UKRAINIAN CATHOLIC UNIVERSITY

BACHELOR THESIS

Development of analytical system for sport fencing

Author:
Oleh SMOLKIN

Supervisor:
Oles DOBOSEVYCH

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Declaration of Authorship

I, Oleh SMOLKIN, declare that this thesis titled, "Development of analytical system for sport fencing" and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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Signed:

Date:

"The First Sword of Braavos does not run."

Syrio Forel

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Development of analytical system for sport fencing

by Oleh SMOLKIN

Abstract

Fencing is an extremely fast sport. 40ms - time that is needed for hit registration. It's 10 times faster than a blink of an eye, so it's impossible to measure fencer's progress objectively even for a coach.

We are the first who proposed to store and analyze fencers data. Our solution is a small device, which connects to the fencer exactly in the same way as to existing scoring equipment. The device sends information to a smartphone via Bluetooth. Also, it contains a bunch of sensors that allow measuring speed, reaction, and technic of the fencer. All data is gathered in the cloud, so we can process it and provide coach and fencers with analytics. Gamification will make the training process more attractive to children.

We alread have a prototype that is actively tested in local fencing clubs.

Acknowledgements

First of all, I want to sincerely thank Oles Dobosevych, who was always ready to help and gave advice on any question related to the project and just inspired me to work hard during the last four years. Thanks to Oleh Farenyuk who regularly consults on all hardware related issues.

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Finally, I want to thank my family, who everyday supports me.

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List of Abbreviations

USFA	**U**nited-**S**tates **F**encing **A**ssociation
API	**A**pplication-**P**rogramming **I**nterface
REST	**Re**presentational-**S**tate **T**ransfer
NRC	**N**ike-**R**un **C**lub
IMU	**I**nertial-**M**easurement **U**nit
LED	**L**ight-**E**mitting **D**iode
DC	**D**irect-**C**urrent
PWM	**P**ulse-**M**odulation
UUID	**U**niversally **U**nique **ID**entifier

List of Symbols

V	volts
mAh	milliampere hour

Chapter 1

Introduction

1.1 Motivation

Development of science and technologies has had a huge influence on sport in many areas. The main directions are bringing technologies for increasing physical performance of the athlete, improvement of objectiveness of the refereeing system and of course sports analytic.

Sports analytic already shows impressive performance in a lot of team sports such as basketball, football, baseball and much more. In this case mostly are used computer vision algorithms, which allow tracking interaction between athletes and provide insights into team tactics and strategy. However, it's still not such popular in individual sports and in particular combats, where it isn't such a problem to analyze whole picture and statistics, but rather monitor small details of athlete technique. Some solutions introduce devices which allow tracking correctness of athlete moves in such sports as boxing, tennis, swimming, etc. In most cases, they just use a kind of wearable hardware solution, which allows getting a limited amount of data.

Fencing is a unique sport because it connected with electronics for many years, so it's much easier to integrate more sensors. Fencer needs to be connected to scoring equipment to have the ability to determine who hits first during a bout. Inside existing scoreboards 40 ms is a hardcoded duration to differentiate clear hit. If the difference between opponents hits is more than 40 ms, clear hit registered, otherwise - double. This time is ten times faster than a blink of an eye, so even coaches can't objectively estimate the performance of an athlete. If coach see clear metrics of speed, reaction and other athletes qualities he can plan training program more effectively. Introduction of metrics for performance estimation allows easier track athlete progress during the time.

Another problem that most clubs still use wire scoring systems, which are pretty expensive and very complicated in installation. Therefore commonly clubs have only four pistes, so in the same time only eight fencers can practice while other twenty need to wait. This problem is especial crucial with kids groups, when in the same time can practice up to forty children.

1.2 Fencing history

Fencing history can be traced back to the Middle Ages when the art of using a sword was one of the essential military skills. With the development of sword fighting technique, fencing masters produced books about their systems. Accumulated knowledge formed the first fencing schools. Italian and French schools, which were founded in the 18th century set basics of modern fencing.

Fencing developed from military academy classes more into the sport in Angelo's School of Arms in London. Domenico Angelo set up rules of posture and footwork which are used nowadays. In 1896 fencing became part of first Olympics games. [CENTRE, 2017] Since 1990 in fencing rules distinguish three kinds corresponding to weapon: epee, foil, and saber. The epee is a thrusting weapon with the entire body as the valid target. The foil is also a thrusting weapon, but with the torso as an only valid target. The saber cutting and thrusting weapon that targets the entire upper-body, except the weapon hand.

