UNIVERSITY OF TARTU
Institute of Computer Science
Computer Science Curriculum

Karl Valliste

# Disc golf course inference from user mobile location data

Bachelor's Thesis (9 EAP)

Supervisor:
Jakob Mass, MSc

Tartu 2017

# Taldrikugolfi radade tuvastamine kasutaja telefoni asukoha andmete abil

**Lühikokkuvõte:**

Käesoleva lõputöö eesmärgiks on välja uurida, kas kasutaja Android nutitelefoni asukoha andmetest on võimalik piisava täpsusega eraldada taldrikugolfi radade stardi- ja lõpukorvi asukohad. Töö käigus loodi Android mobiilirakendus, mis võimaldab kasutajal saada tagasisidet oma visete kohta ning mis kogub samaaegselt GPS andmeid raja kohta. Kogutud andmete põhjal ennustati taldrikugolfi raja punktid. Ennustatud punkte võrreldi seejärel tegelike asukohtadega ning arvutati andmete täpsus meetrites. Antud teesi käigus oli kogutud andmete täpsus oli alla 6 meetri 91% juhtudest ning 100% ennustatud punktidest olid täpsusega alla 8.5 meetri. Selline täpsus on aga piisav, et tulemusi kasutada teiste radade automaatseks kaardistamiseks ilma manuaalse kontrollita, sest see on täpsem, kui manuaalne sisestamine nuti seadmest.

**Võtmesõnad:** Taldrikugolf, Android, GPS, asukoht

**CERCS:** P175 Informaatika, süsteemiteooria

# Disc golf course inference from user mobile location data

**Abstract:**

The aim of current bachelor's thesis is to investigate whether it is possible with enough accuracy to infer the locations of disc golf starting area and basket locations from the user's Android smartphone location data. During the writing of this thesis an Android application was created that enables the user to get feedback on his/her throws and simultaniously collects GPS data about the course. From the gathered GPS data, disc golf park locations were inferred. The inferred locations were then compared to real life data and accuracy in meters was calculated. The accuracy of the data collected during this thesis was less than 6 meters in 91% of the cases and 100% of the results were less than 8.5 meters. Such accuracy is however sufficient for automatic mapping of other courses without manual verification because this is more accurate than manual input from a smart device.

**Keywords:** Disc golf, Android, GPS, location, Crowdsensing/Participatory sensing

**CERCS:** P175 Informatics, systems theory

# TABLE OF CONTENTS

# 1. INTRODUCTION

## 1.1. Preamble

Disc golf is a sport that consists of throwing a flying disc or Frisbee® from a starting area or tee area in the direction of the target. The most common target is a Pole Hole®, that essentially is an elevated metal basket. As a player progresses down a fairway from tee area to the target, each consecutive throw must be made from the spot where the previous disc landed. The last throw that lands in the basket is called a "putt" and it ends the hole[1]. Commonly each disc golf course has either 9 or 18 holes but this can vary depending on the location. To see an example of a course see the image in Appendix 1. The first permanent disc golf course in Estonia was built in 2004 and the popularity of this cheap and easily accessible sport has grown widely with 35 courses around Estonia in 2014 and with 50 competitions being held the same year[2]. Disc golf is most often played in casual or sporty attire that generally includes a phone in the player's pocket or disc bag.

Android is a mobile operating system, that is designed primarily for touchscreen devices like mobile phones and tablets. All Android devices come with a variety of different hardware like accelerometers, cameras and GPS that can be easily used by the different applications installed to the device. The operating system provides a fluid interaction path for the application and the hardware for the intended use[3]. The Android platform is easily accessible for development and has a wide user base. The applications created for Android also have effortless access to the phone's sensors such as a GPS.

The Global Positioning System or GPS is a system that communicates with GPS satellites in Earth's orbit to calculate the exact location of the device in the global geometrical region. The location data is received by accurate measurements of the communication time between the device and nearby overhead satellites. For optimal results the system needs unobstructed line of sight from the device to minimum of three satellites, preferably four for further accuracy. This means that signal is not nearly as accurate when used indoors, near high buildings or wooded areas. The location data gained is three dimensional by consisting of latitude, longitude and altitude[4]. Additionally in the case of most GPS devices, the end location data also contains an estimated accuracy information in meters among other data. In the course of this thesis, GPS is the tool that enables location data collection from the smart device of the user.

Considering the above-mentioned technologies and the immense number of mobile phones in use today, there exists the opportunity for local data-collection on a global scale. Given the right architecture, those phones could act like sensor nodes and location aware data collection instruments. As these devices are always in the proximity of the user, it should be considered from the start that the system model should prioritize user participation in sensing. Participatory sensing will task the deployed mobile devices form participatory sensor networks that gather, analyse and share local knowledge[5]. For this thesis, participatory sensing was the approach of location data collection as the information was collected by different users during play.

## 1.2. Problem

### 1.2.1. Problem statement

There are two main problems that this thesis inspires to solve:

- Insufficient self evaluation tools available for disc golf players
- No available location data on the disc golf courses

Usually when playing disc golf players have to estimate throw distances by comparing them to the length of the hole. Throw distance is one of the main means for players to gauge their skill improvement along side with accuracy. There are some mobile applications that offer the possibility to get a distance measurement based on the throw starting point and end point. However these does not include the possibility to keep track of your throws based on what disc was used or how accurate the player is with different discs. The latter is important because due to the different aerodynamic properties of the discs, their behaviour is drastically different when thrown both in distance and accuracy.

In many different applications it would be advantageous to know the locations of certain objects, but it is often the case that the only option for locating them would need a user to enter the specific data manually. This is also the case with existing applications that have been made for disc golf players. The locations of the tee area and target that will henceforth called points of interest(PoI). The data on these PoI are either not available at all or have been manually collected by a multitude of users. If the data has not been collected and thus not available, then developers don't have the option of using this information in their applications such as course guides etc. If on the other hand it has been done manually, then this poses a different problem when the courses layout is changed every now and then.

### 1.2.2. Motivation

Motivation for the current thesis consists of two equal parts that each fulfills a different purpose. One half of the motivation is to create such an application that would enable both disc and throw distance support for players as no such solution exists. The second half is to implement an automatic PoI markdown method that would potentially allow for new interesting application and easy visualizations based on the course data.

### 1.2.3. Proposed solution

The solution proposed in this thesis address two problems as a combined solution for both. First of all, the mobile application offers the users a solution for throw distance measurement and self assessment tool that collects data from the GPS sensor and user input to create the feedback the user needs. From all this wealth of data accumulated in the course of the continued use, select information is sent to the server database for automated inference of the actual hole PoI-s.

