it has some restrictions since the choice possibilities are limited to set values. Normally charts only uses the lower available values, meaning 4,8,12,16,24, and 32.

After setting the timing for the notes, is also important to describe the position and the type. This is done using trough the lines' values. The position of a character on a line represent a position in the game interface (e.g. a specific sensor/keyboard key) while its value represent its type, according to the following list:

- 0: nothing
- 1: tap note
- 2: start of a hold note
- 3: end of either a hold or roll note
- 4: start of a roll note (the user has to keep pressing)
- M: mines (the user has to avoid triggering them)

While Stepmania support other special notes, only these are normally used.



```
1000
0001
0010
0001
;
//---------------dance-single - ----------------
#NOTES:
     dance-single:
     Author of the steps:
     Expert:
     16: //level of the song
     0.677,1.000,0.482,0.477,0.263:
1000
0010
0100
0010
1000
0001
0010
0001
,
.....
,
1000
0010
0100
0010
1000
0001
0010
0001
;
```

Figure 3.9: Image showing how files continue after the first chart is finished.

After the first chart is finished, it’s possible to add more just by adding a new ”#NOTES:” like shown in Figure 3.9. No special character is used to signal that a chart is the last (the file simply end).

Now, because the holds and rolls are encoded as start-finish with, as consequence, zeroes (no command) in the middle, finding out where three or more arrows are present is not immediate. To solve the issue a buffer based method has been used. Two buffers were used that could be either disabled (no hold/roll present) or active. When a hold/roll is encountered and not discarded (due to more then three commands present at the same time), its position in the original chart and in the newly created one is then stored in a disabled buffer (making it "active"), thus allowing to keep track of its presence (allowing now to successfully identify when too many commands are present) and position. This last information is used to avoid accidentally placing another command in the middle of an hold/roll on the output chart.

3.5 Communication diagram

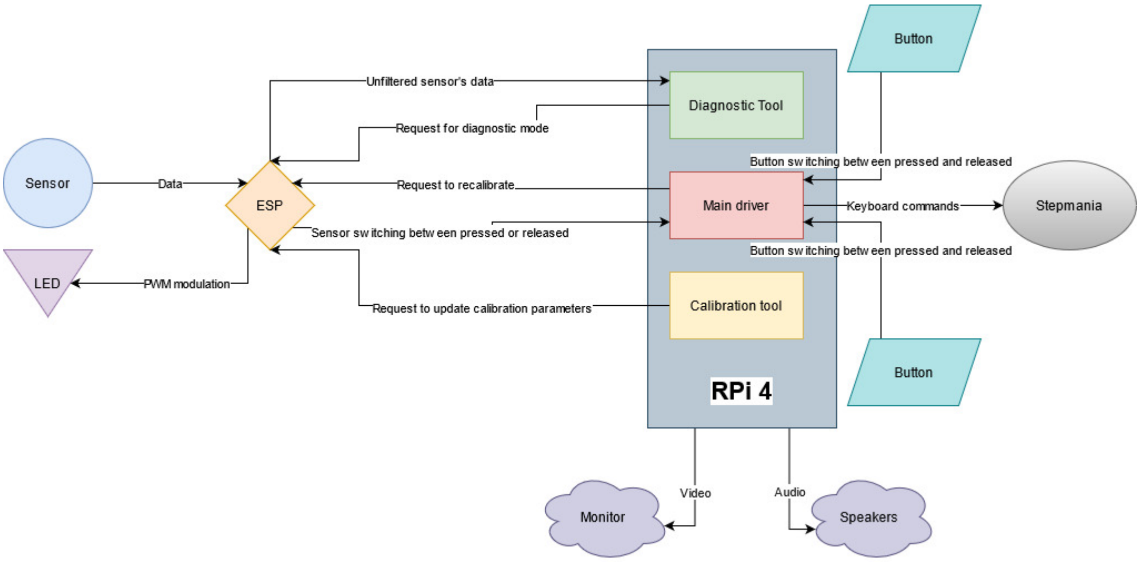


Figure 3.10: Diagram showing how the various components communicate between them.

In the diagram shown in Figure 3.10 only one ESP is shown since adding all seven of them resulted too confusing. Each ESP reads data from the respective sensor and, according to some rules, controls an RGB led. Whenever a sensor is found to be pressed or released, a message containing the ESP ID and triggered/released status is sent trough Wi-Fi to the RPi. There, the main driver reads and interprets the message, and simulates the pressing/releasing of a keyboard key associated with the sensor. The message is then passed to the active window (that is supposed to be Stepmania) and used as game command. The same program also takes care of the two push buttons trough an interrupt routine.

Only one driver can be active at the same time so, to use the auxiliary software, it's necessary to shut down the main driver. The recalibration software simply send a request to the ESPs to update the calibration parameters. The Diagnostic driver instead puts the ESPs into an infinite loop where all read data from the sensor is sent without filters. In order to have a readable output, only one sensor should be active when doing this and it must be restarted after the check is over.

Chapter 4

User Test

4.1 Objective of the test

Even after a fully working prototype was created, many questions were left unanswered. In order to obtain consistent data about its usability and likability, a test with annexed questionnaire was set up. The main objectives were the followings:

- Understand the likelihood of people using the device in relation with some characteristics of their personality and tastes.
- Test the intuitiveness of the UI and the ergonomics of the system.
- Gather opinions and suggestions about the aesthetic.
- Grade the quality of the AI.
- Confirm the technical performances quality on a wider environment.
- Verify that the system is actually easy to customize.

4.2 Testing method

Every person that took the test would be firstly asked to sign an informative consent about the use of the data from them provided in an anonymous form. After that, a brief explanation about the game mechanics and commands would be given and the user would be then asked to reach the playing phase without any help (starting from the main menu). The subject would be then asked to play two songs from the AI stepped ones and then one from the converted ones. The first ones were told be located in folders starting with "A-". After the playing phase the users were asked to, in order, regulate a sensor's, a bar's and the monitor's height. Lastly, a questionnaire regarding their experience was submitted to them.

4.3 The results

4.3.1 Premises

Before talking about the results it's necessary to underline that many factors of bias and confusion were individuated in this test. First of all, all the test subjects were found in AIR and adjacent laboratories (all related to AI and robotics), thus creating a biased sample in terms of interests and age.

It has also been noted that some of the provided answers were, in some cases, too much oriented toward giving the work a positive evaluation. As consequence, all the obtained result had to be questioned. In addition, several users answered open questions incorrectly. In many cases, this was due their misunderstanding of the meaning of the question but in others it was a clear sign of them not fully reading it or not being able to understand it (the questionnaire was provided in English for everyone).

Finally, the words used to guide people trough their experience and the suggested difficulty levels for the played songs changed over time to take into account observed fallacies.

4.3.2 Likeability

The results obtained in this section are extremely positive, to the point where it's almost certain that a significant bias is involved. With almost unanimous score of 4/5 when asked if the game was fun, 92% of the people would play the game if found in a premise, 68% would play it regularly if free of charge and 64% would like to play it till it become physically exhausting. While this data is completely unreliable, a few thing were noted observing the answers user by user. First of all several people who were "supposedly" inclined in playing the game regularly, didn't want it to become an exercise. Those people were typically the ones that practiced minimal physical activity. While this could be considered a partial failure, it's to be taken into account that after getting involved into a such game type with an active community the possibility of them changing idea is not low. Another interesting phenomena is that many people that performed significant physical activity showed no interest in playing regularly but affirmed to be willing to play it as a form of exercise.

4.3.3 Aesthetic

Comments about the aesthetic seemed instead more reliable, probably because there was no way to give it a good evaluation. Regarding the first impression, the opinions were various and contrasted, with assumptions about the game being easy/hard being pretty common. Looking instead at the suggestions on how to improve it, ideas all converted into the same, known, issues. Common critics were about the barren, empty, unstable structure, the lack of colors and the small monitor. All those things would require a significant increase in price to be improved so they were discarded (tough some bars could, in theory, be painted to add more color). In addition, several people asked to have the LEDs turn on when the sensors gets pressed or when they need to be pressed. While the first request was already implemented and people simply didn't notice (maybe more/better LEDs as improvement?) the second has completely been disregarded because impractical, annoying at high difficulties and finally impossible to realize without touching Stepmania's source code. Finally, some people asked for the sensors to be more intuitive respect to the showed commands. The issue was partially addressed with printed instructions.

4.3.4 AI grading

Regarding the AI evaluation, results are not to be considered reliable since a lot of people didn't seem to have actually understood the question correctly. In addition, due the way songs are charted, lower levels have lower sense of rhythm. Nonetheless the results were more or less as expected with 16% voting 2/5, 36% voting 3/5 and 40% voting 4/5.

4.3.5 Technical performances

Several users reported unreliability of the sensors and presence of input delay. These in formations differ from the results obtained from an expert user that, as long as the sensors were regularly calibrated, was always able to effectively trigger them. Regarding the input delay, while it does exist due to the way the system works, no proof of it being perceptible and significant was found even after analyzing in game timing results table. Due to the information contrast, the issue was further investigated by directly asking the subjects. What transpired was that people didn't take into account the fact that it was necessary to "learn" how to properly press the sensors and the slight differences in calibration aggravated the situation.

Input delay

The cause of the perceived input delay was revealed to be the different sensibility of the sensors. This issue is related in part to their physical difference (especially since they were handmade), to the baseline drift but also to the low sensitivity in the used working point, so that fine calibration was impossible. As consequence some sensors could be triggered at higher distances if the hand was put in certain ways, confusing the users.

Reliability

Regarding the reliability of the sensors, the fault is found, first of all, in the way users pressed them. While some people seemed to play whack-a-mole, others tried triggering the sensors with their pinkie. With the currently used sensors it's impossible to reach that degree of sensibility (and not wanted since using a single finger is likely to cause injury). Another reason for the lack of reliability was that, if a few sensors were triggerable in a certain manner, the user would assume (tough, in theory, is not wrong) that all of them were usable in the same manner, thus ending up not being able to press some slightly less sensible sensors. As consequence, the issue can, again, be traced back to the different sensibility of the sensors.

4.3.6 UI

The test was done using the "simply love" theme skin for Stepmania. Unfortunately, being tailored to answer the needs of experienced players, many people had trouble reaching the playing phase without any help. In addition, several people had the instinct of pressing "Escape" when asked to change song folder, thus terminating the game session and going back to the main menu. While this might only related to them trying to figure out how to execute the task given by tester, is, nonetheless, a potential flaw.

4.3.7 Ergonomics

No user reported feeling pain in any way and for any reason during the test. There was also an almost unanimous vote about movements being comfortable. The exceptions were:

Middle sensor

A single user reported difficulty pressing the middle sensor due it being too low for his height. This was most likely caused by the fact that the person used the palm of the hand to trigger the sensors. No other subject with similar or higher height reported such issue.

Lateral sensors

The far right and far left sensor positions have been object of contempt since the start, with people saying that it was hard and uncomfortable to press them. Further investigation revealed that the issue wasn't really lying in the fact that they were physically hard to reach but in the fact that the users didn't know where the sensors were placed due to them not appearing in easier difficulties and not being the player's field of view.

4.3.8 Customization

Most users encountered medium to low difficulty in customizing the frame, with the monitor always being considered a bit harder to fix. Nonetheless, it has been observed a strong correlation between ability with the allen key and how easy they performed task. Only one user was unable to adjust the monitor while another needed help due to its weight.

Chapter 5

Conclusions

5.1 Recap of the work

The objective of this thesis was the realization a new prototype of interactive fitness device. Toward such goal, a fully customizable physical frame and the necessary software to run the electronic was created and tested till a working machine was obtained.

AIR ExDaMa successfully resulted in a fun device that allows for the user to perform at least light/moderate physical activity (no user managed to get to an intensive level but no reason for which it should be impossible to achieve has been identified). The device is easily customizable in almost every aspect, ranging from the shape, to the sensors' positions to the software itself and new game content can be easily created trough the given software. In addition the modularity of the sensors (they can be detached and powered trough batteries) allows them to reused for many kind of applications. Finally, the significant number and the wide distance between the sensors allows for extremely complex movement (that require the control of almost every body part), thus preventing the game from moving into the direction of a simple stamina/speed test like several other games,and preventing this way the user from getting bored after getting good at it.

5.2 General observations

As of now the device is not too beginner friendly due the weak nature of the frame and the sensors being harder to be correctly pressed than they look. On the other hand, once an user has obtained a certain degree of experience, it is possible to reliably use the machine without having any kind of issue, thus making such result acceptable as the first attempt.

Overall the results can be considered satisfactory. While several issues are indeed present, considering the context of the work it can be said that the outcome is acceptable. Nonetheless some quick changes could be made in the future to further improve the system.

5.3 Possible future improvements

5.3.1 Sensor position

While the position of the sensors has been deemed satisfactory, the debate over the position of the lateral ones is still open. On one side an experienced user reported them to be successfully more tiring at a muscular level respect to the others. On the other hand, too many test players had issues with them and since their position is extremely close to the player shoulder line (those sensors must be in front of the user an not behind to avoid being uncomfortable and potentially harmful), shifting them forward by a few centimeters is definitely something that could be done.

5.3.2 Tutorial

In order to improve the experience for new users, letting them play around with sensors for a bit before playing or adding a tutorial song and detailed instructions on how to press the sensors might be a desirable improvement. Originally suggested by a test player, the first method had already been used in the last few trials and seemed to yield good results.

5.3.3 Advanced filters

In order to maximize the polling rate and minimize the input lag, the used digital filter for processing the capacitive data is extremely simple. Since the performance of the ESPs seemed to be high enough, the use of an advanced filter to ignore the baseline drift (and maybe even eliminate the need of recalibrating constantly) could be tested. A possible trade-off solution consists in the use of a circular buffer that gets filled with capacitive reading if all values in the buffer at a given time have the same value Q that differ from the current baseline for less than P, Q becomes the new baseline. For this filter to properly work, in addition to proper parameters choice, it will also be necessary to add an outlier filter, maybe of differential nature (e.g., if two consecutive readings have a difference ¿ R and the past value was deemed ”fine” then the current value s an outlier).

5.3.4 Beginner friendly sensors

While a better filter and a tutorial will definitely help in having more accessible sensors, this won't definitely be enough to make them usable by every beginner user. To solve the issue a brand new design (not even necessarily capacitive) with higher sensitivity and stronger discrimination to the touch is most likely necessary.

5.3.5 Frame stability

The physical bar frame is not perfectly stable. Unfortunately to solve the issue either more bars/weight have to be used or the material has to be changed, thus incurring in a significant cost in both cases.

5.3.6 Game theme

The used theme skin for testing has been found by many users too hard to use without help; as such, it might be proper to swap it with a simpler UI, even if this might mean losing some functionalities.

5.3.7 Notes' skin

Despite the skin used for representing the commands during a song (see E being rational and relatively intuitive, it has been proven of being not immediate. While some people are fine, many users, even experienced ones (with highly reduced frequency), tend to wrongly interpret the command thus pressing the wrong sensor. Unfortunately, even when asked, no one was able to give tips on how to improve it leaving the matter open for more insights.

5.3.8 AI

While the current autostepper produce acceptable results, it's still too naive and might be further improved. While we failed with the NN approach, literature showed some results, so going back to a machine/deep learning method is definitely a possibility.

5.3.9 Automatic grading of songs

The current way automatically generated playable song is pretty naive since it not only consider the average number of commands per seconds as the only parameter, but also tries to stick to the four arrows difficulty scale that has been observed to have an unnecessarily big difficulty gap between adjacent levels. As a consequence, a wider and more refined scaling method might be necessary. One good way might be creating a formula that in function of the required movement and time given for its execution assign a cost to every arrow. The total amount will then be averaged by the number of commands. Some weighing factor that takes into account fatigue for higher levels might be necessary. While this method can definitely produce human level accuracy, it requires experience with the game and massive testing to be effective.