At the earliest competitions, referees paint the tip of epee to register the hit, so a fencer gets a score if he marks jacket of an opponent with paint. Therefore fencers have white equipment nowadays. First electronics scoring apparatus was used on epee competitions in 1933. Epee has button at the tip of blade, epee-fencer need to hit opponent and push button on curtain level. Foil and saber were electrified only in the second half of the 20th century. Foils and saber fencers need to wear electric jacket, so hit is registered, when fencer with his weapon close the circuit on opponent jacket. Modern scoring systems also show score, bout time, info about period, penalty card and other specific functionality. [CENTRE, 2015]

Wireless scoring equipment was first-time officially used on international competitions in 2006.

Chapter 2

Related works

2.1 Fencing equipment

Fencing is connected with electronics from 1930. In epee it uses button on the tip of blade to registrate hit. Epee is connected to scoring equipment with wire which is weared under fencer jacket.

At the market already exists wireless scoring equipment. The main providers are StM, Leon Paul and Favero. All existing solutions have pretty similar functionality. They all contain a pair of hardware transmitters which connect to fencer and send information to hardware scoreboard. All scoreboards are limited with the standard functionality of hit registration. StM solution transmits data via Bluetooth and also is compatible with an existing scoreboard. Leon Paul presents themselves as the most accurate system, but because it works with radio transmitter it can't be scalable to use with external devices. Favero is the cheapest solutions and also includes "training mode" - simple ability to signal hit without delay after the previous hit.

The main disadvantages that all systems are pretty expensive and provide limited functionality.

2.2 Sport analytics applications

At this moment fencers haven't any application for analytic, so we investigated the best solutions for other sports.

2.2.1 Nike Run Club

NRC is most downloaded run tracking application on Play Store. It use GPS data to track position of runner and provide statistic about speed, pace per each kilometer, route of run. All data about runs is stored and user can track his/her progress during the time. It also has levels, achievements and challenges for motivation of user and you can share progress with your friends . It builds personal plan based on profile data and gathered statistics.

2.2.2 Strava

Strava is more multifunctional application and oriented not only on runners but also on swimmers, cyclist and even for gym workouts. It also gathered data about speed, pace and burned calories. It's more concentrated on building global community. Also it has some interesting features such as visualization of gathered data during all workouts.

2.2.3 Garmin

Garmin is wearable fitness watches. As the most fitness trackers it allows to gather data about hear-rate, GPS location. In addition new version of device use IMU sensors for tracking technique of swimmers.

Chapter 3

Background information

3.1 Bluetooth

Bluetooth is a wireless technology which allows to transfer data on short distances. It was developed in the 1990s by telecommunications company Ericsson. The first purpose of technology use was for the development of wireless headsets.

Communication implemented with master//slave architecture with ability of master connect up to seven slaves.

In 2010 Bluetooth 4.0 was introduced. The new version implemented Bluetooth Low Energy protocol, which significantly reduced power consumption and made Bluetooth great again. Also, it increased bandwidth range to up to 100 meters with the stable signal up to 10 meters. [S.L., 2015]

Disconnected devices broadcast advertisement packets. For latency reduction, packets are broadcast on three different frequencies.

Client can read server data by accessing of characteristics UUID. Curtain characteristic contains curtain type of data, for example, heart rate or charge level. Similar characteristics are combined into services.

3.2 Madgwick filter

Madgwick filter is the state-of-the-art approach for correction of space orientation with inertial sensors. Euler angles are used In the most cases for description of orientation. Angles are represented as three by three matrix. Gimbal lock is the main problem of Euler angles. Matrix representation can be the same for different states. Also matrices is more calculation expensive.