To this end, an Android app was developed that the user could use it to track his throw distances with different disk types. This application is called DiDrive as an abbreviation of Disc and Drive(first throw from a tee area, usually the longest throw on the hole). By using this application the user will generate a wealth of location information that can be separated into each hole location data including the tee area and the target basket. This data can then be averaged with data other users gathered to get a specific location for each PoI. To verify that the data is true enough for automated use, it will then be evaluated against location data manually collected with a high-precision device. As this is a proof of concept, all the data gathering will be limited to Tähtvere Puhkepark Disc Golf course.

It often happens that the course is slightly changed every now and then. This is not handled in the scope of this thesis. However this can simply be addressed in the analysis of said data should all the new entries consistently differ from the old, then the old entries can simply be disregarded.

The expected outcome of this research is that the collected location data from a multiple users could depict the locations of every tee- and target area more accurately than the Android platform alone would allow. This in turn would facilitate the use of this PoI data with no further need for manual verification.

## 1.3. Research Objectives

This thesis aims to reach three objectives:

- Develop a software solution for supporting the throw tracking and location related activities
- Use the geolocation data gathered in the process to automatically map out disc golf holes on courses.
- Verify the performance/accuracy of the automated course mapping using manually gathered test data

## 1.4. Related work

### 1.4.1. Related Android applications

The number of Android applications for keeping track of Disc Golf play scores is quite large. However most of the applications are made with the intent of manually entering the number of throws on the hole. When it comes to tracking GPS location data for tracking individual throws there are only two applications available.

Disc Golf Drive Measure free is a simple application that is meant for measuring the throw distances in disc golf. The main use of this application would be during practice as it only measures throw distances. It is also possible to mark throwing spot and then use that one start location for multiple throws.[6]

Disc Golf Fanatic-Course Guide is a paid application that also has a free version available. With the help of GPS it tracks every single throw and keeps score statistics on every hole. The application provides a real time map of the area, next target location and a thorough stats overview from past games and throws. The design is nonintrusive and the amount of data that the application provides is staggering[7]. The free version offers the same features, but with a limited number of games with the free versionlocing up after five games.

#### 1.4.1.1. Discussion

Disc Golf Measure free proved the basic premise of the core principle how the data is collected in this thesis. Despite the somewhat negative accuracy feedback the basic idea is very similar. However the application is for practice throws rather than use on the course because all the information that it shows is the distance. DiDrive on the other hand will show both thrown disc and throw accuracy on each throw and keep track on what number hole you currently are playing.

Disc Golf Fanatic-Course Guide is much more similar application to what is proposed by this thesis. The possibility to track the distance of every throw throughout the course is not only similar but almost identical. What makes the on hand application different is that it will be keeping score of each disc throw distances separately, the ability to record the accuracy of the shot. The main difference is that where Disc Golf Fanatic-Course Guide uses the manual input of its users to get the tee area and target locations, DiDrive will attempt to do this in a more automated way by using user generated data.

## 1.5. Thesis Outline

This thesis has the following outline: Chapter 2 familiarizes the reader with the technologies used in this thesis. Chapter 3 gives a detailed look into the developed applications architecture. Chapter

4 explains the application implementation and how the user should use the application. Chapter 5 concentrates on how the automatic PoI inference is performed and compared to the verified location data. Chapter 6 is the conclusion.

# 2. STATE OF THE ART

## 2.1 GPS

GPS location data collection usually involves either a handheld GPS device or a mobile smart device with built in GPS like a phone or tablet. Handheld GPS devices are devices specifically built for GPS use and are quite a lot more accurate than smart devices with the manufacturer's promising signal accurate to less than 4m on most handheld devices when used outside in clear areas. Smart devices on the other hand usually achieve signal accuracy of 5 - 8.5m in the outdoors with similar conditions[8]. Both handheld and smart devices were used during this thesis, the former for verification and the latter for data gathering.

### 2.1.1. Structure of location data

Application that has been built for the Android platform and have been built with Java, receive the GPS information as the instances of the Java android.location.Location.class class. The variable contains a lot of data that can be used to pinpoint the user location. However this information is usually much more extensive than is needed for any one case. Most commonly used information in the Location variable are the following:

- Accuracy - Signal coordinates approximate accuracy in meters
- Latitude - numeric coordinate, one third of the exact location
- Longitude - numeric coordinate, second third of the exact location
- Altitude - user altitude from the sea surface, last part of the exact location
- Bearing - user bearing in degrees
- Speed - user speed at the time of recording
- Time - timestamp when the information was

In the scope of this thesis, only accuracy, latitude and longitude are used.

### 2.1.2. Average GPS location data acquisition on a smart device

Average GPS use can be divided into two groups continuous use and point location determination.

In the case of continuous use, user location is updated after a time interval when a new location is received by the device. By using it this way it is possible to mark down a route on a map with each new location variable update. The result is a continuous set of points that can be assimilated into a path. In this manner GPS data is used by all manner of map applications.

Point location determination is when some geodata is collected for marking down current location. This is used for example by adding geolocation data to pictures or adding your location to Facebook posts.

The data collection method used in this thesis is more similar to the latter than the former of the two because it is the starting and ending points that are collected by the application. The path of which the user took to get from throwing point to the recovery point is irrelevant and is not gathered.

## 2.2. Android Studio

Android Studio is the official IDE for developing Android applications. It is developed by Google but it is based on a JetBrains Intellij IDEA.

Android Studio both visually and functionally resembles the Intellij editor but it has a lot of android specific features added to it. These include instant APK rebuilding, fast and feature-rich emulator, Android APK signing features and additional tools and frameworks[9].

## 2.3. Google Firebase service

Google Firebase is a platform for mobile and web development that was acquired by Google in 2014. Initial Firebase service was a easy to use real time database, but since then Google has added multiple new services including authorization, storage and hosting[10]. All of the services are paid services, but Google does offer a free trial of up to 300$ worth of services during the first year after signing up.

Google Firebase Service connection is set up with a built in feature of the Android Studio IDE. This makes Firebase one of the best choices for any number of back-end applications when using Android Studio as a development platform for Android application development. Connection from the developed application to any of the Firebase services is a simple setup that consists of three steps:

- Create an instance of the desired service in the Firebase webpage
- Log in to your Google account in the Android Studio plugin
- Select the service instance you want your application to connect to

# 3. APPLICATION ARCHITECTURE

The result that this thesis is trying to prove depends on the analysis of gathered data. Data in turn needs to be collected by voluntary individuals who play disc golf and the method of collection must have some benefit for the user. If there is no personal benefit from it's use during the game, there won't be enough users to do the collection. In this case the method of collection is an Android application that collects data from user input and stores it in a server database for later analysis. This chapter will introduce the individual parts and bring a little light to why the average user would want to use the features offered.

## 3.1. Overall structure

The application DiDrive is data driven application that consists of the data generating and processing Android application in the users phone and a server database that collects the data needed for analysis after data collection has been concluded.