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Appendix A

Tables

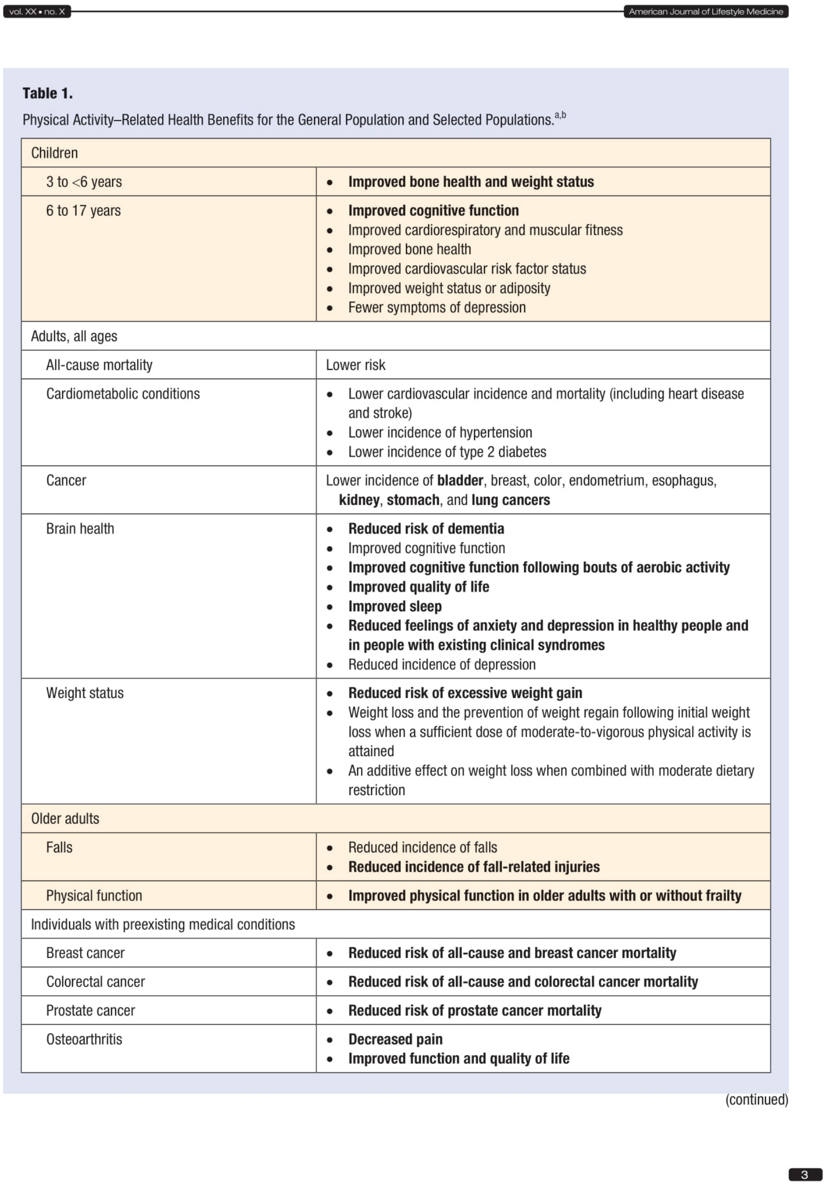

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Table 1.

Physical Activity–Related Health Benefits for the General Population and Selected Populations.[a,b]

Children	
3 to <6 years	• **Improved bone health and weight status**
6 to 17 years	• **Improved cognitive function** • Improved cardiorespiratory and muscular fitness • Improved bone health • Improved cardiovascular risk factor status • Improved weight status or adiposity • Fewer symptoms of depression
Adults, all ages	
All-cause mortality	Lower risk
Cardiometabolic conditions	• Lower cardiovascular incidence and mortality (including heart disease and stroke) • Lower incidence of hypertension • Lower incidence of type 2 diabetes
Cancer	Lower incidence of **bladder**, breast, color, endometrium, esophagus, **kidney**, **stomach**, and **lung cancers**
Brain health	• **Reduced risk of dementia** • Improved cognitive function • **Improved cognitive function following bouts of aerobic activity** • **Improved quality of life** • **Improved sleep** • **Reduced feelings of anxiety and depression in healthy people and in people with existing clinical syndromes** • Reduced incidence of depression
Weight status	• **Reduced risk of excessive weight gain** • Weight loss and the prevention of weight regain following initial weight loss when a sufficient dose of moderate-to-vigorous physical activity is attained • An additive effect on weight loss when combined with moderate dietary restriction
Older adults	
Falls	• Reduced incidence of falls • **Reduced incidence of fall-related injuries**
Physical function	• **Improved physical function in older adults with or without frailty**
Individuals with preexisting medical conditions	
Breast cancer	• **Reduced risk of all-cause and breast cancer mortality**
Colorectal cancer	• **Reduced risk of all-cause and colorectal cancer mortality**
Prostate cancer	• **Reduced risk of prostate cancer mortality**
Osteoarthritis	• **Decreased pain** • **Improved function and quality of life**

(continued)

3

[138]

Figure A.1: Table 1A

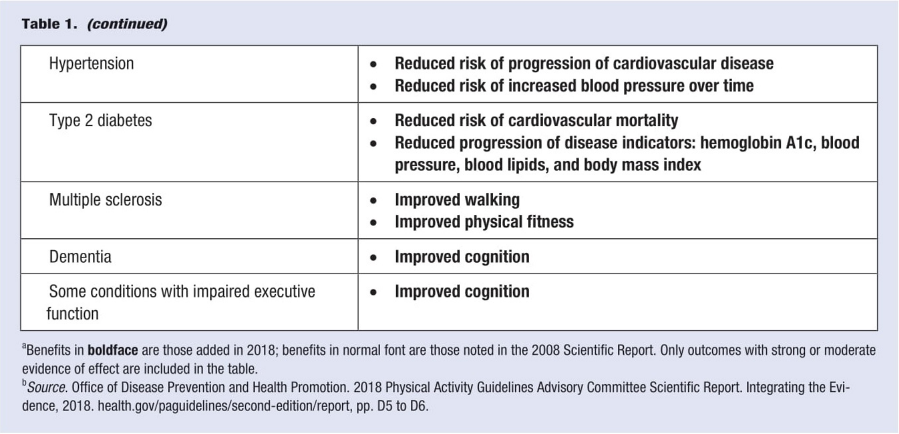

Table 1. ***(continued)***

Hypertension	• **Reduced risk of progression of cardiovascular disease** • **Reduced risk of increased blood pressure over time**
Type 2 diabetes	• **Reduced risk of cardiovascular mortality** • **Reduced progression of disease indicators: hemoglobin A1c, blood pressure, blood lipids, and body mass index**
Multiple sclerosis	• **Improved walking** • **Improved physical fitness**
Dementia	• **Improved cognition**
Some conditions with impaired executive function	• **Improved cognition**

[a] Benefits in **boldface** are those added in 2018; benefits in normal font are those noted in the 2008 Scientific Report. Only outcomes with strong or moderate evidence of effect are included in the table.

[b] *Source.* Office of Disease Prevention and Health Promotion. 2018 Physical Activity Guidelines Advisory Committee Scientific Report. Integrating the Evidence, 2018. health.gov/paguidelines/second-edition/report, pp. D5 to D6.

[138]

Figure A.2: Table 1B

Appendix B

Building methods and materials

In this appendix, how the various parts were built is explained in detail, so that it can also act as a guide for maintenance/rebuilding.

B.1 Frame

In this section, the physical structure of AIR ExDaMa (see Figures B.1-B.2) is presented.

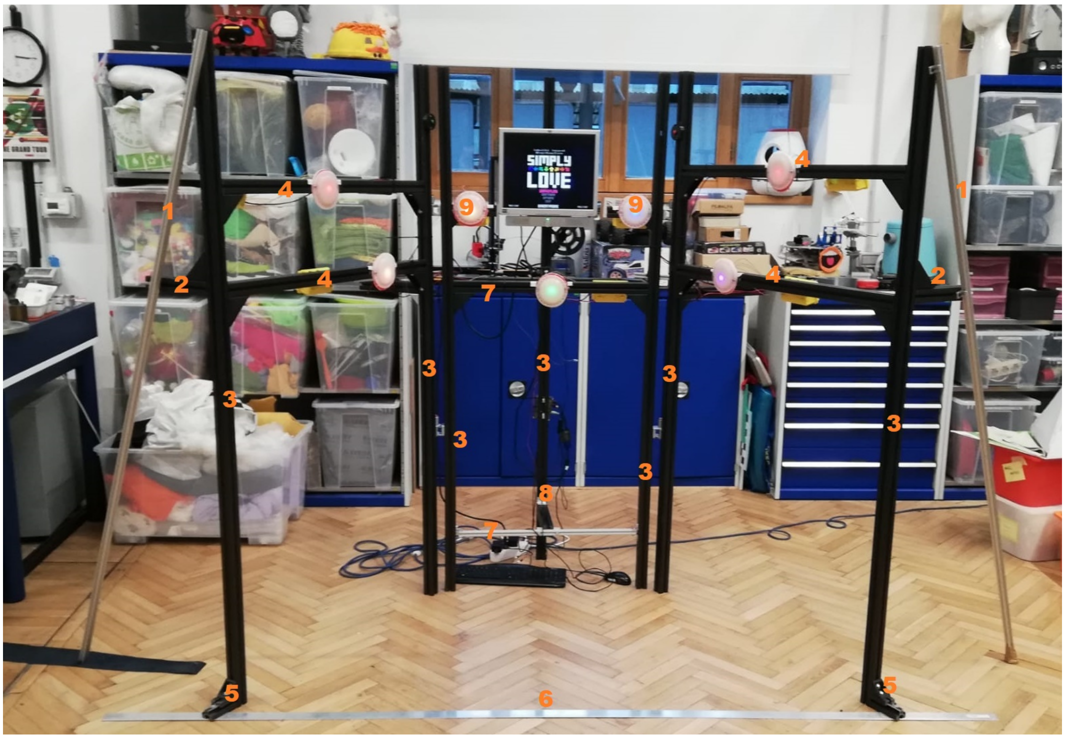

Figure B.1: Image of AIR ExDaMa, with numbered bars.

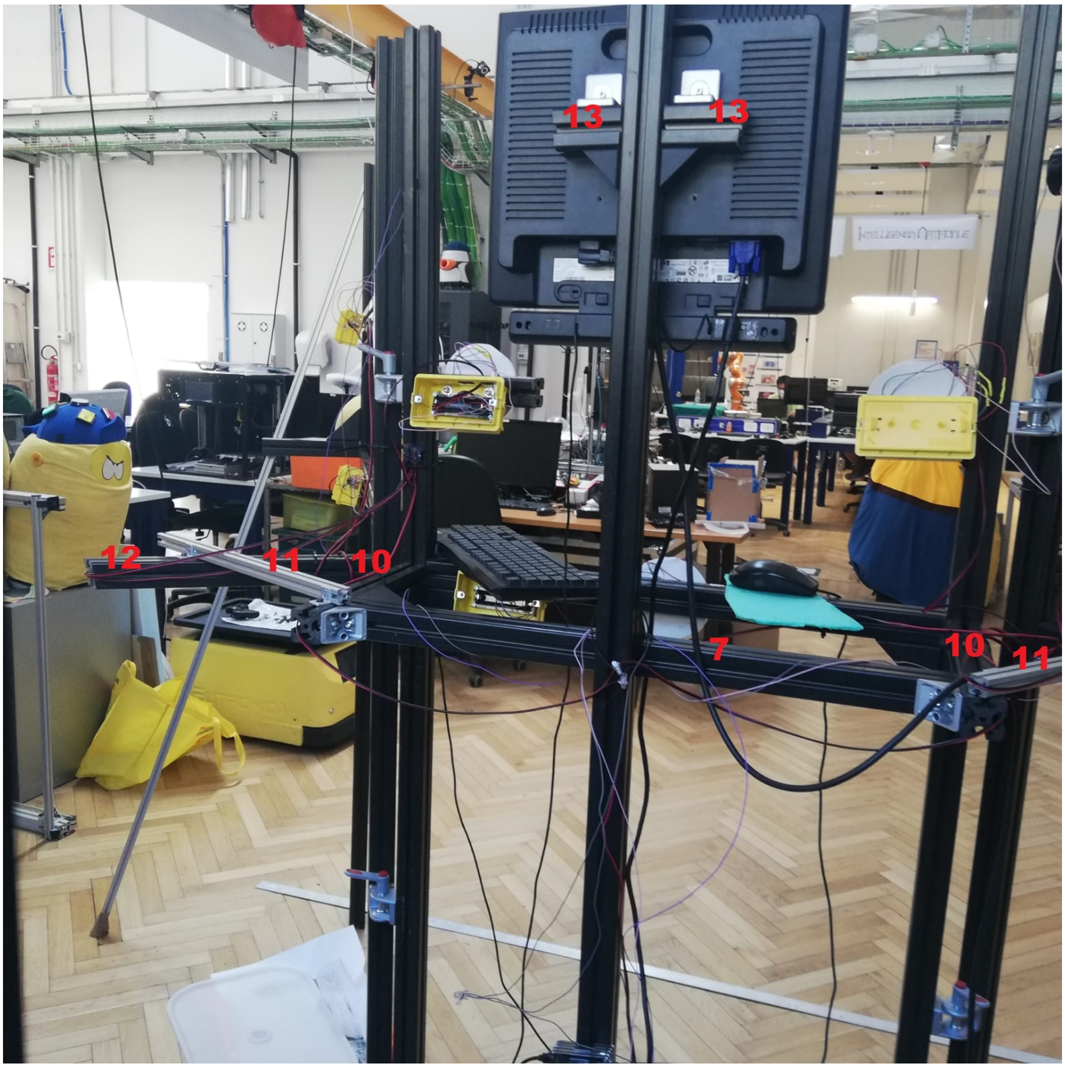

Figure B.2: Image of the rear of AIR ExDaMa, with numbered bars.

B.1.1 Dimensions

Here, the number and sizes of bars are listed:

1. 2 oblique metal bars, reasonably longer than the vertical ones (for 190 cm of height, around 200 cm were used). Metal can be used.
2. 2 short support bars, at least 15-20 cm long.
3. 7 vertical bars, 190 cm tall
4. 4 long lateral bars, 95 cm long

5. 2 short feet, around 7-10 cm long
6. 1 slim horizontal metallic bar at ground level, 260 cm long
7. 3 supporting middle bars, 70 cm long
8. 1 supporting perpendicular bar for the T junction. With the used bar types and length it resulted to be 27 cm long.
9. 2 very short bars for the frontal sensors, 15cm long
10. 2 perpendicular middle bars, 30cm long.
11. 2 rear supporting oblique bars, at least 50 cm long
12. 2 bars to join the oblique rear supports to the side wings, at least 25 cm long
13. 2 short supporting bars for the monitor. They should be as short as possible given the chosen monitor. In this work they were 6-7 cm long.

A total of 26-27 meters of material were used plus: a slim metal bar, 26 triangular joints, 8 L joints, 8 oblique joints, 2 special L joints (for the monitor) and 4 variable angular brackets.

B.1.2 Assembling

B.1.3 Using sliders

All the components that need to be fixed on the frame's bars, use sliders (see figure B.3) that can fit in the grooves as a link. In case of bars, triangular or L brackets are used as intermediary between the two pieces (see figure B.4) while other components (e.g. sensors, boxes, buttons) are directly screwed.

Figure B.3: Image of a slider inside a bar's groove.

Figure B.4: Image showing a triangular bracket fixed only on one side.

Frame

To assemble AIR ExDaMa it's recommended to start from the vertical beam pairs in the middle. Using two angular joints stitch two "3" together while being extra careful that both bars touch the floor when on even ground. After that, move on to the middle part of the frame by connecting the two pairs with two "7" and add the posterior supporting structure (two "10" and one "7") and the vertical middle beam ("3"). Finish by attaching "8". After this, the structure should be able to stand on its own and the lateral wings can be mounted. Subsequently, proceed by adding an oblique bar

(”1”) and the necessary support for it (”2”) to each of the remaining two ”3”. After that proceed to attach the newly crafted pieces to the middle body trough two ”4”. Next add a ”12” on both of the external bar of the middle pairs at the same height of ”10”. After carefully measuring and setting the aperture angle (the used one is 30 degrees from the normal to the central piece) like in figure B.5, join ”12” and ”10” trough ”11” on both sides. Subsequently, proceed to add the two feet (”5”) at the front and link them with ”6”. Lastly attach two ”13” at the desired monitor height.