Madgwick proposed to use quaternions for position representation. The quaternions are four dimensional complex numbers. It is represented in the form:

$$a + b * i + c * j + d * k$$

With property:

$$i^2 = j^2 = k^2 = i * j * k = -1$$

This property allows easy represent spatial rotation, which make it useful for orientation estimation. [Madgwick, 2010]

So first step is to read data from sensors and represent it as quaternions. Next step is to calculate offset of accelerometer through gradient step:

$$\nabla f\left({}^{I}_{W}\hat{\mathbf{q}}_{est,t}, {}^{W}\hat{\mathbf{g}}, {}^{I}\hat{\mathbf{a}}_{t+1}\right) = J^T\left({}^{I}_{W}\hat{\mathbf{q}}_{est,t}, {}^{W}\hat{\mathbf{g}}\right) f\left({}^{I}_{W}\hat{\mathbf{q}}_{est,t}, {}^{W}\hat{\mathbf{g}}, {}^{I}\hat{\mathbf{a}}_{t+1}\right).$$

$$ {}^{I}_{W}\mathbf{q}_{\nabla,t+1} = -\beta \frac{\nabla f\left({}^{I}_{W}\hat{\mathbf{q}}_{est,t+1}, {}^{W}\hat{\mathbf{g}}, {}^{I}\hat{\mathbf{a}}_{t+1}\right)}{|f\left({}^{I}_{W}\hat{\mathbf{q}}_{est,t+1}, {}^{W}\hat{\mathbf{g}}, {}^{I}\hat{\mathbf{a}}_{t+1}\right)|} $$

In the same way we represent gyroscope offset:

$$ {}^{I}_{W}\dot{\mathbf{q}}_{\omega,t+1} = \frac{1}{2} {}^{I}_{W}\hat{\mathbf{q}}_{est,t} \otimes [0, {}^{I}\omega_{t+1}]^{T} $$

With obtained value for accelerometer and gyroscope we can fuse it to estimate correction:

$$ {}^{I}_{W}\dot{\mathbf{q}}_{est,t+1} = {}^{I}_{W}\dot{\mathbf{q}}_{\omega,t+1} + {}^{I}_{W}\mathbf{q}_{\nabla,t+1} $$

$$ {}^{I}_{W}\mathbf{q}_{est,t+1} = {}^{I}_{W}\hat{\mathbf{q}}_{est,t+1} + {}^{I}_{W}\dot{\mathbf{q}}_{est,t+1}\Delta t $$

After all calculations we need to repeat this steps with new data.

Chapter 4

Proposed approach

4.1 Business analysis

4.1.1 Market

We consider the USA and West Europe as the main markets. By estimations, there are 100000 fencers in the USA. 36000 out of them are members of the United States Fencing Association. According to statistic average spends of US, fencers is $3000 per year. Spending includes club and association membership, blades and equipment. The average club membership price is $700.

The estimated amount of fencers on the German market is 200000, 26000 of them are members of the association. China market estimated in 300000 fencers with 49000 members of the association. UK association consist of 12 thousand members. Italy association consist of 20 thousands of fencers. From available statistics for different countries, we estimate the international market in 1.5 millions of people. Based on survey we calculate approximate spending of kids, juniors and high-level fencers. We estimate size of each segment and specify different conversion rate. Also, for different countries we assume different financial conditions.

As our product makes a much cheaper and easier club space arrangement, it gives the ability for young coaches to open new clubs and expands the number of athletes in existing ones. So in case of successful product launch, we can expect the growth of market size.

			Kid		Junior		Hig-level				
Blades	30	2	60	10	300	0	0				
FIE Blades	167	0	0	1	167	9	1503				
Tips	10	1	10	3	30	9	90				
Trips	200	0	0	6	1200	10	2000				
Competition	20	1	20	5	100	30	600				
Club	600	1	600	1,5	900	2	1200				
Association	70	0	0	1	70	1	70				
Repair	10	1	10	2	20	4	40				
		Total	**700**	**Total**	**2787**	**Total**	**5503**				
	USA	Number	70000	Number	13000	Number	1000				
Coef BM	1	Cost	49000000	Cost	36231000	Cost	5503000				
		Millions	49,00	Millions	36,23	Millions	5,50				
	Germany	Number	50000	Number	10000	Number	800				
Coef BM	0,8	Cost	28000000	Cost	22296000	Cost	3521920				
		Millions	28,00	Millions	22,30	Millions	3,52				
	UK	Number	10000	Number	6000	Number	500	**TAM**	**296,35**	**millions**	
Coef BM	0,73	Cost	5110000	Cost	12207060	Cost	2008595	**SAM**	**109,67**	**millions**	
		Millions	5,11	Millions	12,21	Millions	800	**TM**	**38,38**	**millions**	
	Italy	Number	10000	Number	10000	Number	500				
Coef BM	0,83	Cost	5810000	Cost	23132100	Cost	2283745				
		Millions	5,81	Millions	23,13	Millions	2,28				
	France	Number	9000	Number	5000	Number	500				
Coef BM	0,86	Cost	5418000	Cost	11984100	Cost	2366290				
		Millions	5,42	Millions	11,98	Millions	2,37				
	Other	Number	100000	Number	40000	Number	2000				
Coef BM	0,35	Cost	24500000	Cost	39018000	Cost	3852100				
		Millions	24,50	Millions	39,02	Millions	3,85				