### 3.1.1. Android application

The Android application of DiDrive is the sole face of the project for the user. This is the interface that allows the user to use the functions of the application and to indirectly collect the location information that is vital to this thesis. The mobile stores most of the user data locally, that consists of user input and the GPS location data. Only select few of the information generated is sent to the server Firebase database through the internet in real time.

### 3.1.2. Server database

The server database is set up with as a Google Firebase real time database that the mobile application connects to directly. The ease of connection from a mobile platform and the eliminated need for an additional back-end program was the main reasoning behind choosing Firebase as the server database. This service exists only as a data collection point for all the different user devices(Figure 1).

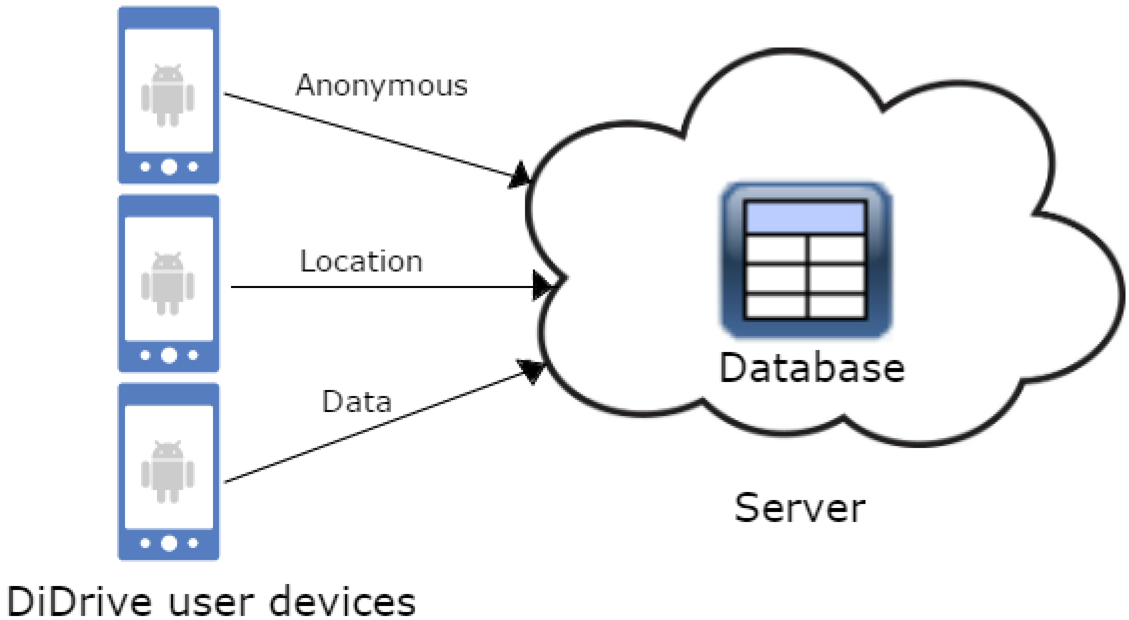



*Figure 1 Basic structure of the application*

## 3.2. User incentive

The client-side Android application of DiDrive has a main goal of collecting anonymous data from all participating users to a server database. However for users to use the application in the first place, there must be an incentive to use the application.

DiDrive provides the user with the following benefits:

- Keeping track of different discs the user owns and how often they are used
- Track the user's progress on the course automatically
- Measure individual throw lengths with different discs

What DiDrive gives the user is a good self evaluation tool. With the information that the application provides, the users can improve their play and analyse their abilities with different discs. This in turn should lead to a more informed choice of play styles and disc selections.

# 4. IMPLEMENTATION

The DiDrive application was built with commonly available methods and tools but it had to be compatible with the devices of a large portion of the userbase. In September 2016, it was possible to cover over 50% of the available Android devices by developing an application that runs on Android version 5.0 and newer[11]. This is the reason that the DiDrive was created using the Android API 21 that is compatible with all devices running on Android 5.0 Lollipop and newer instead of the latest version only.

## 4.1. Mobile application

For the user the application "DiDrive" has three main features:

- Create discs that you own in the application
- Mark down the start point, end point and accuracy of your throw via GPS and associate this throw with a disc you own
- See statistics of the throws you have made and of what discs suit your play style the best

### 4.1.1. Main menu

As the DiDrive is opened, the user is shown a main navigation page with two navigation buttons. The two navigational buttons direct the user to either "Discs" or "Throw" views.

### 4.1.2. Discs menu

Discs menu gives the user the possibility to both see the complete list of discs and to insert into the app or "create" all the discs the user owns and uses during play. The owned discs are shown in the form Android ListView container. (Figure 2)

There is a separate sub menu for creating the discs. The disc creation is made as simple as possible with four consecutive drop down menus or Android Spinners. The four spinners contain the information in the following order:

- Disc manufacturer
- Disc type
- Disc name
- Disc colour

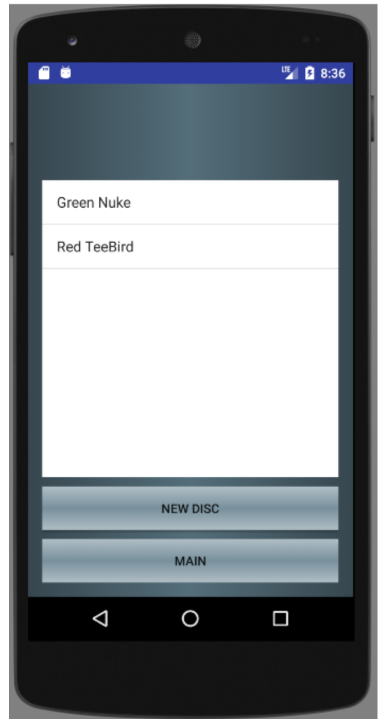


*Figure 2 - Discs menu*

The data mentioned in the previous paragraph is web scraped from www.infinitediscs.com and compiled into a *XML* file. This file contains the data on all available discs on the market and their data. Data included is disc manufacturer, disc type, disc name, disc stats and a picture location on the site. Both the stats and picture location are currently not used in the scope of this thesis, but they can become useful in the further development of the mobile application. This *XML* file is bundled in the Android application and is updated manually before next release.