Figure B.5: Showcase of the goniometer use for setting up the aperture angle.

Tips while assembling

While assembling make sure that all the bars are bubble levelled and that all vertical bars touch ground. In addition, it has been shown that some components (like the T junction) can bend adjacent bars if wrongly cut, so it's necessary to pay attention to such issue and fix the beams accordingly in case of mistakes. Lastly, once everything has been assembled, check again for any bent/not levelled part and fix it.

Electronics

First of all install the sensors in the desired positions. Make sure the LEDs' perfboards are properly placed inside the beams' groove with their cables being properly spanned to avoid accidental short circuits due to the poor soldering. The sensors shouldn't be screwed too tightly and washers must be used to not ruin the holes. Regarding their positions, standard tested ones have been found and will be here reported (numbers according to figure D.1):

- Sensors 0 and 6 are placed 43 cm from the inner side of the bar the lie on. Their center's height was measured to be 153 cm.
- Sensors 1 and 5 are placed 20 cm from the inner side of the bar they lie on. Their center's height was measured to be 122 cm.
- Sensors 2 and 4 are placed so that their border touch the start of the bar on the outer side. Their center's height was measured to be 142 cm.
- Sensor 3 it's placed in the middle of it's supporting bar. It's center's height was measured to be 115 cm.

The horizontal positions are measured up to first encountered border, since it was more objective than the center. The sensors were 12 cm long.

Once finished, it's time to add the ESP cases. Place such boxes behind the sensors but, if the cables are too long, move them to the side till they are nearly tense, so that they can be hidden nicely behind the bars.

After the sensors have been taken care of, it's the turn of the buttons. After attaching two sliders to their case, fix them on the external middle bars at a reasonable height, green on the left and red on the right. Since one case doesn't have a groove for the wires, don't tighten it too much to avoid damaging them.

The used RPi case didn't have usable holes to screw it. As consequence cable ties were used to fix it on the back of the middle beam. To make sure the board doesn't fall, sliders with a screw were added, one under the RPi and other two to support the ties. The buttons must be then connected to the board.

Cable net

The power net can be set up according to section 3.3. A main cable connected to the mains, it branches into two at mid-height at the back of the structure and then branch again into a set of four and a set of three. Joints are done trough mammoths. The seven resulting extremities are directly plugged into the sensors so the the cables used for those must have appropriate length. In order not to have too many flying cables, the use of cable ties is recommended. When applying them, don't tighten too much so that the cable can easily slip in and out. This way is won't be necessary to cut the ties every time the structure is disassembled and reassembled.

B.1.4 Power supply

The power supply consist in a multiple socket hosting the monitor, RPi and the ESPs. The monitor and raspberry's have a factory provided supply while the sensors have a recycled one sized at 2A and 5V. This transformer can be connected to with an USB head. As consequence, to transmit current, an USB charger cable (two wires) was cut and two different connectors were attached to the internal wires' extremity to avoid any possibility of inverting the polarity. Matching connectors were then added to the a new cable with the job of transmitting power to the power net (see section 3.3). The result can be seen in figure B.6

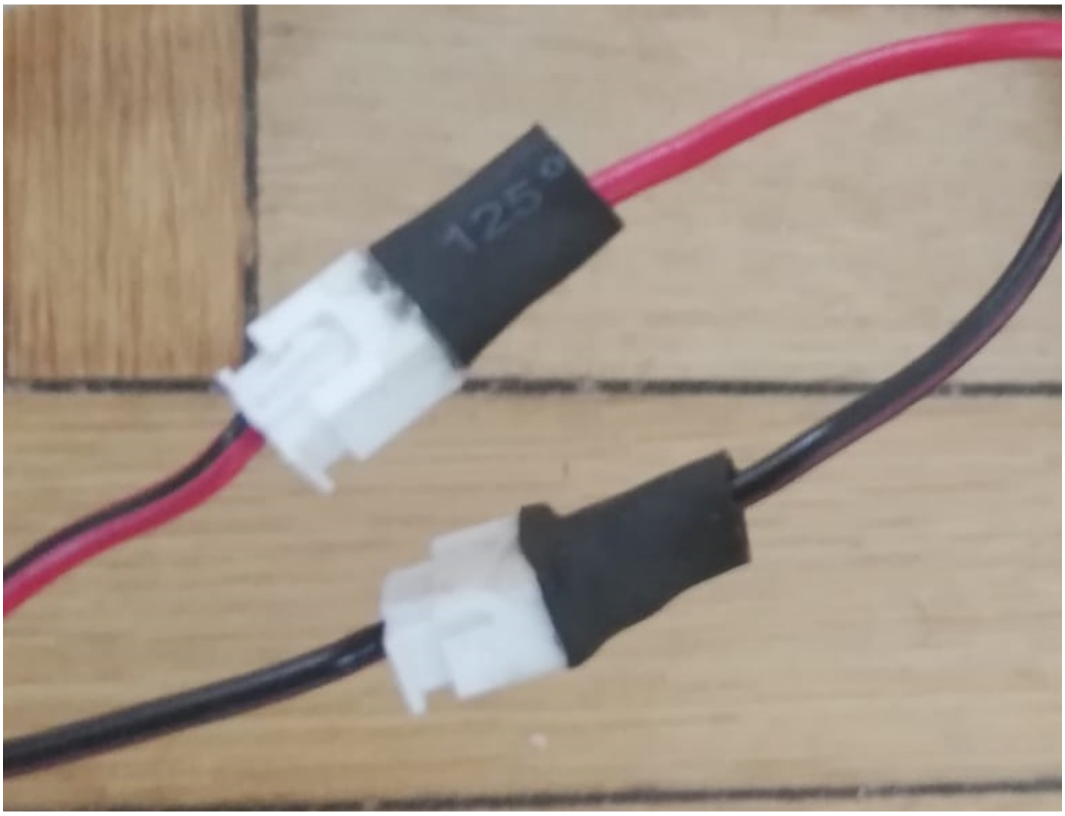

Figure B.6: Photo of the connectors used to power the sensors' net

Next some tips on what yielded the best results when producing the above mentioned parts, together with some in depth details, will be presented.

Connection between the ESPs power supply and the net

The link between the ESPs power supply and the net is trough a two pin and a three pin JST connectors (one for GND and one for power) Since the insulation of the used cable might result too tick for the used connectors, only the peeled part should be put in while crimping on the net side. Hot glue should also be added to better isolate the terminals and strengthen the connection.

Connection between the net and the ESPs

The endpoints that connect the net with the ESPs are made using two pins JST joints. Since crimping only the exposed part (for the reason stated in the above section) of the cable leaves some room for an accidental short circuit (due to stray conductive filaments), hot glue must properly be applied to ensure isolation. The result can be seen in figure B.7

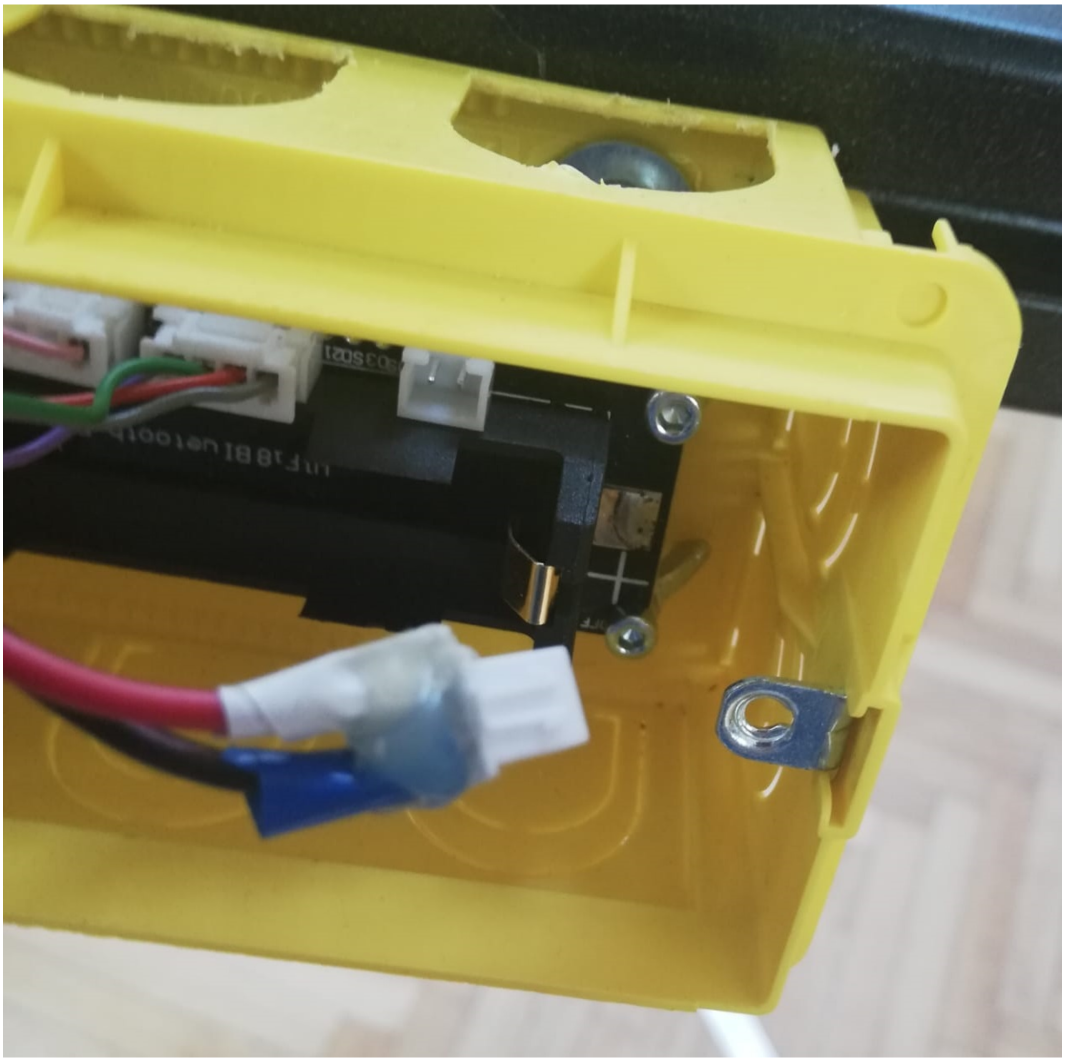

Figure B.7: Image showing the resulting connector used to power the ESPs

B.1.5 ESPs

The ESPs have to be bought without the standard presoldered pins headers. Three different JST connectors and a cable must to be added for the use according to what shown in section F.1.

Important to notice that the 5V input can never be accidentally short circuited to the adjacent unused pin since the board work on 3.3V (while for other pins it doesn't matter matter). Finally, is necessary to remember to keep an high temperature of the solder when adding the connectors or the tin won't firmly fix on the conductive ring of the ESPs.

B.1.6 Capacitive sensors

Sensors can be easily made using a cylindrical/semi spherical mold. First of all it's necessary to cut and partially peel a single filament cable in a way that, after producing a desired pattern in the mold, the exposed remains on both sides could be knotted and so that the insulated part would be enough to reach the sensor with some leeway. The chosen values with the used mold and pattern have been found to be around 45-50 cm of insulated cable and 95cm of peeled cable tough it's recommended to shorten the insulated part since it has been observed to be excessively long. Once wire has been prepared and set in the mold (The used pattern can be observed in figure B.8) it's necessary to make sure that the cable never touches the bottom and the "top" (imaginary) of the mold (aside from the exit points) as much as possible, in order to avoid unnecessary exposed parts. Once everything is set use an elastic polymerizing silicon (Pro-lastix was used in this case) to fill the mold (the used amount was 150g) and wait for the reaction to finish. Important is to notice that if a mold with screw placeholders is used (like the one showed in figure B.8), if the wire is too tight around the small cylinders, they might break when extracting the sensor. On The other side, being too loose on them, will make placing the wire pattern correctly insanely difficult. Finally, after the silicon has dried up, use a screwdriver to extract the sensor starting from where there is the lowest placeholder concentration and, after the first bit is done, proceed to extracting it with fingers. Note: cleaning the tools immediately after making the sensor is a waste of time and paper. After the solution dry up, it will be extremely easy to perform the task.

Figure B.8: Image showing the used cable pattern for the produced sensors.

B.1.7 LEDs

Every sensor has an associated LED that has been placed inside a cavity drilled in the middle back of the sensor and that it's soldered to a perfboard which connects it to the cables whose endpoints have been made into a JST connector to plug into the ESPs. A 220 ohm resistance ha been knotted in the middle of all cables (aside from the GND) to avoid over current damage. The result obtained this way was unsatisfactory due to the high precision requirements and difficulty of the work. The reason why such approach was used was due the fact that it was discovered too late that the used cables didn't interact well with the melted tin, making the soldering process of the LEDs impossible by hand. Since the final product ended up being cumbersome (the perfboard barely fit in the frame's grooves) and prone to internal short circuits if a thin layer of hot glue was not applied (causing unwanted color changes and malfunctions), a complete remake with a simpler approach and a solderable cable is recommended in case of damage to this component.

B.2 Sensors' back cover

The sensors' back cover uses a material which consistency is in between that of plastic and cardboard (oriented towards the plastic side). To make this component a sensor's profile has to be drawn on a sheet of material and cut out. After that, two 4.5 mm holes are to be drilled in correspondence of two opposite holes on the sensor (possibly selecting the ones that did not have exposed cable inside them). If the mold didn't take into account for the holes, drill them after aligning sensor and cover for the best accuracy. A bigger hole (large and deep enough to host a LED) has then to be drilled equidistantly and in line with the previously made ones making sure not to neither pierce the sensor completely nor to cut the internal wire in the process.

B.3 ESP's case

The ESP case is a junction box that can be fixed to the frame's bars trough sliders. The board is kept suspended trough the use of wing nuts (placed like in figure B.9. Cables can pass trough an opening on the side if the user desires to close the lid.

Figure B.9: Image showing how nuts are used to keep the ESPs floating inside their box.

B.4 Buttons

The push buttons are hosted in a 3D printed case (blueprint stored in the GitHub repository F.3 fixed to the frame trough sliders. Two cables are knotted and soldered to to them (plus and minus) and, out of them, the GND of both buttons have been short circuited trough a mammoth. The resulting three cables connect to the RPi with standard female pins.

B.5 Audio

To produce sound, the built in monitor's speakers are used. In order to produce a strong and clear sound, an USB to jack adapter has been used to connect them to the RPi (this way the signal is on 5V instead of 3.3V, resulting in a massive volume difference).

B.6 Monitor

The used monitor is not only heavy (thus making it hard to move around if not experienced) but also uses a screw size that wasn't compatible with the available pieces. As such, when changing its position the bubble level is not enough to ensure a good work. It's also necessary to check whether the screws are touching the upper side of the L brackets holes in order to guarantee it's alignment with the ground even after it gets shaken up.

B.7 Set up the RPi

- In order for the RPi to work properly, some ground work must be done. First of all it is necessary to configure the board as an access point, making sure the used SSID and password are the same used by the ESP code. This can easily be done by following the tutorial at the this link: https://www.raspberrypi.org/documentation/configuration/wireless/access-point-routed.md.
- Next step is the installation of the required software. Go into the GitHub repository (see section F.3) and copy the `"stepmania_driver"` folder in /usr/games and the content of the "Quickstart files" on the desktop. They can be found in the "RPi" folder.
- Once everything is ready, make sure python 3.7 is installed and manually add all the missing libraries that are used in the scripts present in the folder installed in /usr/games.
- Set up /usr/games/`stepmania_driver/Driver_final.py` as daemon. This can be done using systemd.
  - Copy the file present in RPi/Service files on the GitHub repository to /etc/systemd/system and sudo chmod 664 it.
  - type sudo systemctl enable `"stepmania_driver"`
  - type sudo systemctl start `"stepmania_driver"`

  - If the sensors are already connected, open any text editor and verify the script is running (if the sensors act as a keyboard, it means it's working).
  - For any change to the service file type sudo sytemctl daemon-reload.

