WiFi Environment Mapping with Arduino

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Abstract

With wireless technologies becoming more widely available, we are faced with a plethora of possibilities that can take advantage of these wireless frequency ranges. This project investigates to what extent and accuracy wireless radio signals can be used as points of reference in order to locate other wireless devices within a localised geographic location such as a building. This assumes that there are plenty of wireless devices located around the environment all running on the same standard, 802.11. This report discusses similar work that has been researched and solutions that have already been devised within this area of research. I also discuss electronics platforms that have made themselves more appealing to the consumer market in recent years to accomplish autonomous data collection and why I feel that this is a necessary. I then follow on with how I intend to further this work to allow for data interoperability so that data collected during the surveying phase of the project can be reused in other application.

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Chapter 1

Environment Mapping in a Wireless Environment

1.1 What is the Context of this Project?

This project is based around the understanding that wireless signals are becoming more and more prominent in most everyday locations as the technologies behind them become cheaper and the standard more popular. It is because of this there have been numerous studies into the feasibility of using wireless signals to determine the location of wireless devices or users; that being a user that has a wireless enabled device on their person. Similar to that of a Global Positioning System (GPS) whereby a GPS enable device can be located using a global navigation satellite system, I wish to use wireless access points to locate a wireless device within an indoor environment.

I will be trying to accomplish this task by building up a set of training data which will consist entirely of points (coordinates) and sets of wireless signals associated to each of the points. More specifically each point will represent an x and y coordinate from where a scan of the wireless networks will be performed, returning a set of wireless access points which have their own unique media access control (MAC) address and signal strength from that specific location. By building up a large enough set of points, I am hoping to be able to accurately (within a few metres) calculate the location of a wireless device or user. This idea of building up a wireless intensity map is not unique to my project as it has been done before, however I wish to replicate this procedure of indoor location determination and further it so that the collected data may be used within other applications.

I wish to collect this data autonomously, meaning there has to be some means of collecting the data required to build up my training points without any interaction with the system. This is where the Arduino platform is to be introduced, which is a cost effective electronics platform that can be used with off the shelf components to build up electronic prototypes. With this I will be constructing a wireless enabled autonomous entity; that is an entity that can move around freely, avoiding obstacles, and correcting it's path whilst periodically sampling the wireless environment to create fingerprints of the wireless signals at various points of it's physical environment. It will also be necessary to determine the current position of the robot and the direction in which it is facing from a relative point so I will be able relay this information to an application that will determine the wireless user's location.

From the training data I will be investigating how accurately the location of a wireless device or user can be determined within the same indoor environment. I will investigate this by issuing a wireless enabled device, such as an Apple iPad, with an application that uses the training data to determine the probability that given a set of observed signals what is the likelihood that this reading came from a specific location, thus calculating the location of the wireless device.

The practicality of this project is to demonstrate how feasible it would be to use autonomous systems to collect data points and for that data to then be reused by another application to locate a wireless device. This kind of system could be useful in such situations where a wireless user is unable to find their bearings within a building and could therefore be used to either locate themselves or to perhaps guide them to their desired destination.

1.2 Aims of the Project

1.2.1 Locating Wireless Devices Given A-priori Knowledge

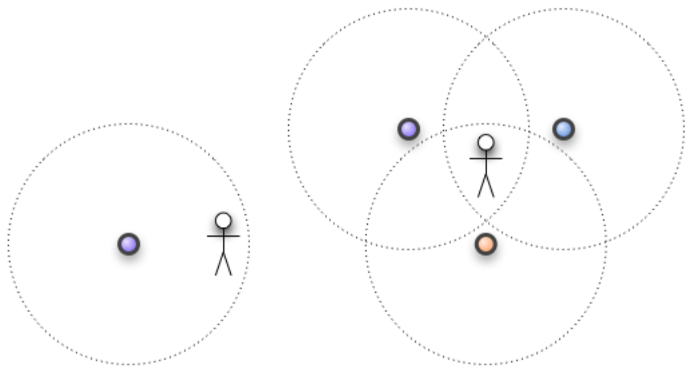
Data collected from the autonomous system makes up a model of the environment in which it scanned. This model is unique to this particular environment and can hopefully be used to locate a wireless device or user within that environment. This is our A-priori knowledge, and through this project I wish to be able to use this data within another application running on a wireless device, most likely an Apple iPad. Doing this I wish to address the project's overall goal to locate a device by looking up fingerprints within the collected data and use some sort of probabilistic deduction to determine the likely location of the wireless device.