### 4.1.3. Throw menu

The throw menu is where the user spends most of the time. There are five accuracy buttons side-by-side with self explanatory indicators and a score button below that. These don’t become active before the device has a accurate enough GPS signal. Below these buttons, there is an Android Spinner that enables the selection of the disc currently in use. Hole number is always indicated at the bottom and at need can be changed manually. As the user marks down throws, the below ListView will be populated by the previous throw information. (Figure 3)

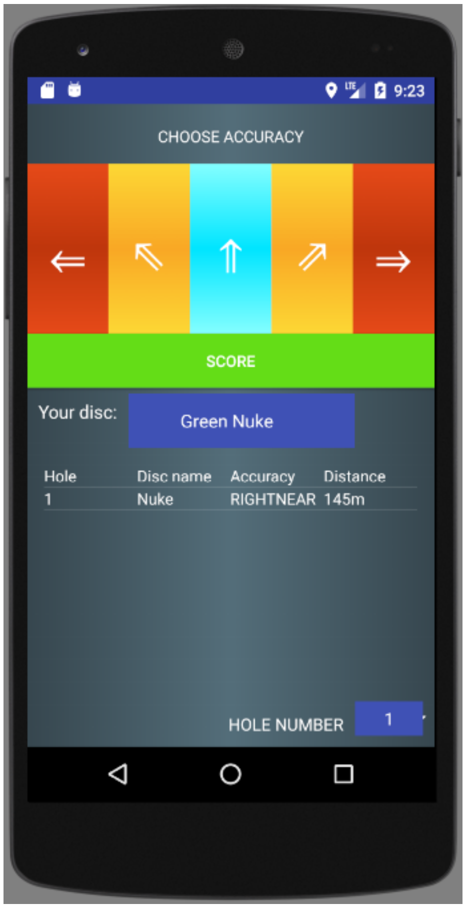



*Figure 3 - Throw menu before marking accuracy*


*Figure 4 - Recover disc*

User opens the DiDrive application throw menu when playing. The application assumes that the user makes the first throw on every hole at the starting tee area. When the disc has been thrown, the user must indicate the accuracy of the throw. Accuracy is in split into six parts: far left, near left, center, near right, far right and score. Of these, the first five are for the user to estimate how accurate was the throw compared to where the disc was intended to fly. Score marks that that this throw scored and thus accuracy was perfect. When any accuracy is pressed, then the throw starting point is saved as the user's current position. This hides all the previous buttons and instead shows a recover disc button(Figure 4). This is pressed when the user picks up the disc and this marks the throw ending coordinates. If however the user clicks the “SCORE” button instead of the accuracy buttons, the application marks this as a final throw on the hole and on recovery.

## 4.2. GPS location data collection in DiDrive

DiDrive uses continuous GPS updates to get the most accurate signal available and only enables its use if the signal accuracy is below 15m. In other cases the user will have to wait for a more accurate signal. This enables to minimize the amount of false data gathered by the DiDrive Android application.

During play the application assumes that the player always begins the throws on the tee area and this coordinate is set aside for further use down the line. As the player continues playing, more and more throws are marked down. When a scoring throw recovered, the application gathers the starting location from the first throw and the ending location prepares the data for transport. This data is then anonymously sent to the application database along with the hole number and the course id. All the other throw location data is kept in the users phone for personal use. As the server connection is completed, the application expects the player to walk to the next tee area and start with the next hole in a similar manner.

It is natural that there will be variations in the data not only due to signal accuracy and user diligence, but also due to the basket size. Since the official Professional Disc Golf Association approved baskets inside diameter may vary from 63cm to 70cm[12] The result will depend on the direction the user advances to the basket but his is only natural and overall will not have a distinct effect on the final results.

## 4.3. Server database structure and use

The Firebase server database is a nosql database with a very simple structure. The database has two sub databases called “location” and “test” that contain data with the same structure. “test” is used when developing the application and “location” is for actual data collected during play. Each entry is in the form of a timestamp that in turn holds the entry information. All of the server database entries are non user specific and thus anonymous. The location information that is stored contains all the wealth of information that is stored in the java android.location.Location.class variable by querying the GPS service for location data. Example of the database structure can be seen in appendix 2.

The information in the database must be easily accessible for the analysis, explained in chapter 5. Firebase provides two possible methods for this. Firstly it is possible to connect a second application to the web database and read live data from there directly. Second option is to download the database as a *.json* file and analyse it this way. For the analysis part of this thesis, the second option is used. This enables the database connection to be only one way and keep the connection as simple as possible.

# 5. ANALYSIS

## 5.1 Method and goal

In this chapter, all the data collected by the users was analysed to find the most probable pinpoint location. This could then compared to verified data to see how accurate is the final result. The collected data was narrowed down to 36 PoI locations and then each was assessed for accuracy. The goal of this chapter is to see, if the result after data processing based on the data gathered by participatory sensing is accurate enough for automated use in the future on other courses. All of the graphs shown in this chapter visualize only a section of the whole data for the sake of clarity. Full graphs can be found in appendix 3, 4, 5 and 6.

## 5.2. Analysis of data

The data was accumulated by 22 people using DiDrive while playing at Tähtvere Puhkepark Disc Golf collecting a total of 618 location points. The analysis of the collected data was done by a python script that takes the *.json* file that was explained in section 4.2 as input.

### 5.2.1. Collected data

The collected data has already been clustered upon insertion to the database by current hole number. This enables the data to be automatically sorted into 36 clusters(18 tee areas and 18 baskets). For better clarity, each PoI data cluster is visualized in a different color(Figure 5). It is noteworthy that the sample size was smaller than initially intended with from 16 to 22 location points per cluster, but this is deemed enough for a conclusive result.

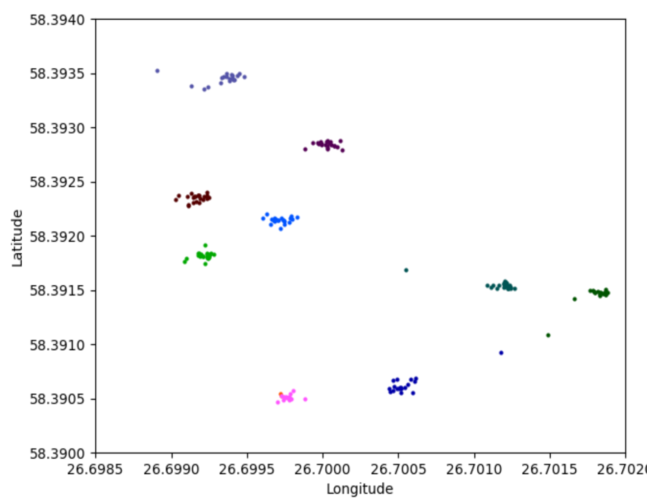



*Figure 5 - Raw data visualization*

5.2.2. Centroids of each cluster

Before looking for central points, the outliers in each PoI cluster must be eliminated for a more accurate result. This was done by removing all the points that had a larger than 0.0001 deviation in latitude or 0.0002 deviation in longitude from the mathematical center of the cluster. The thresholds are set at these numbers because at the latitude Estonian is located, these amount to approximately 11m. This in turn is large enough to have a negative influence on the measurement result. As a result of this midway step, all of the clear outliers have been removed from the clusters(Figure 6).