- Next step is the installation of Stepmania/OutFox. Extensive use revealed the presence of several bugs relative to both Raspbian's versions and the seven arrows mode for Stepmania. As such, using OutFox only on a new system is recommended. Unfortunately, only Stepmania's version configure itself as daemon automatically, so such operation will have to be done manually for OutFox.

- To conclude it's necessary to install and modify the game's theme and skins. On GitHub it's possible to find an arrow skin for the seven commands mode and some edited files for the simply love theme that modify the judgement scoring to make it more beginner friendly.

Appendix C

History of the project

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C.1 Formulation of the problem

The goal of this thesis is the development of an interactive fitness device focused on exercising the upper part of the body. The produced device have to be suitable for any age, body size, physical prowess and, at the same time, being enjoyable, competition stimulative and capable of inducing people into its use for long periods of time.

C.2 Preliminary analysis and decisions

C.2.1 Initial choices

The body parts stimulated by the device were chosen to be, in order of importance, upper limbs, abdomen and lower limbs.

First of all, the game genre had to be decided. It had to be something neither too complex nor too flashy, with an intuitive interface, so that it could be enjoyed by people of any age.

The choice fell upon a rhythm game. This genre requires the user to trigger a variable number and types of sensors according to visual instructions that follow the musical rhythm. The main reasons for such a choice were that listening to music is something that almost everyone enjoy, at least to a certain extent, and that the game mechanics are extremely simple and intuitive. Another advantage of this kind of game is that it can be set to any level of difficulty and it is also possible to compete between players (even of significantly different skill level) by comparing scores on songs that are feasible to every contestant.

C.2.2 Legal constraints and costs

The next addressed issue was the legal part. A research about similar products and music copyrights was performed in order to check if, in the first place, the project was feasible and what were, if any, the legal limits. No relevant patent was found and, regarding the copyright issue, not only payments and regulations resulted to be heavily country dependent, but also often there wasn't even a specific rule for applications of this kind (or, at least, it was not found). Due to this, it was decided that no-copyright songs had to be used but, at the same time, the possibility for the user to add extra songs for which he has rights was taken into consideration (taking inspiration from OSU and Rhythm horizon that had already developed ways to address the issue). After objective and limitations were made clear, a rough check on the expected cost and needed materials was performed and then the project moved on to the design phase.

C.2.3 The game

Even if the interface is relatively simple, creating a game from scratch is a time consuming operation. In order to avoid this problem, the use of a third party software was considered. The program that was chosen was Stepmania. Stepmania is a PC emulator for multiple rhythm games, it has an open source license and several Linux-based releases, one of which even for Raspbian. In addition to a significant number of game modes, the game is highly customizable in both modifiers (options that change how the player see the arrows and that, ultimately, simplify the reading) and skins (everything about the graphical interface can be customized by simply adding a file in the right folder), making it an ideal choice for the project.

C.3 Design constraints

The physical structure had to respect a significant number of hard and soft constrains that are here listed together with the corresponding guidelines.

Movements

First of all, the hardware design had to be able to, while respecting the successively listed constraints, maximize the number of body parts involved during the movements and reach high levels of muscular activity for hard difficulties.

Ergonomics and safety

The player's achieved positions and the executed movements should be natural and should not induce any undesired pain, even during long playing sessions. In order to make users more willing to continue playing, positions that were in any way uncomfortable had to be avoided. Same went for movements that require a fast interaction with a load or that reach the proximity of the articular motion limit, in order to avoid to harm the user. Finally, how the player would look while moving had to be taken into account. A discussion with an expert in the field of arcade games brought to light that a reason for which several arcade exergames failed was due the user looking ridiculous while playing. As consequence, the movements' aesthetics had to be considered.

Number and position of sensors

The importance of the number and position of sensors stems from their ability to single-handedly define the spectrum of the possible movements. While deciding them it was important to take into account that having too many commands would make the game too complex and end up discouraging players, especially the new ones.

Sensor types and technology

While buttons are the most intuitive form of interaction, there is no rule about the need to use them or the impossibility to mix them with other types of interfaces (e.g. pulleys). Because of this, different types of inputs were considered and their ability to stimulate the body was taken into account, together with their downsides. For this part, it was also necessary to consider that the perceived value of an object can be decreased by adding non-liked elements [7]. This means that adding a new possible movement, even if it could easily be disabled or being rarely used, would make the experience less fun and the product less appealing. Finally, a research about the most appealing sensor types was made to ensure that a sensor with the desired specifications was either available in the market (at a low enough price) or cheaply realizable with the equipment available at AIRLab.

Structure

The structure had to be (roughly) human sized, able to resist significant loads and impacts, having negligible vibrations and being able to effectively fix all its parts and accessories in place. It was also important for it to be comfortable for the user in both a physical (e.g. not to harm the user in case of an incorrect execution of a movement) and psychological (e.g. avoiding being intimidating or inducing claustrophobia) way.

Flexibility

Since the game was supposed to be used by people of any age, shape and height, a frame that could be easily modified to suit the user was needed (eventually even with the possibility to change the position of the I/0 peripherals).

Cost

Given the significant cost due to the numerous components, processing units and size, careful cost-benefit optimization was necessary.

Recyclable sensors

Since it was requested for the sensors to be reusable for other purposes (e.g. treasure hunt), a modular design and the ability to wirelessly communicate had to be taken into account.

C.4 The frame design phase

C.4.1 The initial designs

At first two main concept designs were taken into consideration: one required the user to be standing while the other expected a lying position.

The lying design

The lying version was the initial runner up. The user was supposed lie as if doing sit-up and, from there, he could hit two sets of sensors: one that was supposed to be used while lying and one that was supposed to be used after rising with a sit-up. The big advantage of this method was that it allowed significant abdominal training trough dynamic exercise (concentric and eccentric contraction) and holds (isometric contraction). Unfortunately, there were a considerable amount of disadvantages.

First of all the gameplay would have been way too stressing on the abdominal region for anyone to enjoy it for extended periods of time, making it also way too similar to a pure exercise, with the addition of looking ridiculous, and a high risk of incorrect and potentially dangerous movements. Even taking into account that the number of sit ups and the amount of time spent into a hold position could significantly be toned down, this design was still deemed not acceptable for several reasons:

- Executing sit-ups at a fast pace is kind of awkward and feels sloppy. Moreover, it may induce risks to the user's health due the possibility of incorrect movements.
- By limiting the hold time, a significant and cumbersome part of the frame is barely used. This was likely to have a negative effect on the perceived experience.
- There could have been issues if the game were to be placed in a public space (excluding gyms). Due to the contact between an hypothetically sweaty body and the frame, cleaning tools and a towel would have been necessary.
- The aesthetics of the movements was not convincing.
- The structure was fairly complex (thus prone to issues and hard to realize with scarce resources), limited in the ability of accommodating users with different height and build and, ultimately, extremely invasive ad cumbersome to the point that several movements would have been required to get out of the machine.
- The inability to use legs was likely to discourage prolonged sessions due to torpor or a general feeling of discomfort.

The standing design

The standing version was less sophisticated. Sensors were attached on wall-like frame positioned in front and on the sides of the user. The advantages of this design were its simplicity and freedom of movement but, as downside, it had a low, in not null, ability to force the user to use the abdominal region.

Note on the designs

Both these designs took into consideration the possibility of having the user perform load-based tasks or using non button-like sensor types but, since the verification of the correctness of the movements was often hard, if not impossible, and since adding a string/load based exercise (whose execution had to be forced to be slow to prevent harm to the user) would interrupt the flow of a naturally fast paced activity, this possibility was reluctantly abandoned.

C.4.2 Improvements on the standing design

New shape and sensors

Since the lying design was faulty beyond recover, improvements were focused on the standing one. First of all the "wall" was bent toward the user making it "U" shaped (projection on the transverse plane). This way, it would have not only been easier to press even the furthest buttons (user's applied force direction closer to the perpendicular to the surface and bigger contact area), but it would have also made possible to force the player to turn his torso significantly trough the use of particular patterns, adding some use of the abdominal muscles, even tough it could most likely be considered negligible.

In addition, the possibility to add sensors dedicated to kicks, crouching and jumping was contemplated. Ultimately the kick sensors were discarded since they would not only have increased the number of commands excessively but they would have also worsened the way people would look while playing. The jump/crouch was, instead, suspended indefinitely since the decision was hard and it could have easily be added at the end of the project if deemed worthy.

Versatility and flexibility

While developing the model further, the position of the sensors and the monitor was analyzed. Unfortunately, due to the wall-like structure, people with different height would have felt way differently during the use, not to mention that some might have ended up not being able to play properly. Making the size easily adjustable for different heights in an hypothetical production process was an option but it wasn't welcomed since for some of its possible uses (e.g. public spaces) being able to adapt was considered important (not to mention that the actual object produced in this thesis is just one, so its flexibility is mandatory).

Determining the ideal sensor position would have also been extremely tricky since, in order to find the best positions for the sensors, practical testing (from several people) and bio-mechanical simulations were required, but, at the same time, these were not possible without a working prototype.

This never ending loop further encouraged the pursuit of a flexible structure that could be easily adapted.

C.4.3 A new modular structure

In order to obtain a versatile structure and reduce costs compared to a full wall, the frame was developed using beams that could attach sliders on their sides, so that components could easily be moved along their length. Several versions of this structure were designed, each improving the previous one by a little bit, till a supposedly effective and optimized one was obtained, as shown in Figure C.1. On the left we can see how the side wing would have been in case of a fixed angle (one vertical bar) while on the right it's shown how it would have looked if a variable angular joint have been used (two bars). The transparent cylinders represent a human.

The design used profiled bars that allowed the presence of sliders on every side so that they could move respect to each other. This allowed full customization of the sensors' number and position in both height and length. The vertical bar in the back works as both stabilizer for the structure and as a slider in height for the monitor. It can also slide back and forth thus regulating the screen's distance.

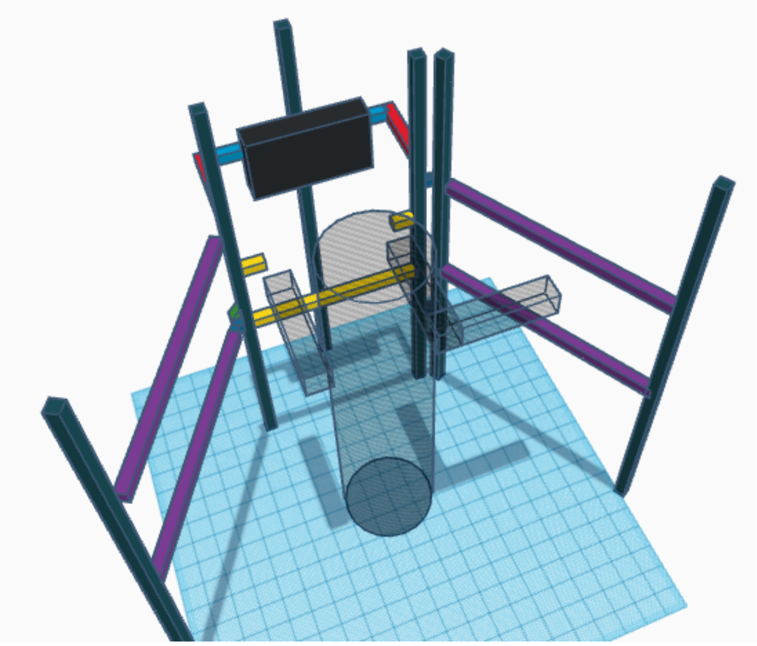


Figure C.1: 3D model of the initial frame's design.

The hardest tackled issues to get to this design were the monitor placement and the angles between the three horizontal sides.

Monitor placement issue

Initially, the monitor was supposed to be placed along the frontal plane, on a beam that could have also been used to host sensors. The monitor would have, obviously, been protected by a rigid transparent sheet in order to avoid collateral damage to it. Unfortunately, screens of appropriate size were all too wide to host sensors on their sides. To make up for this, it was decided to put the screen on a beam placed behind the sensor's one, thus also giving more structural stability and the possibility to regulate the monitor's depth. As consequence of that, the frontal beams couldn't have been placed freely, as not to impede the vision when positioned before the screen. This issue was solved trough the use of short beams that are connected only to one side of the frame.

Variable angular's issue

The frame structure was, at this point, shaped like a trapezoid and, as a matter of playability, a question was due: at which angle should the oblique sides be, respect to the parallel one? The choice of an angle was an extremely important factor that significantly influenced the gameplay and which optimal value was affected by the user's physique and the sensors' configuration. To solve this problem a variable angular joint was used. This way, not only the angle could have been user tailored but it also allowed for different playing modalities (short user movement range with a low aperture and wide movement range with a high one).

C.5 Building phase and issues

After no more major sources of problems could be found in the design, the project moved onto the building phase. As mentioned before, a type of beam that could be equipped with sliders was used and, and far as it went for the material, a mixture of plastic fibers and bamboo was used since it has good mechanical properties, was already present in the laboratory storage, and wasn't likely to give problem with the capacitive sensors' signal readout (compared to metallic materials).

C.5.1 Issues and modifications

Sizing

First of all the actual size of the beams had to be chosen. Even if the sensor were able to be moved around freely, this only applied within the space allowed by the frame. In order to choose a proper length for the beams, several dummy tests and basic trigonometric calculations were done till supposedly suitable values for an average sized person were obtained. From there a margin was added for taller people.

Structural rigidity

Differently from what was expected, the sliding junctions weren't enough to fix the frame in place due to clearance phenomena and the low rigidity of the beam, that was found to be extremely vulnerable to torsion along its length. This problem was further complicated by the uneven flooring that made impossible to have all beams touching the ground and discharging weight whenever the frame was moved. This was partially solved by adding some extra junctions and by placing beams more carefully along the axes. Consequence of this was that the structure ended up requiring a bubble level to be properly assembled/modified.

Oscillations

After finishing the frame another consequence of the clearance and beam plasticity was discovered. After a slight hit/push, it was possible to notice that the two sides vastly oscillated. Numerous solutions were tried, like connecting the sides with a beam, adding a pendulum to act as a dampener (as done in skyscrapers), adding more horizontal bars or even doubling up in depth on the sides. Unfortunately most of those had negligible if not null effect. The solutions that, in chronological order, could significantly and effectively reduce the problem were:

- Adding an oblique beam that from the top of a side's vertical beam landed on the outside (see Figure C.2. This solution strongly reduced the oscillations. Unfortunately, as mentioned before, the beams are weak to torsion and since most of the momentum was supported by the middle ones, significant effect could still be seen due to the long arm that strongly amplified a few degrees of displacement.

Figure C.2: Oblique bar used to increase stability

- In order to reduce the stress on the middle beams a second junction posterior behind them was added (see Figure C.3. This gimmick almost eliminated the torsion phenomena. Unfortunately, clearance and beam deformation couldn't be significantly reduced with the used components. As consequence, after the previous modifications, the sides became able to "hop" upon push, progressively moving backward due to an accumulation of bending and torsion in multiple beams. Finally, due to its lightness, the frame had a tendency to move after a certain threshold of energy was accumulated inside the beams. It's also important to consider that the previously mentioned solutions only strengthened the resistance to pushes, while pulls still gave rise to significant swings.