FIGURE 4.1: Market estimation

4.1.2 Business model

Cost of our device is $50. It includes hardware parts, development, and production. After analyzing the market we decided to set a price $200. Also, we introduce recurring revenue from monthly premium subscription with an average price of $20 per month. Also we propose discount system for users who buy club subscription.

For now we develop more flexible system of subscription prices for different segments of user.

4.1.3 Market acquisition

Fencing is a pretty closed community with strong-tie connections around the world. Investigation of social networks shows that most fencers from the global community can be linked through up to 3 connections. From one side such structure makes product expansion on the market much easier, but on the other hand, any negative feedbacks can spread fast and complicate product promotion.

As in any other community fencing has people who are thoughts influencers and followed by the community. Easiest way to cover as many fencers as possible is first of all to approach high-level Ukrainian fencers, such as Olha Kharlan, who is the best saber fencer in the world; Bohdan Nikishyn – second epee fencer; Yana Shemyakina – Olympic champion at the 2012 Summer Olympics; Andriy Demchuk - Paralympics champion at the 2016 Summer Paralympics Games. In case of their adoption of the product, we plan to sign the contracts about promotion, which will facilitate entry into the market.

Next steps to promote our product are visiting the international competition. It's much easier to catch them through live demonstration when they really see how it works. Another advantage of competition promotions that it the most simple way to access professional fencers from the international market. All conversed athletes can evangelize on the local market.

Also, we have advantages, because a lot of fencers from Ukraine became coaches in clubs worldwide. For example the USA, Japan, Hong Kong, German, China, Czech and much more. Their understanding of local cultures and authority can make much easier expansion on new markets.

With a developed brand and arranged processes we can to communicate about signing contracts with local clubs and equipment suppliers.

We distinguish three segments on the market: high-level fencers, kids and amateurs. Each segment have different needs and financial abilities. High-level fencers already spend moneys on equipment and for them our main value is analytic. When we consider kids segment our aim is to help coaches motivate children through achievements and gamification. People who consider fencing as a hobby are more interested in community building.

4.2 Analytic

After discussions with coaches and investigation of available technologies, we introduce new metrics which will allow track progress of a fencer during the time and find patterns in athlete technical and bout dynamic. For the first step we plan visualize all this data to make it accessible for coach. In the next step we will analyze it with machine learning algorithms and make recommendations for athlete on our own.

4.2.1 Reaction

One of the easiest and one of the most important metrics is speed of reaction. As we said above forty milliseconds are hardcoded time into existing scoreboard. If fencer hit later than opponent for more than 40ms only opponent hit will be register. However it's important how much late. Difference can be 41ms or 500ms, both durations are so small, that it's almost indistinguishable for fencer and coach. But if we know exact result coach can more effectively set fencer tactics and technique and build athlete training program. For example, if lag is small as 41ms fencer doing everything right and he/she just need to work out a little bit more. If lag is higher may be the best way is to change tactics from attack to protection or vice-verse.

Except of analytic of fencer performance during the fight, we can introduce practice mode through interaction of the fencer with a smartphone. Smartphone give audio or visual signal and we measure distance between signal and fencer hit.

4.2.2 Speed

Also important metric is a speed of fencer movements. During the bout we can gather data from an accelerometer inside our device. For estimation of speed we need to integrate gathered data. Of course, due to limited frequency of sensors reading we will have a precision error. But we can correct measurements, because in most cases we have not so long duration between hits. Also for bout analytic is more important change of speed during the time than exact values.

For personal workouts we propose estimation of speed as time between two hits of target with displacement on fixed distances.