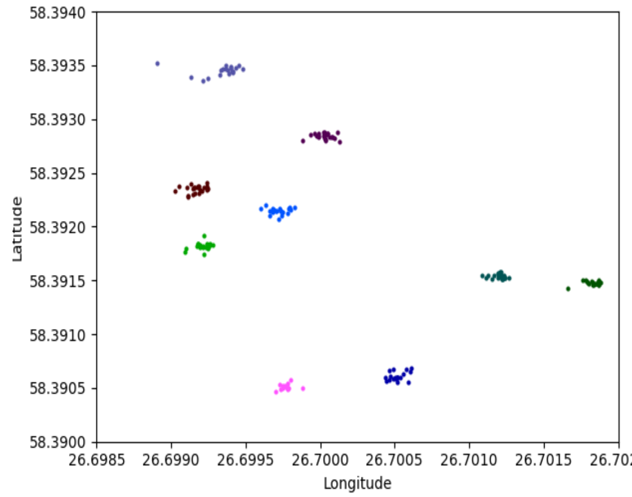



*Figure 6 - Data after removing the largest outliers*

The central point in each cluster is what will from here on be considered as the final location of that PoI. It can be found arithmetically by finding the arithmetical average of both latitude and longitude over all the points in the current cluster. For a clearer visualization all the cluster points have been turned gray to more easily distinguish the center points from the cluster points. The central points are marked with a red '+'(Figure 7).

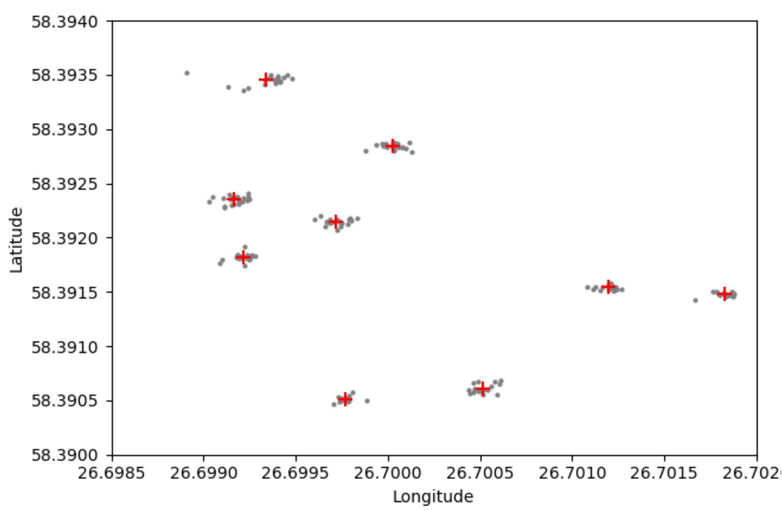



*Figure 7 – Centroids of each cluster*

## 5.3. Evaluation

5.3.1. Verified data collection


*Figure 8 - Garmin Trex 20x*

In order to determine the accuracy of the found centroids in comparison to the real life PoI locations, collection of verified data was done with a handheld GPS device Garmin Trex 20x(Figure 8). The device has a signal accuracy of +-12 feet or 365.76cm[13] according to its manual and thus is much more accurate than the GPS signal in smart devices. The verified data was collected on the course manually and added to the analysing program input.

Garmin devices formulize the data into a *.gpx* format which has a basic *XML* structure. From this verified coordinates were extracted and they were added to the graph as blue ‘x’-es (Figure 9).

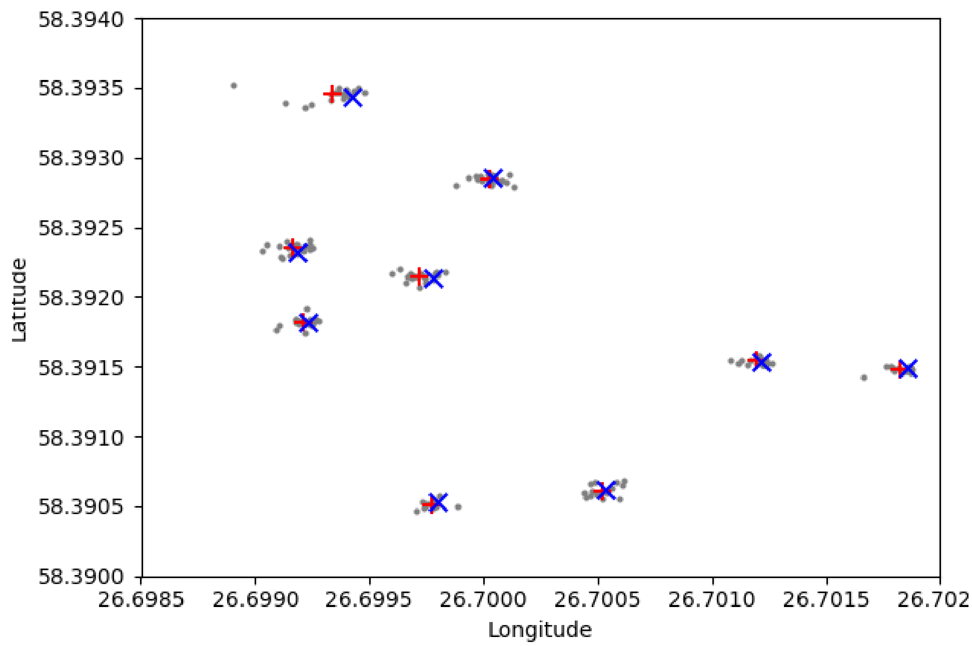



*Figure 9 - Verified points anlong side centroids*

5.3.2. Accuracy

So far all the data collected during this thesis can be narrowed down to 36 PoI cluster centroids and 36 verified PoI locations. To get the distance between the two corresponding points in each set, a python script written by John D. Cook is used[14] and the results are collected into a table(See appendix 7). The data in the table has been summarized in Figure 10.