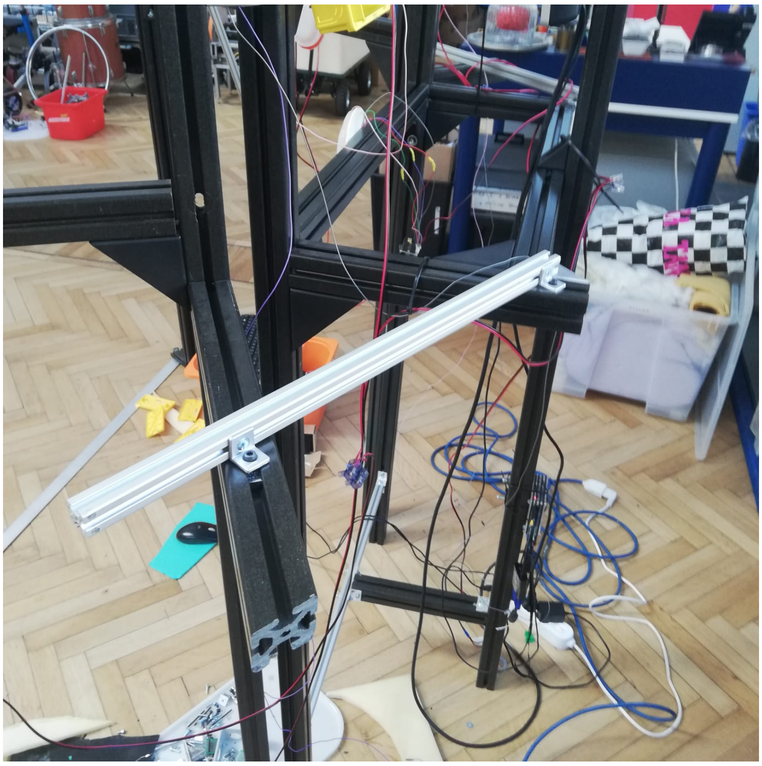


Figure C.3: Support added in the rear to decrease the momentum on the middle beams

- In order to, at least, prevent the sides to drift apart due to the hopping phenomena, a bar connecting the two was added (see Figure C.4). Initially, it was positioned on top where it would have had the strongest effect but, in addition to its annoying presence slightly above the head, it made the situation worse since the tilt ended up spreading to the other side (and then to the overall structure) with an increased effect due to the addition of mass above the center of rotation. As consequence, a slim (to prevent tripping) metallic bar was used join the sides at ground level. This resulted in a fairly stable result that was deemed sufficient for the final product.

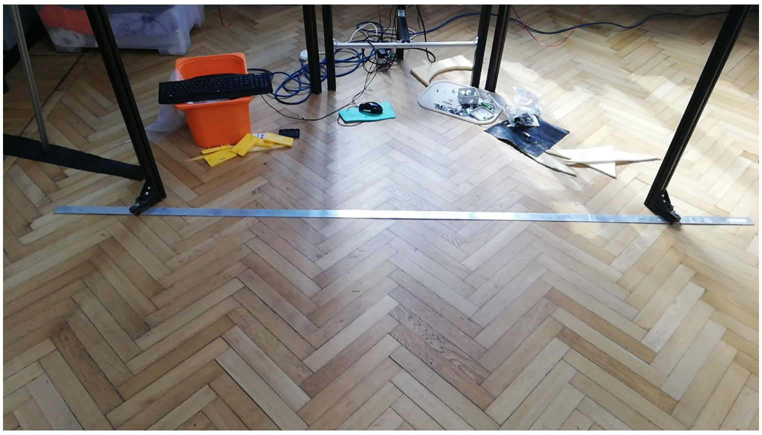


Figure C.4: Bar used to connect the two side wings at ground level

- Unfortunately a new problem was discovered after mounting the screen. Despite the use of two vertical joints the back-structure wasn't able to firmly hold the central bar straight. Result of that was that the monitor would keep tilting every time the frame was touched. The issue was perfectly solved trough the use of a T-shaped structure connecting the three vertical bars in the middle was used (see Figure C.5).

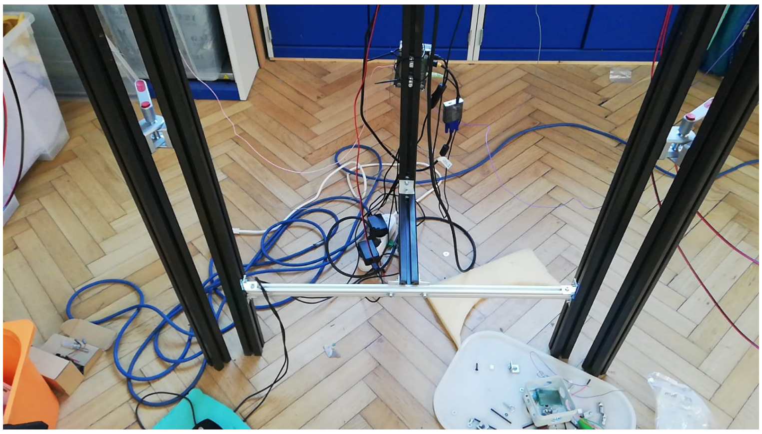


Figure C.5: T-shaped joint used to fix the posterior vertical bar

C.6 Sensors

The choice and design of sensors, circuitry, processing units and power supply was instead tackled as a separate problem. This was possible since the number of such systems was relatively low so that, as long as a little tough was given to it beforehand, no significant problem was expected to occur.

C.6.1 Sensors

The first addressed issue was the working principle of the sensors, since it was regraded as the potentially most problematic component. Different technologies for realizing touch sensors were extensively compared with capacitive, piezoresistive, and variable resistance sensors occupying the spotlight. The choice was originally oriented toward the piezoresistive and variable resistance types due to their higher response speed and noise immunity but, in the end, capacitive sensors were selected due to their cheap price, simplicity and ability to produce DC signals.

After the working physical principle had been chosen, two more things had to be defined: make or buy and technology type.

Make or buy

To start with, it was necessary to decide whether producing or buying the sensors. Given the wide sensing surface required to fit the palm, the necessity of being able detect the hand at significant distance (higher cost) and the simplicity of the technology (a working sensor can be created with just aluminium foil), it was deemed that producing one was the most cost effective choice.

Technology

Regarding the sensing method, it was instead necessary to choose between single plate and double plates sensing.

- **Single plate**

  The single plate sensor is the simplest capacitive technology. It exploit the human body to connect the plate to the the ground, thus closing the circuit. This method has the advantage of having a single surface as sensing element and can detect conductive objects even at significant distances (with enough power and surface it can even detect at meters). Unfortunately, these advantages come at the price of higher noise, baseline drift and necessity for the electric ground to be equipotential with the floor (penalty would be the presence of extra noise).

- **Double plate**

> The double plate mode is instead based on the capacity variation of a parallel plates capacitor. This change can be triggered by adding an object in between the sides, reducing the distance between them or moving them in different directions along the parallel plane.
>
> Due to the button like function of the sensor and the high speed of the user's movements, having him placing the hand in between two plates was out of question due to the risk of injury. Furthermore, the parallel translation method also wasn't suited due to its geometrical constraints.
>
> As consequence, the only viable method was the use of pressure to deform one plate or to push it towards the other (in this second case, springs to pull it back would have been necessary), thus reducing the overall capacity.

Since the double plate capacitance would have required the touch/push of the sensor, higher mechanical stress was expected due to an increased number of touches and force used, thus requiring a significantly more durable design, in addition to a significantly higher crafting difficulty. Furthermore, an online research showed that single plate sensing was extensively used for DIY projects, yielding good results with barely any complication.

In the end, taken also into account that fine sensing precision was not required since it was a binary task (pressed/not pressed), the choice fell upon the single plate technology.

Sensor's materials

As far as it went for the design and the used materials, it was decided to reproduce a patented sensor that had already been successfully used for other projects in AIRlab. The object in question was made of an elastic silicon gel with a conductive cable waved inside, to produce the capacitive effect.

C.7 Power supply and processing units

C.7.1 Power supply

Since it was requested for the sensors to actually be reusable for other applications, a double power supply system was chosen. Every sensor was given a set of batteries to work when detached from the frame but, in order to prolong the batteries' lifespan and avoiding having to recharge them too often, a power cord was added for the stationary use.

Battery supply

Originally, the sensors were powered up by three AA batteries filtered by a stepdown linear regulator, so that the final voltage would be 3.3V. A toggle switch to swap between supplies was also present. When the relative microcontroller was later switched from ESP8266 to ESP32, such things ended up being useless due to the presence of a battery holder and charger (for Li-Po batteries) integrated with the board.

Power cord supply

To size the power supply, testing with a bench power supply was done. The results showed that limiting the current consumption to roughly 80 mA would turn off an ESP8266 running the required software. Taking into account noise, the fact that the minimum amperage didn't guarantee a proper functioning (especially in case of hardware/software upgrades) and the sensors' number, an amperage of 800mA-1A was set as minimum target. An oversized 2A one was finally adopted. No test was done after switching to the ESP32 since the consumption was reported to be similar on several sources, and the supply was oversized anyway.

C.7.2 Controllers

Raspberry Pi4

First of all, a master processing unit able to receive and interpret data, output sound and video and run the game was needed. The most famous series that could potentially meet the previously mentioned criteria was the Raspberry Pi (RPi). An online research showed that it was indeed possible to run Stepmania on a RPi but even on a Pi3 it would have been impossible to have constant 30 fps, as consequence, a Pi4 was selected.

ESPs

It was now necessary to decide on how the data ware supposed to be sent to the Rpi. Using cables wasn't ideal due to the analog nature of the signal, in addition, sensors had to be reusable for long distance purposes so a microcontroller able to use either Wi-Fi or bluetooth was needed. The initial choice fell upon an ESP8266-based board. ESP8266 boards have an extremely low price, integrated Wi-Fi and offer superior performances respect to more famous ones like Arduino. They are also easy to program (it is possible to use Arduino's IDE, software, and libraries, aside from several other methods) and are relatively small compared to other boards (like the ST Nucleo). Finally, they have been vastly explored by the community so that lots of libraries and hacks are available for them.

Unfortunately, due to an issue with its case resulting quite cumbersome to put hand to, especially for the troublesome access to the batteries, the board was successively switched to an ESP32. ESP32 are the big brothers of the 8266. They offer more pins, higher specs but, most importantly, have pins dedicated for capacitive sensing purposes. While the change was made because of the discovery of a special ESP32 board that had an integrate Li-Po battery holder/charger (and thus allowed a much simpler and smaller case), it also ended up greatly increasing the accuracy of the capacitive sensing.

C.7.3 Sensors' case

Originally the case was supposed to be an electric box containing the esp 8266, batteries, a perfboard and a toggle power switch (see Figure C.6. Unfortunately, in addition to being hard to mount/dismount due the cramped components, it was hard to charge the batteries.

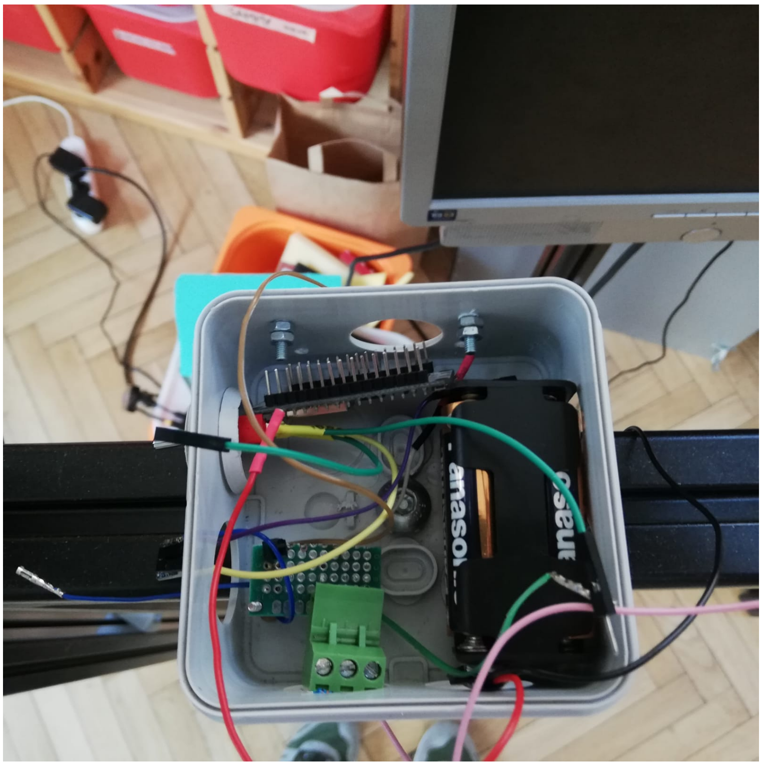


Figure C.6: Old case setup

Since the battery holder had to be fixed to the box, its unscrewing was necessary for charging, operation that, other then being time consuming, was also not that easy and required pliers to properly reach the nuts. This problem could have probably been solved by executing the charging process trough the holder but, even then, the operation would have been long and annoying since it would have required to recharge the sensors one at a time.

While thinking to an alternative, we stumbled upon the existence of an ESP32 board with an integrated battery holder/charger. This allowed to significantly simplify the design, reducing the required space by eliminating the battery pack, perfboard, toggle button and several cables.

In the final design the ESP32 is fixed at the bottom of a junction box, in a way that allows air to flow below it to cool the components (see Figure C.7. The I/O sockets are accessible trough holes on the side.

Figure C.7: Final version of the case. Lid and cables are not shown.

C.8 Navigation and buttons

In order to open Stepmania, execute the sensors' drivers and navigate in the game menu, an input device was needed. Since fixing a keyboard on the frame and explaining the user how to do everything is not effective approach, an alternative method was needed. To avoid any problem regarding the software launch, both the sensors' driver and Stepmania were configured to start at boot. Regarding, instead, the ability to move within the game menu, its feature of automatically overlapping four of the keys (that can have up to two aliases each) used to catch the notes with the navigation keys was used. Unfortunately, this wasn't enough since the necessary buttons "Enter" and "ESC" cannot overlap with any other command.

Since no effective software approach was found, it was decided to add two extra inputs. Due to the sensors being cumbersome and expensive and since the needed keys are only necessary to navigate the menu, two standard buttons connected to the RPi GPIO were used for the task (see Figure C.8). It was successively noticed that a single button acting as "mode changer" (e.g. like the ”shift” key) could have been enough. Tough this could have been a valid alternative, it would have probably the navigation less fluid and intuitive.

Figure C.8: The "ESC" button within its case. Cables have a small canal in the back to safely get outside without getting smashed

C.9 Official mode

As result of some preliminary testing, a default position for the sensors was decided. The reasons why a standardized configuration was deemed necessary, were that, first of all, it is the only way scores can be made comparable since people needs to be in the same situation to have a fair fight (tough the use of different official setups can be used to address people’s differences). The other reason is that, in order to have consistent results for the user test phase, it was mandatory for everyone to experience the game in the same way. In order to make the sensors positions easily recognisable, markers were placed on the bars (see Figure C.9).

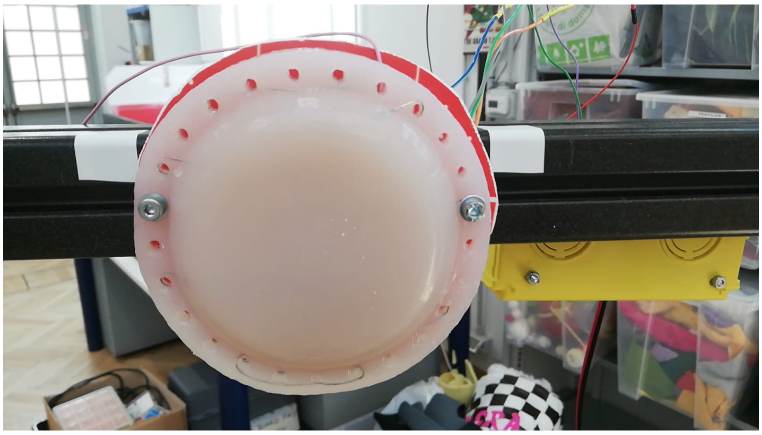


Figure C.9: Marker used to easily find the correct sensor position for the default mode

C.10 Software

The software can be divided in two parts: the drivers, that have the job of converting the input from the sensors and the buttons to a keyboard output, aside of some basic diagnostic and calibration features, and the AI, which role entails the automatic creation of playable content.

C.10.1 Drivers

The drivers are composed of a series of Python scripts and data files located on the RPi and by a C++ program installed on the ESP.

ESP code

The minimum tasks that the ESP was required to do were the reading, elaboration and WI-Fi transfer of the capacitive sensors' data. While such things would have been enough to have a working system, several quality of life upgrades were deemed necessary. To start with, the ability to receive data from the RPi was found of utmost importance in order to be able to calibrate the sensor without having to re-upload the code. This feature is also used for the activation of the diagnostic mode, in which the sensors keep sending unfiltered data to the RPi.