4.2.3 Bout dynamic

Analogical to speed estimation of speed we can calculate displacement. Of course, precision is much more than for speed, but we don't want to estimate exact position, but rather vector of movements. From this data we can retrieve is fencer more protective or attacking. Estimate performance of fencer on his side or opponent side. This information can be analyzed by coach, it will allow to set up tactics and strategy of fencer more effectively. Also we plan to find patterns in gathered data from athletes bout and make our own recommendations.

4.2.4 Hand technique

Another idea is to introduce additional accelerometer sensors, which will be attached to wire on fencer hand. For the first experiments we plan to use three sensors on biceps, ray bone and inside epee guard, but in the next steps we plan to use only two sensors, which give the most full information. As hand technique is one of the most important thing for fencer, we can retrieve a lot useful information from this data. As general correctness of movements and curtain positions and statistic of performance of different actions as in bout dynamic.

4.3 Technologies

4.3.1 Architecture

Main parts of the architecture are devices which are connected to fencers exactly the same way as existing scoring equipment. All gathered data is sent to a smartphone

via Bluetooth. Up to seven users can connect to single application. We already have Android implementation and start development of iOS application. After receiving data, the smartphone synchronizes information from all device and make a decision about hit registration. Processed data is sent to REST API written in Flask. On the server side, all data is stored in PostgreSQL. Coach can access students data via a smartphone or web dashboard.

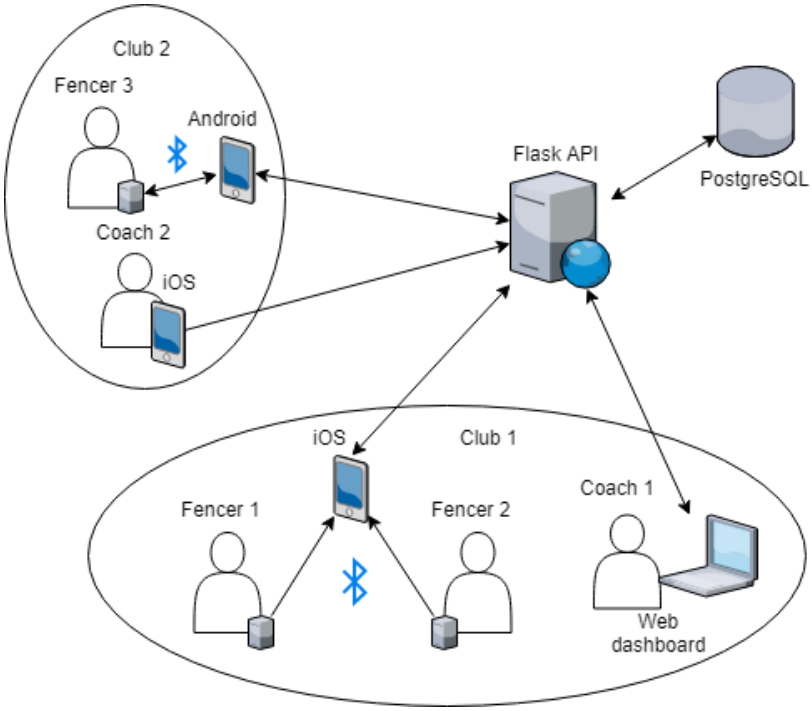

FIGURE 4.2: System architecture

4.3.2 Hardware

We developed our first prototype, which have already been tested in local clubs. We use Arduino Nano for prototyping purpose, but want to switch to more advanvce controler later.

Three contacts are connected to epee. Two of them connected to button on epee tip, third to epee guard. We generate PWM on the middle contact and try to read it with contact connected with guard to registrate hit into opponents guard.

Nine degree of freedom sensor connected to Arduino via I2C. It contains accelerometer, gyroscope and magnetometer. Accelerometer measure change of velocity due to Earth gravity, gyroscope - changes in orientation due to Earth gravity and magnetometer - orientation due to magnetic field. All data is corrected with Madgwick filter, which was described above.

Device transfers data to a smartpone via Bluetooth Low Energy using established protocol. It uses different characteristics to transfer hit, accelerometer and charge level data.

Arduino is powered from li-ion accumulator with 3.7V and 1500mAh. We used high voltage DC to DC converter to step up voltage to 6V. Also accumulator is connected to micro-usb charge module. Charge level of device visualize as LED color.