1.2.2 Wireless Signals as Points of Reference

All wireless access points carry specific information such as their service set identifier (SSID), MAC address and security protocol among others. What I would like to accomplish from this project is to determine whether this information can be used to uniquely identify an access point so that it can be used as a point of reference. Similar to how the human brain uses visual aid to determine where they are through the use of landmarks, signs and other such stimuli, I need to build a system that can take a set of wireless signals, containing information unique to an access point, and use this as a 'landmark' to determine the likely location of a wireless device.

Given that an access point will always have a unique MAC address assigned to it's wireless interface it should be feasible to identify which access points are within range. However this does not necessarily determine the location of the device within range of the access points. For this, another piece of information will be required. Using the signal strengths received at a particular location may also help in identifying that location, given that the further away from the access point, the lower the signal strength, and the closer to the access point, the higher the signal strength.

Although the signal strength may not uniquely identify the exact location of a wireless device in range of the access point, using several readings from multiple access points will narrow down the number of possible locations that a wireless device may be. This is shown in Figure 1.1. By using just one access point as a reference as in Figure 1.1(a) the wireless device or user could theoretically stand on any side of the access point, providing that they remain the same distance from it and the



(a) Single access point (b) Multiple access points

Figure 1.1: Determining location with one and multiple access points.

access point is omni-directional, and receive the same signal strength. Therefore this will not help in determining their location. However if multiple access points are used, as in Figure 1.1(b) the wireless device is a lot more likely to have unique signal strength readings (collectively) and therefore can be located more easily.

1.2.3 Autonomous Data Collection

Being able to collect data autonomously is often a desirable property. This allows for the system to take care of itself while the results are monitored from an external application. Automaticity can also prove to be a attractive property when the task that needs to be performed is lengthy and repetitive and would normally require a lot of accuracy and consistency. It is this where machines come in most use. Provided that they are built and programmed effectively, machines are capable of performing tasks with greater accuracy than that of a human. This characteristic of machines is perfect for data collection and therefore I wish to use this to eliminate inconsistencies that may occur if I were to collect the data manually. Also considering that wireless propagation [Breezecom, 2008] may be affected by the continuous presence of an entity, it may be best that this data be collected unaccompanied.

1.3 Assumptions

Some of the assumptions I will follow are that the environment I will be running all my experiments is fairly static over time. This means that I will not be expecting major changes within the environment such as any sort of equipment being left in the corridors for a prolonged period of time that would affect the wireless propagation. Since the autonomous system could be unmanned at any time, I will also assume that it moves smoothly and avoids obstacles such as corners appropriately therefore covering as much ground as possible.

1.4 Why is this Problem Important?

Wireless environment mapping is important because it brings about another use for wireless signals already radiating throughout many buildings, meaning that further equipment is not required to implement a solution for this problem. Having a working implementation which solves this problem could not only be used for the obvious application of locating oneself within an unfamiliar environment but could also be used, given the right application, to heighten security within an organisation or educational establishment by being able to track wireless devices which are usually carried by people within the building.

Chapter 2

Background Study

2.1 Existing Wireless Mapping Implementations

2.1.1 Existing Work

In recent years there has been great effort put into building localisation systems that have taken advantage of sensor networks. Typically these sort of systems use the concepts of triangulation, trilateration or fingerprinting to determine the location of an entity which have proven successful methods in such systems as GPS. However these networks are purpose built and therefore are often expensive to implement. Therefore this has led to research into using the 802.11 standard to try locate entities within environments where a wireless infrastructure has already been put in place.