An RGB led was also added to show the status of the program and whether the sensor is getting pressed or not, making it an useful troubleshooting method in addition to the improved aesthetic effect.

RPi code - main script

On the RPi are present three Python scripts. The main script reads the data sent by the buttons and ESPs and convert them into keyboard inputs. In addition, if the assigned key combination is pressed, it tells all connected sensors to recalibrate using their stored values (used to counter the baseline drift). The way data are handled is the same as a keyboard. A message containing the sensor's ID and press/release condition is sent and received every time there is a status change.

RPi code - recalibration script

The first auxiliary script is for recalibration purposes. It allows to select between two different modes: absolute and automatic. Before explaining the working method of these modes, it's necessary to understand the nature of the capacitive signal and how the trigger condition is handled.

The values read by the ESP32 are integer numbers (normally between 30 and 75 when the sensors are not pressed) that, for variable periods of time (the signal is susceptible to a baseline drift phenomena) remain in a range of two units. When the sensor is pressed, the measured value goes down. Unfortunately, there is also an outliers issue for which, with a low probability, the ESP read a seemingly random number of value inferior to the environmental value. Despite this, the signal is still extremely stable.

In order to fully exploit these properties, a pair of thresholds were used as discriminators for the trigger/release conditions. First of all the threshold for the sensor activation was defined. In this case, the event is triggered when the measured value goes below the threshold. On the other hand, in order to increase the noise immunity, a second value for the release got defined. Whenever, after the sensor get pressed, the reading goes over the second threshold, the release condition is satisfied. In addition, to address outliers, the first reading above and below the triggers' threshold is discarded.

- **Automatic mode**

  The automatic mode is the default one. In this mode the ESP32 computes the mode of the environmental signal (the player is required to stay away from the sensors during the calibration process) and uses the user defined values as distances from it to define the trigger thresholds. This mode is intended to make the process immune to the outliers.

- **Absolute mode**

> The absolute mode allows the user to decide the calibration thresholds directly. This can be useful in case of a high noise situation but, on the other hand, it requires that the values are periodically updated in order to counter the baseline drift. Due to this big downside this method is kept more as a legacy then as an actual alternative.

The script also allow the user to choose between testing and saving the changes. When selecting the test option the sent values are only changed in the RAM, to increase the EEPROM lifespan.

RPi code - diagnostic script

The diagnostic script requires that only one sensor is turned on. It forces the ESP32 to keep sending unfiltered data to the RPi, that will, in turn, show them. This command put the ESP32 in a never ending loop so a reset is necessary after the check is over. This mode is useful to find out whether there is anything wrong with sensor readings.

C.10.2 AI

C.10.3 Necessity of autostepper

In order have the game appeal to a wider range of users, the ability to let people add any song they wish was necessary. Unfortunately, there were two issues to achieve this goal. Before going further is tough necessary to specify that making a song playable (charting/stepping) is an extremely long and difficult process that requires a lot of experience.

- The first issue is that a song might be under copyright. Naively, someone might think that if someone has the right to a musical piece and chart a song, another person might just download it if he or she owns the rights as well. Unfortunately, unless they own the same track (e.g. they bought the exact same track from ITunes) this is still considered illegal. As consequence, if anyone wanted to play any copyrighted song, they would have to chart it by themselves.

- The second issue is that, even if someone wanted a non-copyright song, there is no guarantee that someone charted it in the past, forcing again the users to do the job by themselves.

Since these issues cannot be completely solved even with the method OSU players use (explicitly asking the authors for the right to chart a song), the existence of a software able to step automatically was needed.

First of all, it's necessary to specify that, in order to create fun/challenging patterns, significant playing experience was needed. Since, for obvious reasons, this condition was almost impossible to achieve in the short time frame between the working prototype and the end of the thesis, it was decided to randomly select the location of the arrows.

The first tried approach was to use an existing autostepper for other rhythm games to allocate notes to position of the arrows in time. Unfortunately, all the existing ones either couldn't be run, due to incompatible OS/libraries, or placed arrows in a seemingly random fashion (like Stepmania's official autostepper).

Deep learning approach

A resulting research in literature for similar tasks, showed that neural networks were predominant respect to signal processing methods for generic polyphonic music analysis. As consequence, the we decided to use of a deep learning network.

Starting from three of papers that tackled our specific issue ([116] [110] [126]) and then broadening up with the state of the art for similar tasks, the aim was to produce an improved version of the best autostepper ever released: Dance dance convolution. Unfortunately, after months of work, the network still had learning issues. As a consequence this approach was indefinitely suspended and a signal processing approach based on the use of ready made onset detection functions was used.

Signal processing approach

With the new method, all the available onset detection functions in Essentia [76] and Librosa [117](two famous python audio processing libraries) were extensively tested and mixed till a suitable result was obtained.

Given the high amount of detected notes, the chart obtained trough the conversion of every detected onset to an arrow was decided to be "Expert" (maximum) difficulty. At this point, it was necessary to find some filters to pass from "Expert" to lower difficulties. Other onset detection functions were taken into account, but, unfortunately, all of them had either too many positives or were inconsistent with the music genre. Taking into account this, from experience, after doubling up or halving in speed a constant sequence notes the chart still feel on rhythm, the first realised filter was set up to locate such parts and remove one step every two.

Unfortunately, using the same kind of solution for the second filter wasn't feasible since the song would just end up with extremely slow constant parts and insanely fast patterns everywhere else. As such, an alternative route was searched. Since the original prediction isn't in any way perfect and since the second filter will have to remove a significant number of arrows anyway, potentially disrupting any form of rhythm, for the second, third and fourth filter the established rule was to simply keep, respectively, one arrow every two, four and eight.

Unfortunately, testing revealed that a low (but acceptable) number of arrows wasn't enough to make a chart suitable for beginners since the high number of sensors ended up being a significant challenge. To address the issue, the external arrows were given a lower probability to be used for lower difficulties.

Difficulty levels

Every song has five different difficulty labels (Beginner, Easy, Medium, Hard, Expert) but that doesn't mean that two charts with the same label offer the same degree of challenge. In order to properly convey to the user the difficulty of a song, an automatic level detection was due.

This could be represented by a number obtained after the careful analysis of an experienced player and takes in account every aspect of a chart. Unfortunately, since such experience wasn't available, a simpler method had to be used. Under the (faulty) assumption that arrows are evenly distributed, it was decided to use the average number of arrows per second as an index. From there, every song is assigned a level based on a non-linear scale, from 1 to 13. The non linearity reduces the difficulty gap at higher levels since the further one goes, the harder is to improve.

C.10.4 The converter

Given the current state of art, it will probably be impossible, for years to come, to produce chart with same quality as the handmade ones. In addition, our autostepper only uses normal arrows so that jumps (two arrows at the same time), holds, rolls (like an hold but you need to keep pressing and releasing) and mines (avoid pressing) could not be included. As consequence, to provide some high quality content, a program able to convert four arrows charts into N-arrows ones was made.

C.11 AIR ExDaMa

After everything was defined, before passing to the user test phase, a name was chosen. When deciding on it three thing were taken into account:

- The name had to describe, in some way, the device,
- The name had to be unique enough so that an internet search would not place unrelated results above the correct ones.
- If possible, the name needed to have some common enough parts so that it might show up for related researches.

The best found way to appease all three criteria was an acronym. To decide upon the name, all the words related to the device were written down as a list till enough initial letters were available. The first word that we tried to form was AIR, since it could represent the product in two ways: it was the name of the laboratory where it was developed and it could refer to the ability to sense the hand without touch. After a meaningful acronym for the first word was done, the remaining part was chosen trying to complete the sentence appropriately. The final result was AIR ExDaMa: Advanced interactive rhythmic exercising dancing machine.

Appendix D

User manual

Figure D.1: Image of AIR ExDaMa. Every sensor is here associated with their corresponding ID/key.

D.1 How to play

To start the device, plug in the power cord and make sure that the multiple socket is set on. The system will then boot. During this phase the make sure no one is standing near the sensors or it might interfere with the calibration process. After the LEDs turn off, it's fine to approach the machine.

Use the green (”Enter”) and the red (”Esc”) buttons together with the sensors 1,2,4,5 to navigate. Starting from the game's main menu choose the default option four times using ”Enter” and the song selection menu will appear. Since the interface is intuitive and long to describe, it won't be here explained.

Use sensors 1 and 5 to move around the song selection menu and press enter while holding 2 or 4 to lower/rise the difficulty. Double press enter when selecting a song to change the visual modifiers. The first one is recommended to be set on ”M” mode, the actual value depend on the user's preferences and ability, tough 150-250 have been proven to be a fine range for beginners).

While the song is playing, follow the visual instruction and press the respective sensors at the correct time. The sensors match the in game notes from left to right (e.g. the third arrow on screen correspond to sensor number 2)(Figure D.1)

Finally, if the sensors' sensibility become too low/high while playing, press ”Esc” while holding ”Enter” to recalibrate them. Make sure no one is standing in their proximity until the LEDs turn off.

D.2 How to properly manage the game

Game related rules:

- Avoid wearing magnetic object while playing (or placing them in proximity of the sensors).
- Never clean the sensors with standard disinfectant for surfaces (the correct product for that is yet to be determined).
- While playing, regularly recalibrate the system.
- If the ”enter” button stop working, press both the difficulty change combinations to make it work again.
- Avoid using force while playing, just touching the sensors is more than enough.

- Whenever the sensors are booting or recalibrating (LEDs on), stay away.

- When updating the code, make sure to appropriately select the sensor's ID and LED color.

- When changing the ID/LED color pairings, make sure to change it also for the calibration script. Defaults are rainbow colors starting from red = ID 0.

- Unless necessary, don't change the game's noteskin as it has an high probability of crashing the program if using Stepmania.

- Fine-tune the sensors with the provided calibration program and the in game input delay compensation whenever the game is either assembled or major configuration changes are applied. Remember to also reconfigure the input key binding,

- When calibrating in automatic mode, the trigger threshold must be >=1 and >= of the release one. Unless the debounce time filter (a Stepmania option) is used, it's not recommended for both those values to be lower than 1 and to have a difference <2 (e.g. the most sensitive recommended setting is 3-1).

System related rules:

- **Double, triple, quadruple check before adding a Li-Po battery to an ESP. Placing then in reverse will fry the board and since, in cabled mode, every controller is connected, there is a risk to break all of them.**

- **Never, for any reason, update the raspberry to prevent any back-compatibility issue.**

- **Be extra careful when attaching/detaching cables from the ESP as the pin or the socket might break (especially the power and USB socket).**

- To shut down some sensors without touching the cables, use the ON/OFF toggle present on the board. To shut down all sensors, plug off the USB from the transformer and not the connectors. This will maximize the joints' lifespan.

- Check screws from time to time.

- While assembling the frame, try to keep all bars parallel/perpendicular to the ground and prevent bending.
- Avoid tightening sensors' related screws too much.
- Make sure that the naked part of the capacitive sensors' cable is hidden between the silicon and the plastic back cover.
- While mouse and keyboard are not required to play, they are necessary to use the RPi and activate the auxiliary programs (calibration and diagnostic) so it's always better to have them on hand.
- It's better to keep the used sensor/back cover pairing since the holes might be a few millimeters off.

D.3 Modify the system

D.3.1 Add songs

Create a new playable chart from an audio file

There are three ways to add steps to a song:

- **Autostepper**

  The autostepper is used to produce playable songs with minimum time consumption, at the price of musical accuracy and absence of special commands. In order to use it, a computer with python3 and the "Essentia" library is necessary. After downloading the "Autostepper/Autostepper" folder from the Github repository (F.3), place all the audio files to process in a newly created "CONVERTER" subdirectory (the supported extensions are mp3, ogg and wav). After that, run "Onset based autostepper.py" and wait for the process to finish. The output data will be in the "OUT" folder. Copy and rename it with the name you want to see for it while playing.

- **Song converter**

  The song converter can be used to convert a song from a four arrow format to an N one (seven is the default). This is the best method if the song in question already have a chart of the desired difficulty. Only python3 is necessary to run this program. After downloading the "Song converter" folder from the Github repository (F.3), place already charted songs in a newly created "CONVERTER" subdirectory (the way files are organized doesn't matter) and launch the program.

After the execution has ended, all input file will have been converted. WARNING: All the data files are substituted by the program so, in order not to lose the original version, make a copy of it beforehand.

- **Manual stepping**

As, the saying goes, to get what you want you need to do it yourself. If none of the above methods is suitable, it's possible to manually add steps to a song. There are many ways to do it, ranging from writing everything by yourself with a text editor to the use of dedicated software. Here it will be reported how to do that with Stepmania's built-in editor. First of all, go into the game directory where songs are stored (/usr/games/stepmania-5.1/Songs). Once there, open the folder where you want the track to be added to (or create a new one) and make a new directory where to you can place the song (using the same name as the song is recommended but not necessary). Stepmania support all the autostepper's extensions and some more, check the official game wiki/site for more info.

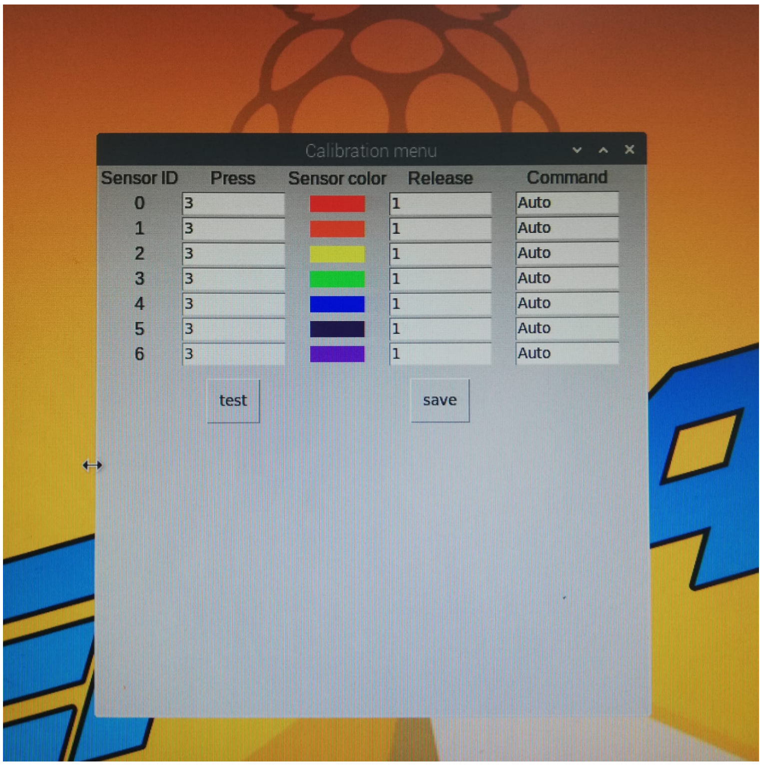
After this, open the game and select "edit mode". Search for your song and choose the type of chart (dance mode, difficulty etc..). After the editor opens, follow the instructions to know which keys to use. In case of getting stuck, several guides online can give a better explanation that what could ever be done here.

The edit mode also allows to change already existing songs, if needed.

Add songs

Songs are organized by the game in packs. Packs are directories that contain a list of folders storing, in each one, the files necessary to play a song. As a matter of tidiness and loading time, packs should never have more than 50-100 songs tough, a real upper limit, shouldn't exist. In order to add a new song, add its folder to the path "/usr/games/stepmania-5.1/Songs/Pack-name". Use "Reload songs/courses" within the game options menu to make sure changes are applied.

D.3.2 Change calibration parameters



Sensor ID	Press	Sensor color	Release	Command
0	3	🟥	1	Auto
1	3	🟥	1	Auto
2	3	🟨	1	Auto
3	3	🟩	1	Auto
4	3	🟦	1	Auto
5	3	⬛	1	Auto
6	3	🟪	1	Auto

Figure D.2: Image of the calibration tool's GUI.