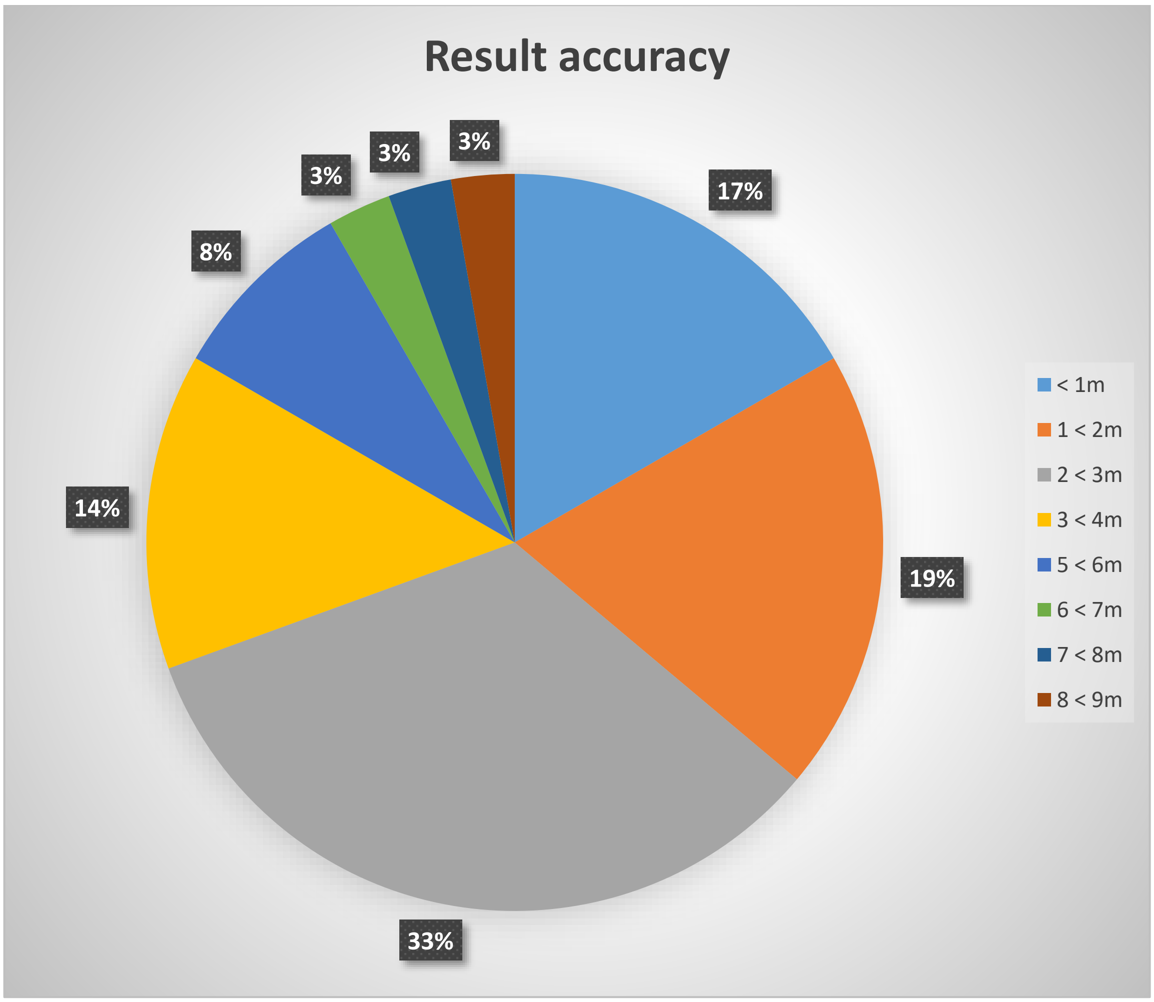



*Figure 10 - Accuracy of the centroids*

As can be clearly deduced from the graph that result accuracy of 4m or less, covers 83% of all the PoI locations that have been collected by the users. With result accuracy of 6m or less, the number climbs to 91%. The overall accuracy of the experiment is very good as a smart devices GPS is considered accurate to 5-8.5m in a clear open space and 100% results were in that margin. However when looking at the data table a pattern that was to be expected emerges. Points most deviating from the verified ones are in wooded areas. This is not true for all PoI that are located between trees, but 100% of the results over 5m are among the trees. This is a limitation of the GPS technology that pinpoint accuracy drastically reduces when the device does not have open space around or a unobstructed view of the sky above it.

# 6. CONCLUSION AND FUTURE WORKS

As part of this thesis a Android application called DiDrive was created and launched. It allowed for marking down throw distances and accuracies with each of the discs owned. Based on data collected from real users playing disc golf in Tähtvere Puhkepark Disc Golf course, analysis was carried out and the final results indicated the difference in meters between inferred PoI locations and actual locations. The results showed a good pattern where 100% of the results were in the smart phone GPS margin of 5-8.5m accuracy and 91% of the results were accurate to the distance on 6m. All of the results that differed by more than 5m were the locations that are located in a wooded area. In total the proposed method is accurate enough for use without the need for further verification and thus can be used automatically when mapping courses anywhere in the world.

Future additions to the DiDrive application will add a function of course recognition in a similar way that the application distinguishes between if the user is Tähtvere Puhkepark Disc Golf course or elsewhere. This enables the application to be used globally and on any course. This way it is theoretically possible to map out all the courses and make this data available to other developers for future applications.

# BIBLIOGRAPHY


[1] What is Disc Golf. http://www.pdga.com/introduction (Accessed: 11.05.2017)

[2] H. Ellam. Lendavate taldrikutega leviv krooniline haigus, *Äripäev*, 2014. http://www.aripaev.ee/uudised/2014/08/23/lendavate-taldrikutega-leviv-krooniline-haigus (Accessed: 11.05.2017)

[3] Android(operating system). https://en.wikipedia.org/wiki/Android_(operating_system) (Accessed: 11.05.2017)

[4] Global positioning system. https://en.wikipedia.org/wiki/Global_Positioning_System (11.05.2017)

[5] J. Burke, D. Estrin, M. Hansen, A. Parker, N. Ramanathan, S. Reddy, M. B. Srivastava. "Participatory sensing," World Sensor Web Workshop, ACM Sensys 2006, October 31, 2006.

[6] Disc Golf Drive Measure Free. https://play.google.com/store/apps/details?id=com.illotus.dgdm_added&hl=en (Accessed: 11.05.0217)

[7] Disc Golf Fanatic-Course Guide. https://play.google.com/store/apps/details?id=com.fivebytestudios.frolf.full&hl=en (Accessed: 11.05.2017)

[8] P. A. Zandbergen, S. J. Barbeau. "Positional Accuracy of Assisted GPS Data from High-Sensitivity GPS-enabled Mobile Phones" *Journal of Navigation*, Cambridge University Press, June 7, 2011.

[9] Android Studio Features. https://developer.android.com/studio/features.html (Accessed: 11.05.2017)

[10] Firebase. https://en.wikipedia.org/wiki/Firebase (Accessed: 11.05.2017)

[11] Distribution of Android operating systems used by Android phone owners in September 2016, by platform version https://www.statista.com/statistics/271774/share-of-android-platforms-on-mobile-devices-with-android-os/ (Accessed: 11.05.2017)

[12] PDGA Approved Disc Golf Targets. http://www.pdga.com/files/pdga_approved_targets_042117.pdf (Accessed: 11.05.2017)

[13] eTrex® owner's manual for use with models 10, 20, 20x, 30, 30x
http://static.garmin.com/pumac/eTrex_10_20x_30x_OM_EN.pdf (Accessed: 11.05.2017)

[14] Cook J.D. Computing the distance between two locations on Earth from coordinates.
https://www.johndcook.com/blog/python_longitude_latitude/ (Accessed: 11.05.2017)