The problem of 802.11 wireless location based systems has been a recent area of study over the past few years due to the huge increase in the use of wireless technologies in everyday environments and applications. It is therefore no surprise that there have been many attempts to try and solve this problem. Before moving onto the solutions that some have implemented I wish to discuss some of the procedures and ideas that have been included in some of the previous works. First it must be stated that the use of robotic systems to collect training points is an idea that has been present in other works [Serrano et al., 2004, Howard et al., 2006, Siddiqi et al., 2003], but having read these works I can determining that these are not autonomous but are instead either, controlled, or just follow a wandering procedure. Therefore I wish to extend these works to include a more autonomous system to try control external influences that may affect the data collection further than sources of interference that are mostly static (computer interference, electromagnetic interference and other such factors).

There has also been some debate whether using a theoretical model of wireless propagation offers more benefits over an empirical model and of the two which produces better results. It has been theorised that by using a theoretical model the same results can be achieved with the added advantage that a wireless intensity map does not need to be produced, which would need to be updated each time the environment changed. However below I discuss that this is not entirely true.

2.1.2 Constraints on the Solutions

One major constraint on building an indoor location system is determining how radio waves propagate throughout their environment. Unlike that of free-space environments there are many obstacles, temporal changes and sources of interference within indoor environments that may affect the propagation of the radio waves. This means it is too difficult to deduce a model that will fit all indoor environments and therefore such a model cannot be used to determine a wireless user's location. It is because of this that other measurements are needed to locate wireless devices or users which has brought about the use of signal strength as an indicator to an entities location.

Another constraint is whether or not the power levels received at a fixed location from the surrounding wireless access points are affected by everyday activities, such as people moving through the environment or objects being moved around. In previous works [Wang et al., 2003, Howard et al., 2006, Smailagic et al., 2000] experiments have been conducted to determine whether or not this will affect the reliability of using signal strength as an identifier. These experiments plot out the signal strength of the wireless access points over time and all seem to produce similar results that suggest that the power levels received do not fluctuate enough to severely affect the usage of signal strength as a suitable identifier. The three experiments that I have read about are all consistent and show results where the signal strengths do not fluctuate more than 5dB about the mean and indicate a more noisy range of signal strengths during the daylight hours, where there should be more activity, whilst a much less noisy range during the night. This is a promising result as this should surely demonstrate that signal strength is largely invariant over time, however I intend to repeat this experiment within the indoor environment in which the system I am planning to implement will be tested and run to see whether I can produce similar results. This can be seen in Section 3.1. Since this experiment has been run before I can expect to see a set of signal strengths that do not fluctuate dramatically over time and have a standard deviation of less than 5dB. If I can manage to get these results, then I can conclude that the environment that I am to test my autonomous system is suitable.

2.1.3 Existing Solutions

As stated in Section 2.1.1 there have been numerous attempts at implementing a wireless location based system, which are fundamentally based around (1) an identifier to associate observed signal strengths to those at known locations, or (2) a function of distance to signal strength, thus determining the location of a wireless device or user. However there have been other works that use theoretical wireless propagation models to locate a wireless entity. In the paper that I had read on this, the authors compare this method of location to that of building up an intensity map of wireless signals to prove that similar results are obtained from using either method. This method of location is similar to that of scene matching, however uses theoretical signal strengths at known locations rather than observed strength. Using this method will be a lot less tedious and time consuming than building up an intensity map which was a point that the authors were trying to get across, but however the underlying methods remain the same whereby a location is then determined by running the set of expected signal strength through Bayes rule; raising the probability of the locations which have expected signal strength readings similar to that observed at the entities location and lowering those with very different strengths and then returning the location with the highest probability. The results from this paper show that the average error produced by both methods is about 1 meter apart, the theoretical method being the larger, however the standard deviations vary too greatly from one another and considering that the average errors are already relatively far apart it would not appear that using a theoretical model of wireless propagation over an empirical model is viable.