At this moment our device is working only for epee, but in the next steps we need to implement switching between different type of weapons.

4.3.3 Application

We plan to have applications both for iOS and Android, but it was easier to start with Android.

Application will be divide in four sections: profile, practices, statistic and settings.

Authorization

First of all to use our application user need to register or log in. We provide registration with Facebook, Google account or email. During registration user fill general data (name, location, club, age), height, weight, amount of workouts etc.

Profile

Profile section contains all personal information about fencer, club info, ratings, list of achievements. User can connect to friends from another clubs to track their activity. Also, we developed levels of information access for different type of connections. Connected user can challenge each other.

Workouts

Practice divided into three parts: workouts, bout and coach program. Workouts section contains different type of regimes for each metric. Each regime has list of exercises.

For each specific exercises user can set settings: time, distance, difficulty. Than he practice for curtain time and after finishing see all statistic, rating compared other club members etc.

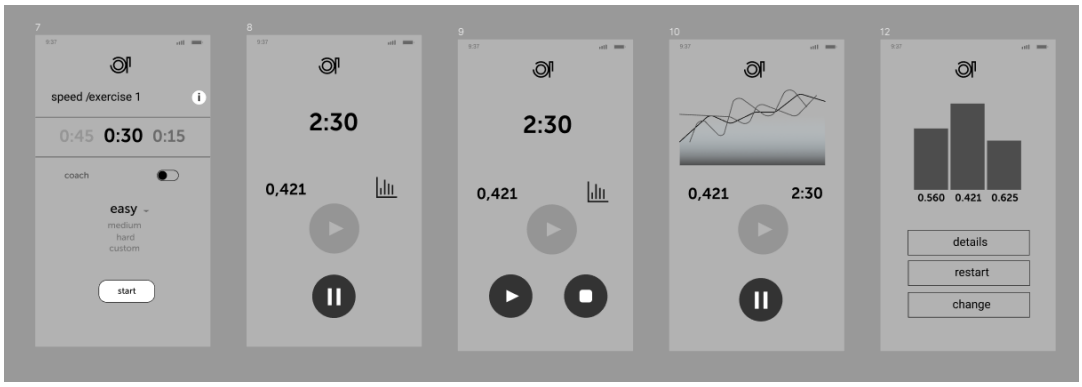

FIGURE 4.3: Workouts screen

Lets consider reaction practice. User choose practice time and set up difficulty level. Next during, for example, 2 minutes with random interval the smartphone make a sound signal and fencer need to react as fast as possible. During practice user can see timer, statistic plot or exact value of last reaction. After exercise athlete can see whole statistic. Next user can repeat or change an exercise.

Bluetooth connection

Up to seven users can practice together. As users can change type of exercises, some athlete can leave or join practice, we need to create comfortable user experience for Bluetooth connection.

So we introduce floating button which available on regime and exercises screen. By click on button user can see all connected devices and which users are bound to them. User can add new device and edit or remove existing once.

At the screen of device search, available devices sorted by signal level (in fact, distance from the smarthone). Also user can choose or type name of fencer. Selection propose the most frequent fencers names.