# APPENDIX

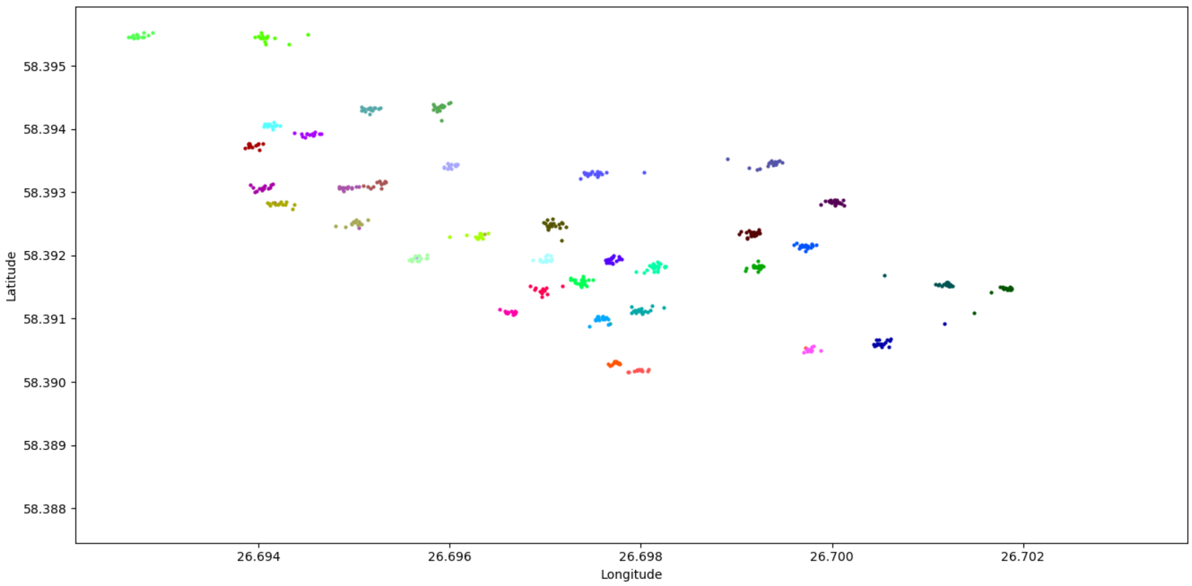
Appendix 1 – Chippewa Banks Disc Golf Course map from http://www.ullerysmith.com


| Hole | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Par | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 | 56 |
| Distance (feet) | 272 | 350 | 400 | 200 | 255 | 300 | 245 | 285 | 361 | 300 | 290 | 340 | 428 | 381 | 215 | 205 | 280 | 360 | 5448 |

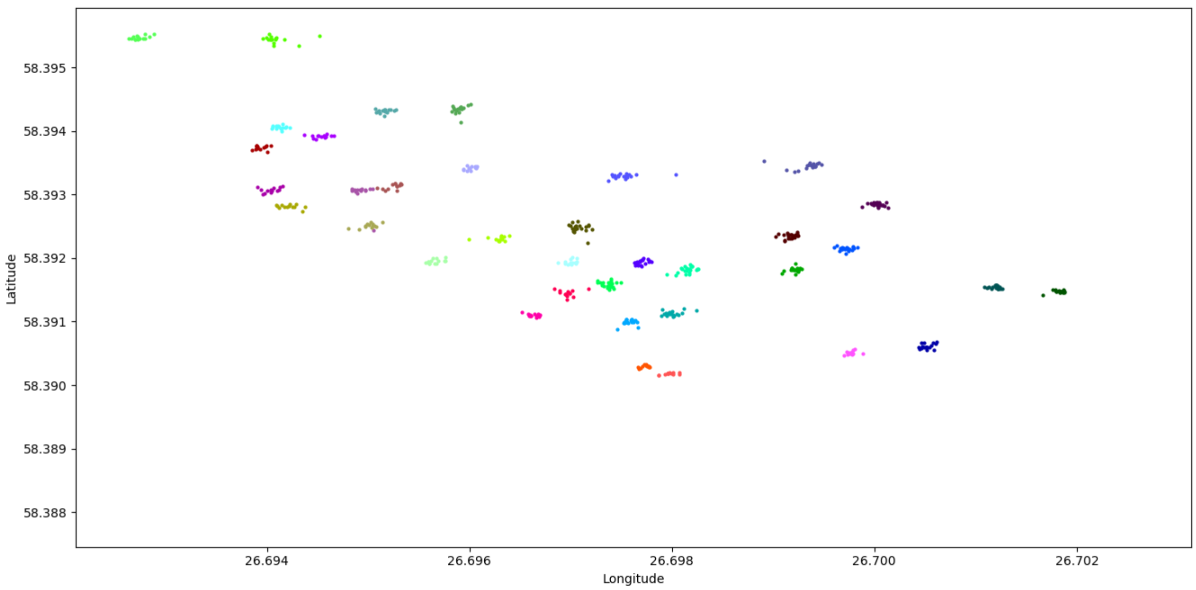
Appendix 2 - Example of the server database structure

```
didrive-147e5
  location
    1491831711743
      course_id: 1
      endLoc
        accuracy: 9.10199928283691
        altitude: 44
        bearing: 0
        complete: true
        elapsedRealtimeNanos: 16211243456333
        extras
        fromMockProvider: false
        latitude: 58.3914909
        longitude: 26.701868
        provider: "gps"
        speed: 0
        time: 149183170400
      hole_nr: 1
      startLoc
    1491831727557
    1491832005272
    1491832005921
    1491832276620
    1491832350520
    1491832459970
    1491832494595
    1491832646508
    1491832666343
    1491832991270
    1491833043794
    1491833337245
    1491833360277
    1491833732043
    1491833749591
    1491834022328
```

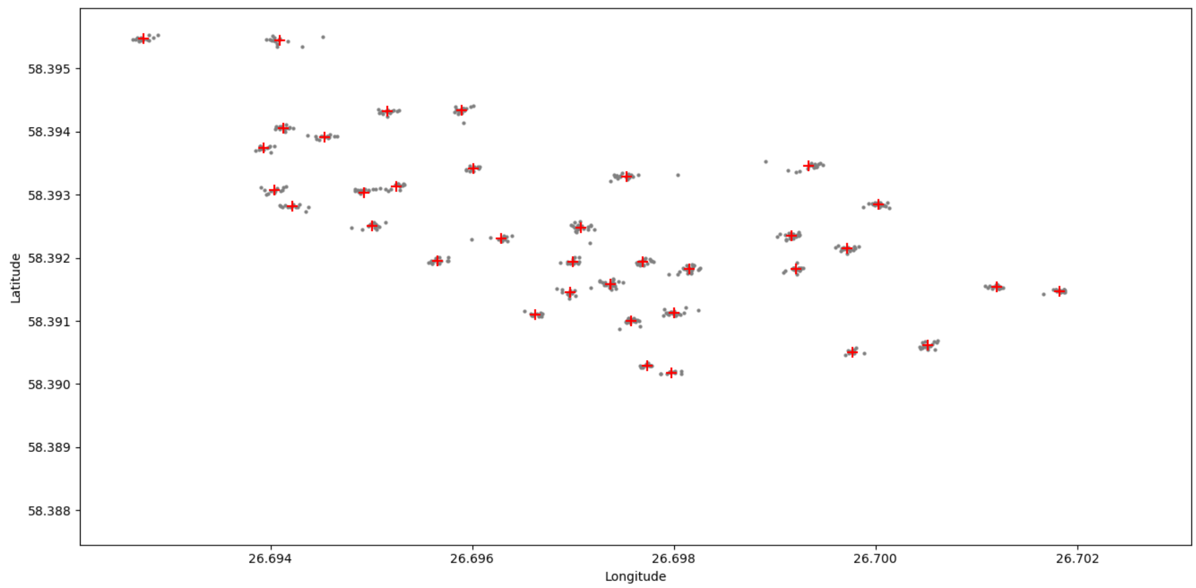
Appendix 3 – Visualization of the raw data