Other methods such as triangulation have been used to try locate wireless entities, however the same authors above state that “these experiments have shown that by using this method only poor resolution can be achieve” [Serrano et al., 2004]. Contrary to this a research paper from Microsoft Research [Bahl and Padmanabhan, 2000] suggest that by using both an empirical and theoretical model of the wireless signal strengths an adequate result can be achieved.

Similar to methods mentioned before, other solutions employ a probabilistic approach of determining the location of an wireless entity that updates its belief function which calculates the likelihood of an entity being at a specific location. This again uses an intensity map which maps observed signal strengths to known points within the environment and builds up a wireless model. In the cases where robots are used this model is not only updated when new wireless signal strength data is collected but also when the robot performs an action (rotates, moves forward and so on). Most other works use variations in how the location of the entity is determined, whereby instead of using simple probabilistic approaches they may instead use joint probabilities and probability distributions [Youssef et al., 2003] or neural networks to develop associations between the signal strengths at known locations to those observed by an entity [Robert et al., 2002].

These solutions do not necessarily address the problem that I wish to solve, such that it is likely that by using the same data collected by the autonomous system to locate another wireless device an inaccurate result may be achieved because say, if the wireless device was used at a distance further from the ground than the autonomous system, different signal strengths may be observed. Therefore I need to implement an acceptance value to counteract the difference in observed signal reading.

2.2 What is my Angle on the Project?

What sets this project apart from work that has previously been done within this research area is my use of an autonomous entity that collects the data from which this project determines the location of wireless devices or users. Although many of the research papers I have read do use some sort of robot to collect the data, there is no mention that they are in fact autonomous and therefore may need to be supervised whilst the data is collected. This was one thing that I did want to address as I feel that having to supervise the entity that collects the data entirely defeats the point in having the entity in the first place, other than having the knowledge that the data collected should be consistently accurate. By having an autonomous entity collect the data, I do not have to be physically present when the data collection is performed, which offers some advantages such as not affecting the wireless signal propagation whilst the data is being collected.

Although only a minor difference, I believe that my using the MAC address of a wireless access point as an identifier may make the algorithm used whilst scene matching more efficient, as it should lessen the sample space required when searching for the most likely location since any access points with a MAC address that does not match any of the MAC addresses from the observed signals can be discarded from the search.

This project also differs in respect to how the collected data is to be used.

In all the other research papers I have read they commonly use the data simply to locate the same entity that collected the data. This should be theoretically more simple considering that the entity should receive similar results each time it scans the network from the same points. Instead I wish to use the data within another application that tries to locate an entirely different wireless device. By doing that I wish to demonstrate the data interoperability between the two systems, the autonomous system and the mobile application, and to give a practical exhibition as to how this data can be reused.

2.3 Platform Requirements

2.3.1 Electronics Platform

To be able to implement my system, I will first need to do an investigation into the platforms that I will need to use which will enable me to make informed design choices. To begin I will discuss the platform that I have chosen to build the autonomous system with. This platform is the Arduino platform and is based on the Processing project [Reas et al., 2007] which was started in 2001 by Casey Reas and Benjamin Fry. Although originally this project was intended for the artistic community to design applications within a visual context it quickly moved into the realm of electronics where the Wiring project began.

Wiring [Igoe, 2007] is a prototyping platform based on the Processing project for those interested in electronics which consists of three essential elements; that being a programming language; an integrated development environment (IDE); and an electronics board on which sits an individual microcontroller. The inspiration behind this platform is to allow for the iterative process of refining a prototype of an electronic system. The platform is capable of allowing components that are connected to the board to interact with the physical world, so that control systems can be produced, such as being able to take input from a sensor and then output feedback through another component. This is of course what I will require in order to implement my autonomous system, specifically to introduce the collision detection and WiFi sampling aspects of the design. This platform gave birth to the Arduino which is essentially a cheaper version of the Wiring platform and therefore more consumer friendly and appropriate for my project. Both platforms share the same programming language so the use of the Arduino and Wiring microcontrollers should be interchangeable. Beside from having a more appealing price tag, I have chosen to work with the Arduino because of its smaller size which is more ideal for the project that I am working on and its flexibility to be expanded through the use of electronic shields. These shields are simply electronic circuit boards that can sit on top of the Arduino to give it further functionality. This is likely to be the method I will use to add wireless capabilities to the autonomous system. This platform is also appealing due to the fact that it uses a language called AVR-C, a simplified version of C++, a language that I am very familiar with.