If the user feels that the sensibility of some sensors is inadequate or want to customize it to his preference, this is possible without reuploading the code. First of all connect mouse and keyboard to the RPi and boot the system. After everything is loaded close Stepmania and execute, in order, the `"a_stop_driver.sh"` and ”calibration.sh” scripts on desktop. A simple UI for recalibrating the sensors will appear (Figures D.2. First of all, find the sensors to recalibrate by matching the UI color with the LEDs'. Then, choose between the ”Auto” and ”Manual” calibration modes and fill the textboxes with appropriate values (see D.3.3). After everything is done press ”test” and wait for the recalibration (like always, stay away from the sensors while the LEDs are on). Once the LEDs turn off, try out the results by checking the LEDs (they turn on while the sensor is pressed). Repeat the process till a satisfactory result is obtained, then press ”Save”, wait for the recalibration and close the program. To start playing again either reboot the whole machine or execute the ”driver start” program. Then run the `"f_stepmania.sh"` script.

D.3.3 How to properly calibrate

How to change the calibration parameters has been shown in last section. Nonetheless, in order to choose the best values is necessary to know how the system works. The necessary information in this regard can be found written in C.10.1.

Here some rules and tips will be listed (assuming the automatic mode):

- The press value must be `>=` the release one.
- The press value must be `>=` 1.
- It's better to have press-release`>=` 2 or the sensors/Stepmania might not work properly due to a bouncing phenomena.
- It's better to have the release `>`0 to add environmental drifting resistance.
- As a result, 3-1 can be considered the highest stable sensibility.

D.3.4 Diagnostic mode

Whenever a sensor is behaving strangely, it's possible to use the Diagnostic mode to check its readings. First of all disable all sensors except for the one of interest by using the ON/OFF toggle on the ESP board. Exit stepmania and run, in order, the `"a_stop driver.sh"` and ”diagnostic.sh” scripts on the desktop (diagnostic.sh must be executed in terminal). The output will show the raw sensor readings with some added special values:

- 0-252 measured capacitance value (in symbolic units)
- 253 reading error -1
- 254 reading error -2
- 255 any other read value

The only encountered situation in which error codes were encountered with an ESP32 board was in case of bad connection with the sensor. For more information about the typical output features read D.3.3. To start playing again turn off the last board and then turn all of them back on. Then either execute the `"b_start_driver.sh"` program and run the `"f_stepmania.sh"` script or reboot the whole system.

D.3.5 Mapping sensors

In order for Stepmania to know which sensor correspond to which arrow, mapping the ESPs is necessary. After starting the game, proceed into "options" and then "configure joystick/keyboard mapping". Here, it's possible to set up input aliases. Move down to where keys for playing are defined and modify them by pressing enter and then the desired sensor.

D.3.6 Input delay

Reading the capacitance value, filtering, wirelessly transmitting and passing data to stepmania takes time. To address this delay the program offer in "options/input options/calibrate audio sync" the possibility to compensate for it. This option is not available while using the "Simply-Love" theme so it's necessary to momentarily change it back to default for this task.

D.3.7 Debounce time

When pressed or released, buttons are known to bounce. Despite the sensors being capacitive, they can behave like real buttons due to the way their data is handled and the presence of noise. Located in "options-¿input options", the "input debounce time" filter allows to push the sensible range of the sensors to their limit since it may grant stability for extreme calibration parameters values (e.g. press-release¡2, see D.3.3 for more details about the calibration process).

D.3.8 Adapt the structure to the user or desired gameplay

In order to better customize the game, the position of the sensors, monitor and the aperture angle can be chosen at will.

Change the sensors' position

To move a sensor along a bar, unscrewing till it can barely slide if slightly pushed it's enough. It might also be necessary to move the case to keep the cables tidy and in reach. If the sensor has to, instead, be placed on another pole, make sure to place the LED's perfboard as neatly as possible to reduce the risk of breaking the soldering. When fixing the a sensor back in place, avoid tightening too much and always use washers on the silicon side.

To change a sensor's height, the correct approach is to slide the bar it is residing on. Unscrew the bar on both sides till it can slide and place it at the desired height and tighten one side. After bubble levelling it, tighten the second side.

Change the monitor height

To change the monitor height unscrew the two small bars holding it (till they can barely slide). After placing it in the desired position, fix it on one side then, after bubble levelling it, fix the second one.

Change the aperture angle

First of all, unscrew the two angular bars reinforcing the back joint (doing so only at one extremity is fine) and remove the ground bar at the front. Then, check that there are holes on the bar to fix the frame's wings in the new position. In case they are absent, make them. Use the angular joint handle to remove the block (DO NOT PUSH THE RED BUTTON ON IT SINCE IT UNSCREW THEM) and, using a goniometer as in figure, fix the wings at the desired angle and mount the front bar back on.

Figure D.3: Image showing one way to use to goniometer to set the aperture angle.

D.3.9 Change the number of sensors

Between the several possible modification that can be done to the game, the change of the sensors number is one of the easiest. If the desired one is lower, no action is required. If the target is, instead, higher, it's necessary to change the `MAX_SENSORS` constant in all the RPi scripts and ESP code. The maximum limit for that value will probably be high enough to have any reasonable amount connected. Remember also that the autostepper and the converter use the same constant so it's necessary to modify them too. In addition, for the autostepper, the probability distribution for the arrows' position has to be adapted too.

D.3.10 Change the sensors' colors

To change a sensor's color it's necessary to update the code. Take note of sensor's ID by matching its LED color with the one showed in the recalibration script and reupload the ESP code (stored in the github repository (F.3) under the "ESP" folder) changing the defined led RGB values and setting the correct ID. After the change has been applied, go into the RPi directory `"/usr/games/stepmania_driver"` and open "colors.txt". There, update the color of the modified sensor (they are in order of ID) using its hexadecimal value.

D.3.11 Add a new request code for the sensors

By fiddling a bit with the code, it's possible to easily add a new request from the RPi to the ESP. In the ESP code, there is a check for incoming Wi-Fi data that, when true, scan the first byte trough an else-if to determine the request. To add a new one, just add a new condition to it. As far as it goes for the RPi side, it's possible to copy paste the "diagnostic.py" code and remove the part that keep reading and printing to obtain a template that simply sends a new message code.

D.3.12 Song metadata and gimmicks

Songs can have attached files (e.g. images, videos) that can be used by the game. In order to add these things, it's necessary to add a code line in the .sm file header in the chosen song folder (consult online guides or check already made files for how to).

Another interesting possibility for songs are gimmicks. Gimmicks are songs that massively change the UI (see figure D.4), making the commands' reading extremely difficult. Nonetheless, due to the extreme care that is usually given when making them, these are extremely fun and challenging to play.

Figure D.4: Image of a gimmick song [2]

D.3.13 Add skins, themes and so on

Stepmania is an extremely customizable program and literally every part of it's UI can be changed. While making a brand new stuff is certainly an option, tons of already made stuff is present online where it's bound to exist something that can satisfy the user.

D.3.14 Run Outfox

The game has been observed to massively drop in fps for high difficulty levels, in order to solve the issue Outfox was installed. Outfox is a Stepmania fork with an optimized engine. It can be run trough either the "outfox.sh" script present on desktop or by going into its directory "/usr/games/outfox". Unfortunately the fps gain on raspbian is minimum if not absent but, on the other side, it provides a good default theme and, since it's being actively developed on most platforms, it's devoid of some annoying bugs present on Stepmania (e.g. difficulty change bug, crash on arrow skin change). The fps issue was fixed trough the in game option that clear the Z buffer.

D.4 Troubleshooting

In this section, a workflow to locate the source of a malfunctioning will be shown. First of all, in order to efficiently spot the problem, it's necessary to understand the role of the various components.

AIR ExDaMa can be seen as the equivalent of a desktop PC setup. There is a computer (RPi), a keyboard (the sensors), a monitor, a power supply and a case (the physical frame) to host everything.

D.4.1 Power Supply

Problems related to the power supply are easy to find out and are most likely to be detached or broken cables. The main indicator of a power supply malfunction is one (or more) component not turning on or randomly switching off.

Luckily, every electrical component has a led that lights up when powered, so it's simple to find out where the problem lies (also, dim LED light might be an indicator of a bad connection).

Important is to remember that the RPi supply has an additional button that toggle the power on/off, if neither the led nor the fan are active and all connections are ok, try pressing that button.

Regarding the ESP's, they have a led on their back emitting a green light while regarding the RGB LEDs, they turn on at the start, while processing requests and every time they are pressed.

D.4.2 Monitor and raspberry

If the monitor is not showing any image then the connection with the RPi should be checked. If nothing happens after a while, there is a broken component. If the raspbian loading screen appear but the OS doesn't boot up, the issue will be there printed. In most cases it's gonna be a problem with the SD card being either badly plugged or broken.

If there is, instead, an issue with the game not running properly, then it's purely a software issue. Unless some data gets corrupted or the if system hasn't been handled properly, this should never happen. The easiest solution in this case is trying to reinstall the game but, if that fails too, reconfiguring everything from scratch might be only way.

D.4.3 LEDs

The LEDs always light up at boot or when the ESPs are processing a request from the RPi. In case one doesn't, (unless the ESP in not working) it means that there is an issue with it. First of all, the connection should be checked and the cables should be moved around a little. If even that doesn't work, it might be that the cable broke or the LED fried. This can be checked with a multimeter.

D.4.4 Sensors

If the issue is about a sensors not working, first of all check connections and recalibrate. If the LED doesn't turn on, try rebooting the ESP. If it still doesn't work after that, either the the cable/joint of the capacitive is broken or the ESP is. WARNING: magnetic fields easily crash the ESP's so avoid any kind of exposure. After pointing out the faulty sensors, start by checking out that the pink cable's peeled part is not exposed (it give rise to strong noise if so). If it's fine, turn off all sensors aside from a malfunctioning one and connect mouse and keyboard to the raspberry. After that, run the diagnostic.sh program on the desktop (make sure to ”execute in terminal” or no output will be visible). A lot of numbers should be getting printed in a terminal window.

Those numbers are the unfiltered readings of the sensor, staying away from it, you should expect all values to be within maximum two points from the mean, aside from a few outlayers that can assume any integer value lower than the mean. If no value is showing, then the sensor is still badly connected or the ESP broken. If the variance is higher then required, then the peeled part of the cable is exposed. If the numbers stop scrolling after a bit, then the power supply link is probably damaged and it randomly detach itself or a magnetic field is interfering. If it's none of the previous cases, try closing an hand in on the sensor and check the values. If they don't change, then it's a problem with the cable connection. If all the sensors are not working then it's most likely an issue on RPi side. Assuming nothing got damaged/corrupted, rebooting everything will solve everything.

D.4.5 Buttons

There is a rare issue for which the enter button stops working. Pressing the difficulty up and difficulty down key combinations often mend the problem. If it persist, rebooting the system is the solution. If buttons still don't work then they are most likely detached.

D.4.6 Conclusion

The previous part was simply a rough troubleshooting sequential approach to quickly spot problems, dedicated to people that lack knowledge of the underlying system. That said, several extremely improbable situations were omitted while some others might just have been forgotten so, to effectively repair AIR ExDaMa, a full reading of the technical chapters is recommended.

D.5 Known issues

Here the known issues and the way to address them will be reported:

- Rebooting just the RPi disconnects the ESPs, so they have to be rebooted too.
- The "Enter" button might stop working for no reason. Pressing the difficulty up and difficulty down combinations usually solve it. If the issue persist or it happen to the escape button, reboot the system. This issue should be already solved tough.
- To avoid soldering, the RPi use weak connectors to read the buttons. As consequence the connection come off at the slightest touch.
- The LED cables might accidentally short-circuit due to the poor soldering. While this doesn't pose any threat, it will change the LED color or prevent it to turn on. Moving the cables around and slightly sliding the sensor can fix it. This issue should have also been fixed trough the use of hot glue.
- If a sensor is not recalibrated for too long, it might get triggered without any input or might became too hard to activate.
- If the monitor's power supply cable is not left lying on the middle height support of the structure, it's gonna detach after while.
- The strength of the white connectors used on the ESPs is quite high compared to the one of the cable joint or the soldering (especially for the power supply one), as such too much plugging/unplugging will result in the need of frequent repairs.
- Presence of magnetic fields or cleaning the sensors with unappropriated products (e.g. disinfectant for surfaces) will cause the ESPs to randomly stop working and requiring a restart.
- The quality of the soldering of the on-board USB port for the ESPs is poor, as such it's necessary to be careful to avoid breaking it (tough glue can be used as fixer as long as the cables don't break).
- Placing the Li-PO battery in reverse will burn the ESP.
- Powering up an esp trough LI-PO or USB port will power up all the connected ESPs trough current exiting the Vin pin. As such disconnecting them before placing batteries or uploading new code is recommended to avoid damage.

- Stepmania might crash when the noteskin is changed, so it's advised to stick to the set one if possible. OutFox should be devoid of such issue.

- The "simply love" theme doesn't have an automatic calibration for the input delay, so it's necessary to revert momentarily to another theme to do it.

- Stepmania start to significantly drop in fps when the difficulty level rise too much. Luckily this will never affect beginners and intermediate players but high level ones won't be able to play properly unless the resolution is lowered (for that a wrong aspect ratio is necessary).

- The frame oscillates, sometimes significantly, while playing. Nonetheless, an experienced player can play without it moving at all.

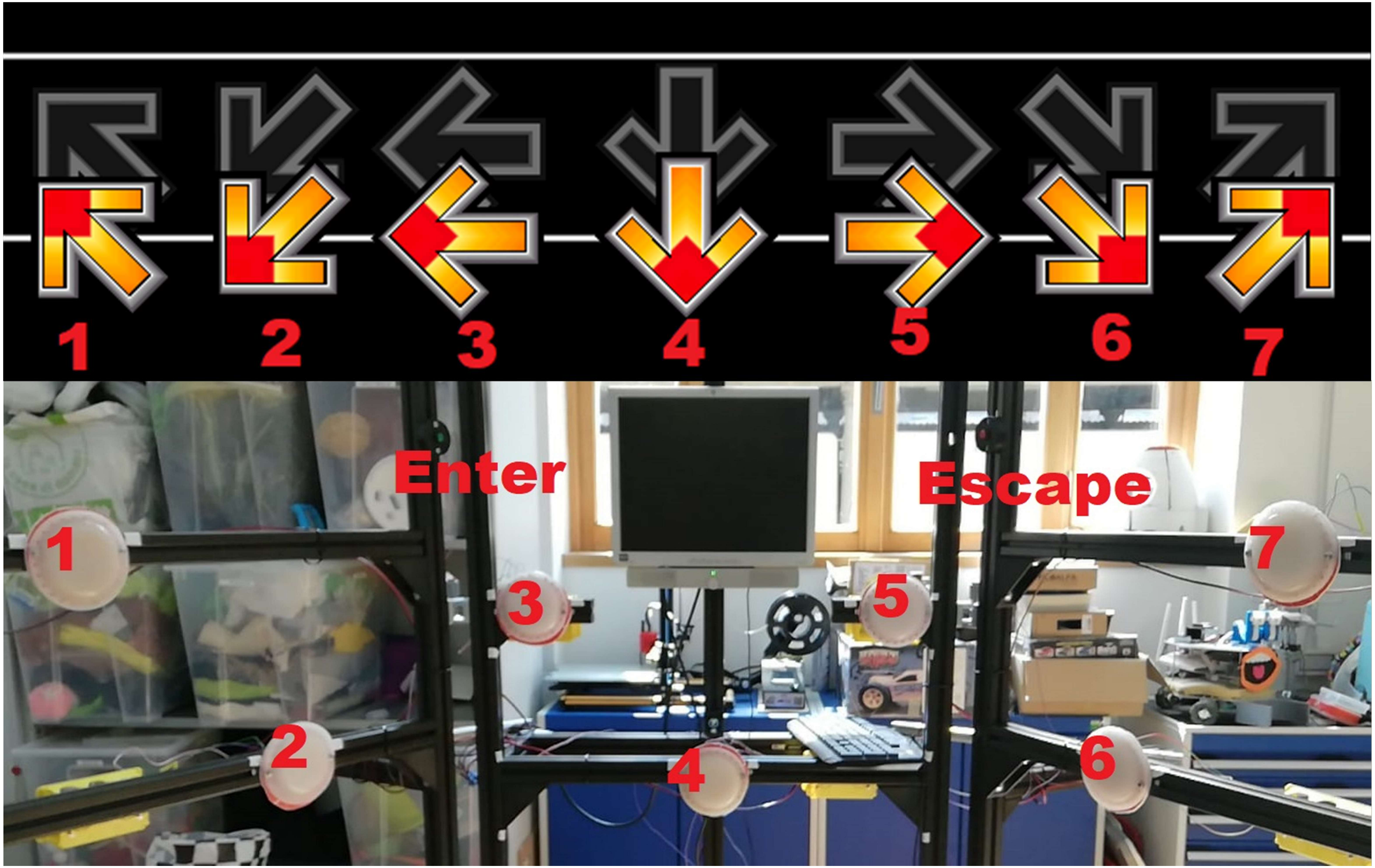
- The ESP might give an error when uploading code. The workaround is to keep trying till it works. Some tutorials on how to fix the issue are present online, but they require hardware modifications.