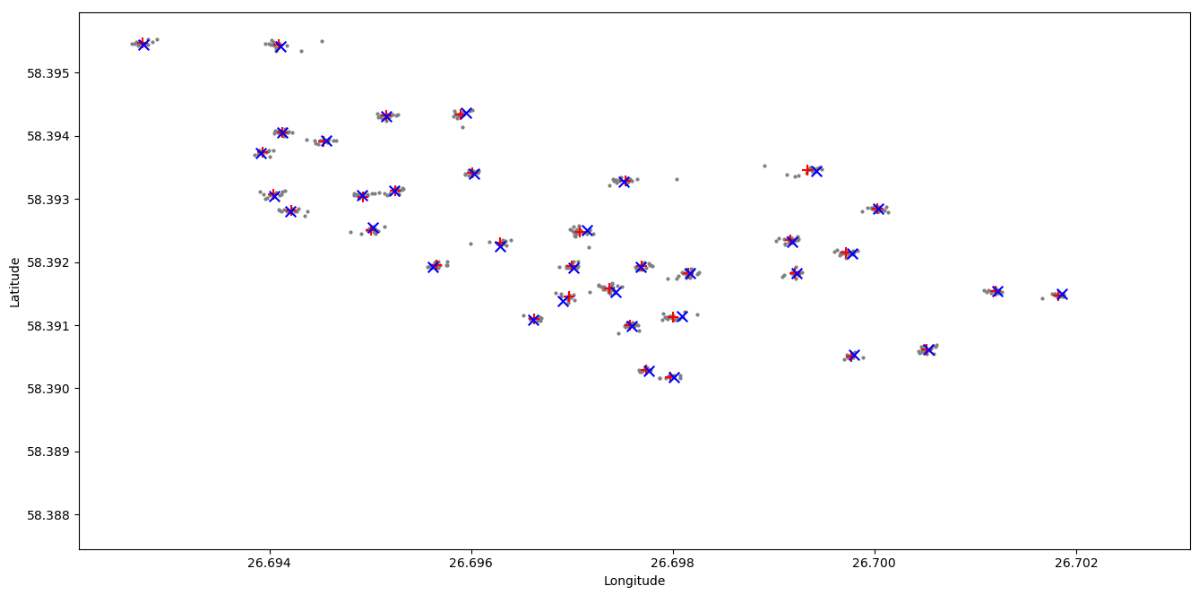

Appendix 4 – Visualization of the data after removal of the outliers



Appendix 5 – Cluster centroids




Appendix 6 – Verified points and cluster centroids



Appendix 7 – Measurements between centroid and verified point with the location conditions

| PoI | Distance between points (m) | Conditions |
|---|---|---|
| Hole 1 Tee | 1.2598544233402609 | Open area |
| Hole 1 Basket | 2.711083136371738 | Open area |
| Hole 2 Tee | 1.0785962011750099 | Open area |
| Hole 2 Basket | 3.9155113923641687 | Open area |
| Hole 3 Tee | 0.8806701104610289 | Open area |
| Hole 3 Basket | 5.616605666610494 | Wooded |
| Hole 4 Tee | 1.9646532713819151 | Open area |
| Hole 4 Basket | 8.052458150237534 | Wooded |
| Hole 5 Tee | 1.4894693978410294 | Wooded |
| Hole 5 Basket | 3.786714767938994 | Few trees |
| Hole 6 Tee | 1.2740905184095666 | Open area |
| Hole 6 Basket | 1.2198488000606447 | Wooded |
| Hole 7 Tee | 5.265213216816595 | Few trees |
| Hole 7 Basket | 5.530850925968432 | Wooded |
| Hole 8 Tee | 2.394928703216613 | Open area |
| Hole 8 Basket | 3.9738100542987222 | Open area |
| Hole 9 Tee | 0.6579375145814693 | Open area |
| Hole 9 Basket | 2.6910502278935273 | Wooded |
| Hole 10 Tee | 2.837852119754729 | Open area |
| Hole 10 Basket | 0.9207208076511112 | Open area |
| Hole 11 Tee | 2.032341896663844 | Open area |
| Hole 11 Basket | 2.7816832483316554 | Wooded area |
| Hole 12 Tee | 1.9692382327431155 | Opean area |
| Hole 12 Basket | 0.6440846470364533 | Few trees |
| Hole 13 Tee | 4.139432753203094 | Open area |
| Hole 13 Basket | 0.6154441903673605 | Few trees |

| | | |
|---|---|---|
| Hole 14 Tee | 3.9430534298029016 | Open area |
| Hole 14 Basket | 1.5719521159192091 | Open area |
| Hole 15 Tee | 6.1044169227819856 | Few trees |
| Hole 15 Basket | 3.6951065739699085 | Open area |
| Hole 16 Tee | 2.6317500583258946 | Open area |
| Hole 16 Basket | 7.756968896419753 | Wooded area |
| Hole 17 Tee | 2.306694271233777 | Open area |
| Hole 17 Basket | 2.6505302191257845 | Open area |
| Hole 18 Tee | 2.041197458852604 | Open area |
| Hole 18 Basket | 2.5125403859339275 | Open area |

Appendix 8 - Non-exclusive licence to reproduce thesis and make thesis public

I, Karl Valliste,

herewith grant the University of Tartu a free permit (non-exclusive licence) to:

1.1 reproduce, for the purpose of preservation and making available to the public, including for addition to the DSpace digital archives until expiry of the term of validity of the copyright, and

1.2 make available to the public via the web environment of the University of Tartu, including via the DSpace digital archives until expiry of the term of validity of the copyright,

“ Disc golf course inference from user mobile location data“,

supervised by Jakob Mass,

I am aware of the fact that the author retains these rights.

I certify that granting the non-exclusive licence does not infringe the intellectual property rights or rights arising from the Personal Data Protection Act.

Tartu, 11.05.2017