2.3.2 Mobile Platform

As for the mobile application that I will be developing to ultimately locate the wireless users, there are many options in terms of the platform that can be used. For instance there is the Android platform, the iOS platform and the Windows Phone platform. I believe for this project I can rule out the Windows Phone platform due to it being a new platform that has not had much time to develop over the one year since it's release which has meant a slow adoption rate as it struggles to get the attention as the iPhone and Android smartphones seem to get. It also requires that the applications to be run on it are programmed in C#, a language similar to Java in terms of syntax but a framework that I am unfamiliar with and will take a lot of time to learn. Android on the other hand has been around for 3 years at the time of writing and is known to be very flexible in relation to the APIs and the usage of the hardware from the programmers perspective. This means that as a platform it is ideal for this project because it will allow me to make use of the wireless hardware the Android device has built in so that I can receive the information required from the device to locate a user. This platform requires that the programs to be run on it are programmed in Java which is a language I am familiar with, however as with the Windows Phone platform I am rather unfamiliar with the framework that is used to build the applications which will again take a lot of time to learn and will likely serve as a disadvantage. Conversely I have had a lot of experience with the iOS platform which has grown into a well established platform over the 4 years since it's release. It requires a knowledge of the Objective-C programming language which is a subset of C, a language I am very familiar with, and has a framework similar to that of OS X which is again a platform I am familiar with. Given the fact that I do not have to spend a lot of time learning this framework it is likely that I will choose to use it, however unlike Android, iOS tends to limit access to a lot of the hardware which may not serve my project well, but there are known ways to get around this problem.

Chapter 3

Approach to the Solution

3.1 Results and Evaluation of the RSSI Over Time Experiment

The results in Table 3.1 show the outcome of performing an experiment to determine whether the wireless network in the computer science building was stable enough to allow me to attempt to try locate a wireless device. The experiment involved periodically probing for wireless access points and recording information such as their SSIDs, MAC addresses, and the signal strength received from the location in which the scan was taken. The device that performed the scans was a laptop which remained in a fixed location throughout the experiment which was conducted over a 24 hour period. I filtered the results to only contain the three main basic service sets (BSS) the school broadcasts, those being CU-WiFi, CU-Guest-WiFi and eduroam; tables of which can be found in Appendix A along with results from a second test that was conducted over a 3 day period.

MAC Address	Samples	Mean (dB)	Standard Variation (dB)
00:26:3E:33:1D:42	15972	-45.75	2.81
00:26:3E:33:27:82	7864	-82.83	1.8
00:26:3E:33:1F:42	14809	-75.35	1.69
00:26:3E:33:1D:43	16342	-63.94	4.07
00:26:3E:33:1C:02	12253	-71.62	2.77
00:26:3E:32:FF:82	3707	-81.58	2.79
00:26:3E:33:1C:03	6596	-81.56	0.93
00:26:3E:33:44:02	15367	-67.90	1.37
00:26:3E:33:2E:02	5130	-84.47	1.03
00:26:3E:33:18:42	724	-86.12	0.95
00:26:3E:1C:59:42	23	-87.48	0.97
00:26:3E:33:48:82	2407	-83.26	1.46
00:26:3E:33:18:C2	1	-89.00	0
00:26:3E:33:27:83	4	-85.75	0.43
00:26:3E:1D:E8:42	1	-87.00	0
00:26:3E:33:3A:82	1	-87.00	0

Table 3.1: A table that represents the results received when sampling the signal strength against time for each access point on the CU-WiFi BSS in test 1.