- Since the command binding on Stepmania is not linked with the driver, when changing the sensors positions it's necessary to edit the "ALIAS_UP" and "ALIAS_DOWN" constants to match the desired sensors for the special difficulty up/down command.

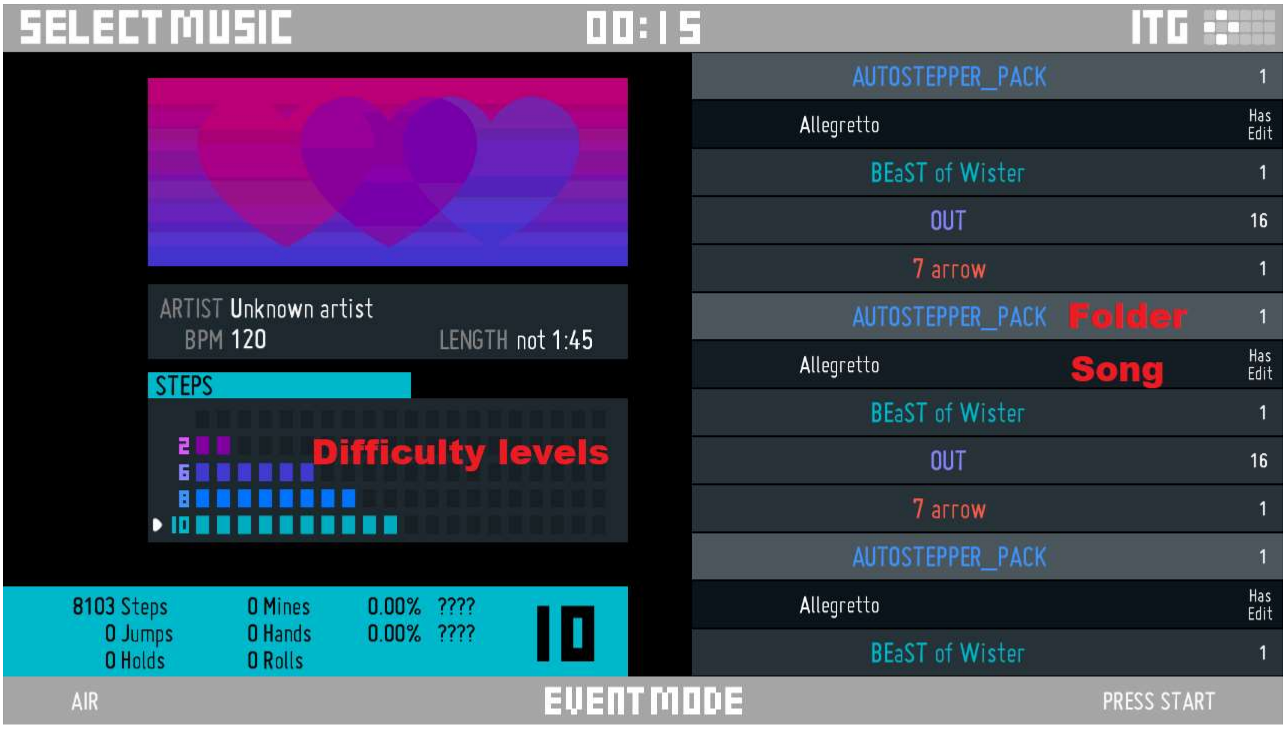
Appendix E

Instructions

In this appendix the instructions for playing the game (the ones printed for the machine build in AIRlab) are reported.


1
2
3
4
5
6
7
Enter
Escape
1
3
5
7
2
4
6

1) From the main menu, select **“GAMEPLAY”** using the **“Enter”** button. From there keep selecting the first option for **other three times**. The song selection menu will appear.



2) On the right side of the screen, you will see the song wheel. Written in **white** are the **songs**, in **colors** are the **folders**. Up to one folder can be opened at a time. Use sensors **“2”** and **“6”** to **navigate**.
3) When a song is selected, an interface is visible on the left side where various data is shown. The most important are difficulties. Press **“Enter”** while holding down sensor **“3”** or **“5”** to respectively **lower or increase the difficulty**.
4) Press **“Enter” to select a song**, double press it to enter the option menu.
5) To **forfeit** a song, **hold down either “Enter” or “Escape”**.
6) **Recalibrate** the sensors frequently by **pressing “Escape” while holding “Enter”.**
7) To turn off the game press “Escape” and then “Enter” for three times. Then select “EXIT GAME”. Once the game has closed press sensor “5” and then two times enter “Enter”.

TIP: If the **sensors do not react**, use **more fingers** or the palm of the hand to touch them.

The best way to trigger the sensor is shown in figure E.1.

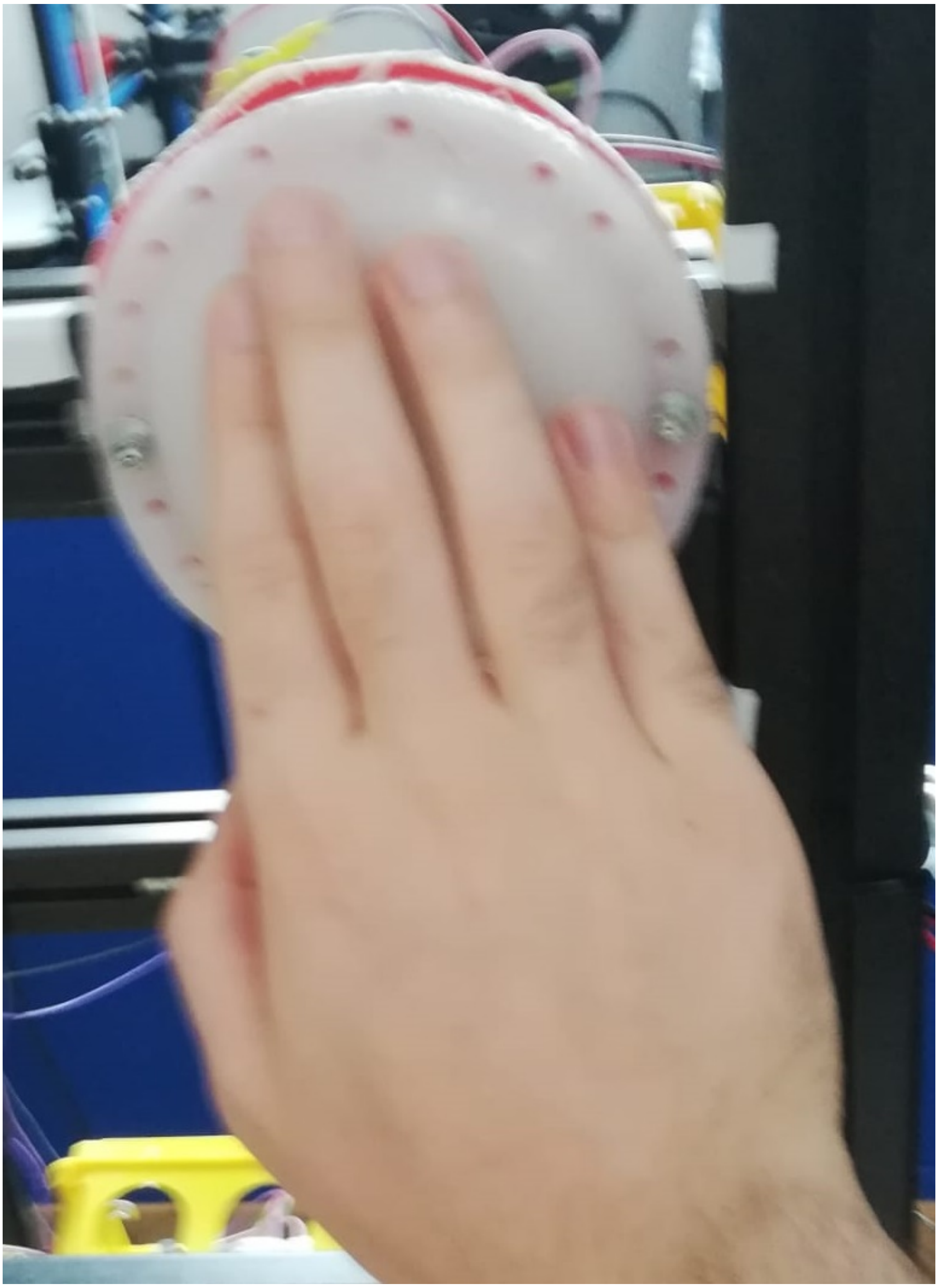


Figure E.1: Here the ideal hand position to trigger the sensors is represented.

The sensors should be lightly touched only by the tips of four fingers. The point of contact is supposed to be on the upper part of the disc so that the hand, coming at the sensor from an angle, is able to contribute to make the movement more easily detectable. The fingers should be slightly arched for both utility and safety reasons. The arrows have to be pressed when the sliding command is over the shadow at the top the the screen. Keeping a sensor pressed won't work, the commands have to be executed with timing. There are special notes in the game:

- Holds: These arrows have a grey shadow below them. After pressing them, it is required to keep the hand on the sensor for as long as the shadow lasts.
- Rolls: These arrows have a green shadow under them. They work like the holds but instead of having to keep the sensor pressed, it is necessary to presss them over and over again (in the process make sure to bring your hand far enough for the sensor to deactivate or it will be registered as an hold).

Appendix F

Datasheet

Disclaimer: more information about the wiring can be found from B.1.3 to B.1.5, in B.1.7, B.4 and B.5.

F.1 ESP32 wiring

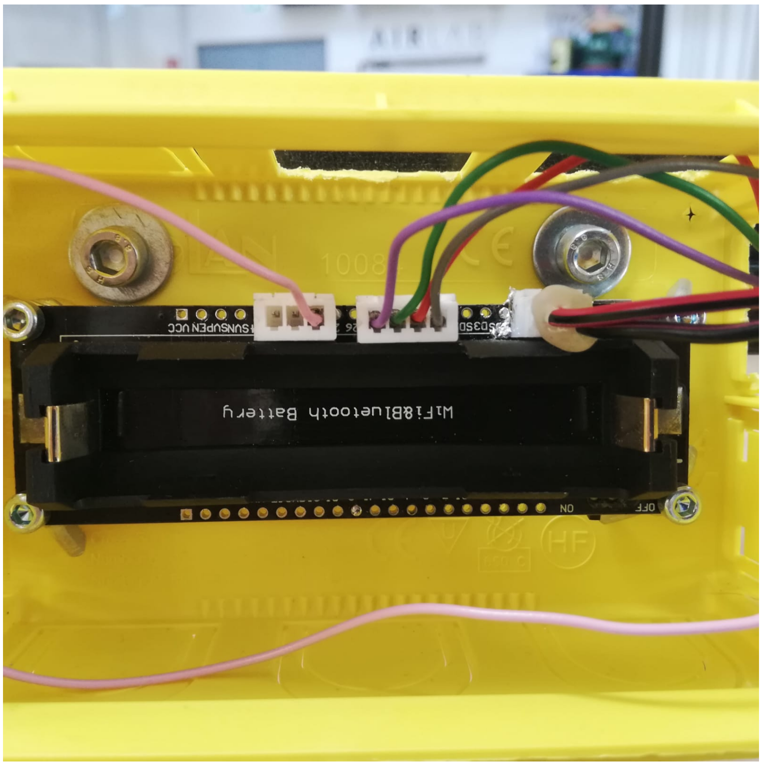
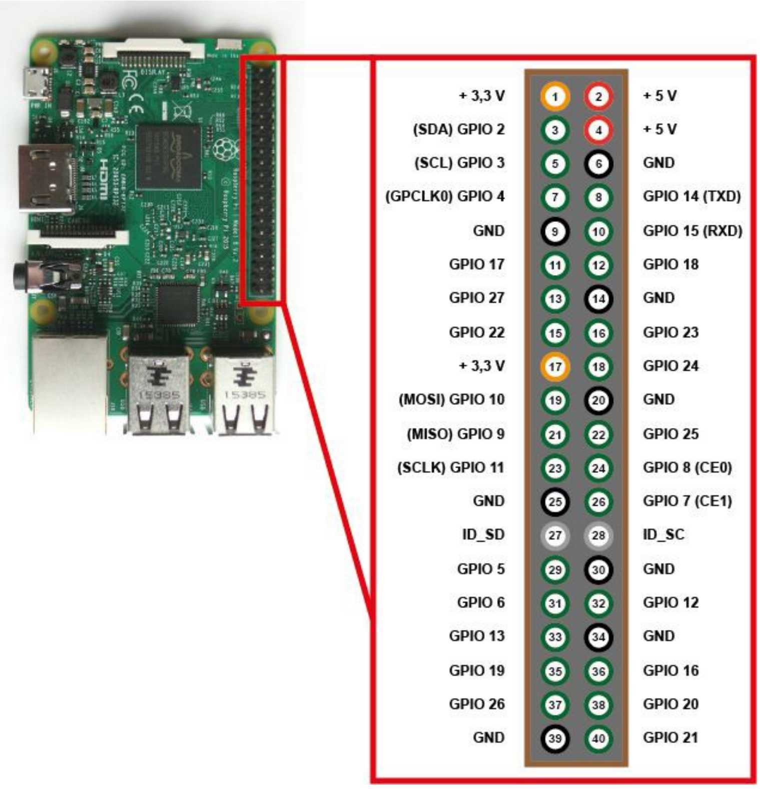


Figure F.1: Image of a wired ESP32

As shown in figure F.1, the ESP32s are wired as following (from right to left):

- The two pin connector used for the power supply is attached to the NC and 5V pins
- The four pin connector used for the LED is attached to pins GND, 12 (R), 14 (G), 27 (B).
- The three pin connector used for the sensor is attached to pin 13 (T8) and two free pins.
- On the back of the board, NC and GND are short circuited trough a soldered cable.

F.2 RPi4 wiring



+ 3,3 V	1	2	+ 5 V
(SDA) GPIO 2	3	4	+ 5 V
(SCL) GPIO 3	5	6	GND
(GPCLK0) GPIO 4	7	8	GPIO 14 (TXD)
GND	9	10	GPIO 15 (RXD)
GPIO 17	11	12	GPIO 18
GPIO 27	13	14	GND
GPIO 22	15	16	GPIO 23
+ 3,3 V	17	18	GPIO 24
(MOSI) GPIO 10	19	20	GND
(MISO) GPIO 9	21	22	GPIO 25
(SCLK) GPIO 11	23	24	GPIO 8 (CE0)
GND	25	26	GPIO 7 (CE1)
ID_SD	27	28	ID_SC
GPIO 5	29	30	GND
GPIO 6	31	32	GPIO 12
GPIO 13	33	34	GND
GPIO 19	35	36	GPIO 16
GPIO 26	37	38	GPIO 20
GND	39	40	GPIO 21

Figure F.2: Here the RPi4 pinout is shown

Using figure F.2 as reference, the wiring of the RPi4 is as follow:

- Pin 34 is the common ground for both buttons
- Pin 36 (GPIO 16) is the weak high for the Escape button.
- Pin 38 (GPIO 20) is the weak high for the Enter button.

F.3 Github repository

All the written code has been backed up on the following GitHub repository:

`https://github.com/AIRLab-POLIMI/AIR-EXDAMA`

F.4 Programs location on the RPi

All the used software on the RPi has been either placed on the desktop or in /usr/games.