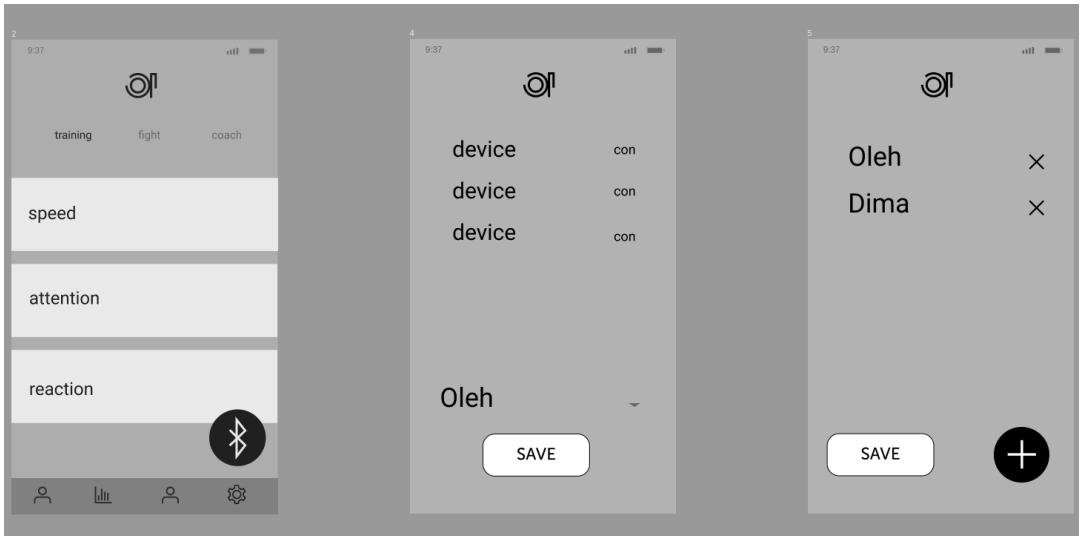

FIGURE 4.4: Bluetooth connection wireframes

Bout

Bout section implements functionality for workouts and competitions. The main pat of section is a scoreboard which reproduce functionality of existing fixing equipment. First of all users need to connect their devices via Bluetooth to left and right part of scoreboard and set names of fighters. Before fight users can set up timing and bout time. During the fight it visualize such information as score, time and number of yellow or red cards. If fencers change they have two possible scenarios. First one just exchange devices and change fencer name or reconnect to personal device of new fencer.

After each bout fencers can see analytic about bout dynamic, speed and reaction statics. All data is stored to analytic section.

Except simple scoreboard we also implement ability to conduct competitions or track fencers queue during casual practices.

Analytics

In analytic section stored all data about authorized user. He can see statics on all saved practices and fights. Also we plan to develop ability to summarize all data to see progress during the time, analyze fencer performance with curtain opponents, make recommendations on skills development.

Settings

In settings user can specify kind of weapon, localization information and buy premium subscription.

4.3.4 Backend

REST API written in Flask provide access to endpoints through http methods. All data is stored in PostreSQL. User endpoint allows get user profile information with access based on authorization token, add or remove user, get user connections. Practices and bout endpoints allows to store and access data about workouts. It provide search of practices by user, date or type. Data gathered during practice or workout stored as JSON. Also, API allows to add and retrieve exercises type for curtain workout regime.

Chapter 5

Results

As a result, we developed a prototype device which already gathering data about fencers speed and reaction and can differentiate valid hits from guard during a fight. First prototypes were tested in local clubs and received positive feedback from athletes and coaches.

It was tested on up to 50 athletes of different experience and physical level. By now we mostly concentrate on experiments with speed of reaction. During experiments athletes heard sound signal and need to react on it as fast as possible. It showed, that with our data we can differentiate athletes level. Fencers with experience more than five year showed result with mean value near 500 ms, when reaction of kids with experience up to one year have mean value of reaction near 1000 ms.

In another experiment we observe how feedback about performance influence statics. First time fencer work out on reaction for two minutes with statistic visualization only after end of the exercise. Second time fencer was getting immediate feedback after each hit. Without feedback fencer reaction was getting slower during the time, but with second experiments it stayed more stable.

Also, we demonstrated it to 11 coaches. They emphasized importance of gathered data and show ways how to interpret it. They advised about new type of exercises and help to developed proposed metrics.

We introduce analytic into fencing sport and make possible for coach objectively estimate the performance of a fencer. We proposed our metrics and way to measure it for speed, reaction, bout dynamic and hand technique.

We investigate sport fencing market, developed our business model and marketing strategy,

Chapter 6

Conclusions and future work

Our product was presented on several events. We won first places on Tech Battle - Lviv student project competitions and Ideathon - new venture competitions. On Ideathon we got ability to present our project in Boston, so we plan to arrange demonstrations of real product in Boston clubs.

To achieve this goal we developed detailed roadmap. First of all we need to finish development to demonstration-ready product. We need to finish with all hardware related issues and transfer our scheme from Arduino prototype to developed board. Also, one of the main goals is the development of the application user interface. In the nearest time, we plan to launch a parallel stream with iOS development.

Next step will be to approach Ukrainian national team. With support of national teams it will be easier to approach high-level fencers from all over the world on World Cup in Budapest. Before demonstration on the global market we will settle up legal issues with patent, trademark After first demonstration we will launch social networks marketing campaign and open pre-subscriptions. With gathered pre-subscriptions we plan to get fundings.

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