The tables show the MAC addresses for each access point that is broadcasting some particular BSS, such as CU-WiFi in Table 3.1. The standard deviation for every result falls under 5dB (with three exceptions that all come from the same access point) which is consistent with other works and is only a minor fluctuation thus suggesting that this is a suitable property of wireless signals to use as an identifier. Since these results were taken over the course of an entire day, or longer, it would be acceptable to say that the data suggests that despite the everyday activity that occurs within the building the wireless signal propagation is not heavily affected.

3.2 Initial Design

3.2.1 Specification

Given the in depth description in the previous sections I can extrapolate and conclude on the specification that I will need to follow to successfully implement this system:

- Use two infra-red sensors and emitters to produce a set of sensors that can be used to detect obstacles in front of the autonomous system. These pair of sensors need be on either side of the system so it is able to detect as many obstacles as possible. The sensors and emitters will need to be aligned in such a way that no light from one emitter is leaked into the other sensor.

- The collision resolution will be done through software such that when a collision is detected in one sensor the autonomous system will stop and then turn about a centre pivot point.

- The autonomous system will use brushless direct current (DC) motors to produce the driving force that moves it and a H-bridge to control them.

- The autonomous system will use a light emitting diode (LED) and light dependant resistor (LDR) combination to keep track of the number of rotations the motors produce, so that the distance the system has travelled can be recorded. This works like an encoder such that when the beam of light is broken, the motors have turned x number of times.

- The autonomous system will use a wireless enabled module, compatible with the 802.11n standard, to scan for wireless access points in it's near vicinity.

- Considering the memory limitations of the Arduino platform, the system will need to process and store the collected data on another machine. Therefore I need an application that listens for requests and then processes and stores the data collected from the autonomous system.

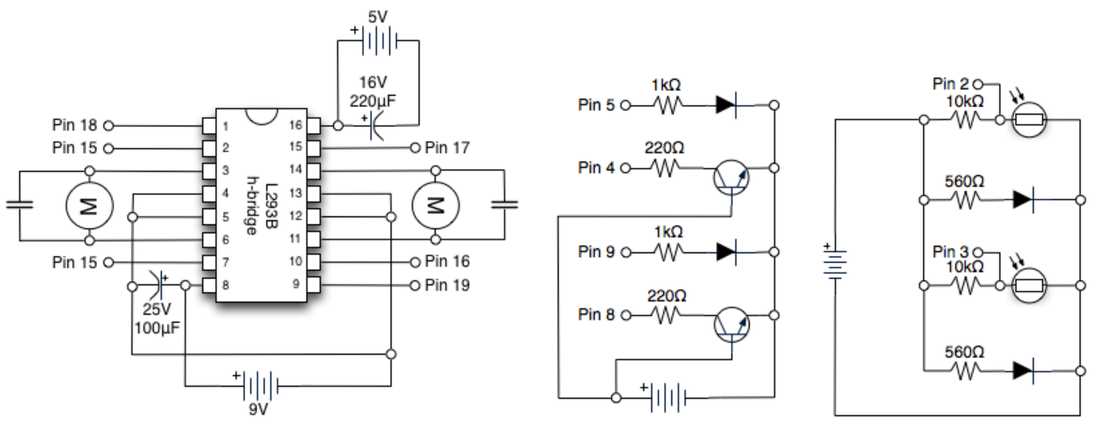
- The application that will process and store the data will be an OS X application.

- As I will be mostly working with Apple products (MacBook Pro and iPad) I will be implementing a Core Data database to store the collected data. Since both platforms implement Core Data in the same way, any Core Data database can be used on either device. This simply makes data interoperability extremely easy and removes the need for an external web server/database to store the data.

- The mobile application that uses the data will be written in Objective-C, required when writing Mac OS X or iOS applications, and will include within it the Core Data database that was built up earlier.

3.2.2 Design

The design of my autonomous system will require that I initially plan out the circuitry of each individual component so that I can adequately prototype and test each part of the system before putting it all together at the end. Figure 3.1 shows the three main parts of the system, those being the motorised means of movement; the vision system; and the encoders which keep track of the position and orientation of the system. As stated in the specification, the motorised component in Figure 3.1(a) uses brushless DC motors and a H-bridge to control them. As for the vision circuitry in Figure 3.1(b), a simple set of IR sensors and IR LEDs have been used to detect whether objects are in the path of the system. The final component, the tachometers, in Figure 3.1(c) use another simple set of sensors and LEDs however in the visible spectrum. The idea with this circuit is that when the light between the sensors and LEDs is broken the wheels of the system have gone round once, thus incrementing a counter. The design for the entire system can be seen in Appendix B.



(a) Movement circuit diagram (b) Vision circuit diagram (c) Tachometer circuit diagram

Figure 3.1: Circuit diagrams for the individual components of the autonomous system.

I also need to design the storage backend of the system that will be responsible for storing every location where a sample of the wireless environment has been taken and the access points associated to that location. This can be found in Figure 3.2 which shows the two objects the storage backend will store. The Access Point object will store all the information regarding an access point which has been observed; this includes the observed signal strength while probing for the access point. This object also has a relationship associated to it, BelongsToPoint, which states that it belongs to a particular Point object that represents the location at which the wireless environment was probed. The Point object stores the relative x and y coordinates from the initiating probe and the orientation of the autonomous system at that point in time. This object has a relationship associated with it, HasPoints, that states it has discovered 1 or more Access Points at that location.

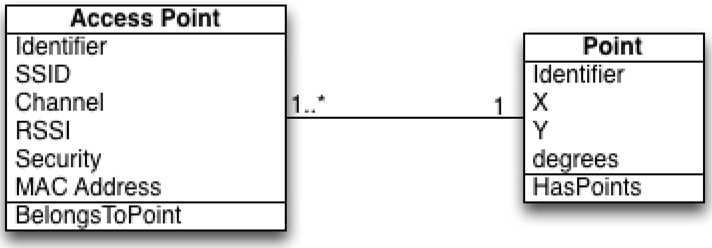


Figure 3.2: Database backend that will store the fingerprints.

Chapter 4

Conclusions

Considering the background study that I have performed, the designs that I have drawn up and the experiment that I have conducted in the feasibility of using wireless radio signals as reference points I can conclude that using the MAC address of a wireless access points along with the wireless signal strength will produce a unique identity for a physical location of an indoor environment. Also the design choices I have made for the autonomous system are simple enough for me to prototype and fully implement into a working robot. In particular I am most happy with my choice in the Arduino as the prototyping platform due to it's simplicity and extensibility in terms of the extra modules that can be mounted upon it, meaning that I do not have to struggle with the complex electronics of wiring up the devices myself.

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Appendix A

Further Experiment Results

MAC Address	Samples	Mean (dB)	Standard Variation (dB)
00:26:3E:33:1D:40	15826	-45.82	3.03
00:26:3E:33:44:00	15308	-68.04	2.17
00:26:3E:33:27:80	6977	-82.86	1.81
00:26:3E:33:1F:40	14775	-75.43	1.74
00:26:3E:33:2E:00	5140	-84.63	1.08
00:26:3E:33:1D:41	16169	-64.32	4.17
00:26:3E:33:1C:00	12782	-71.81	2.87
00:26:3E:32:FF:80	2935	-81.78	2.85
00:26:3E:33:1C:01	5431	-81.81	0.93
00:26:3E:33:18:40	546	-86.20	1.07
00:26:3E:33:48:80	2035	-83.50	1.47
00:26:3E:1C:59:40	9	-87.22	1.23
00:26:3E:33:3A:80	1	-89.00	0
00:26:3E:33:27:81	1	-84.00	0

Table A.1: A table that represents the results received when sampling the signal strength against time for each access point on the CU-Guest-WiFi BSS in test 1.

MAC Address	Samples	Mean (dB)	Standard Variation (dB)
00:26:3E:33:1D:44	15877	-45.82	2.87
00:26:3E:33:27:84	8912	-82.93	1.79
00:26:3E:33:1F:44	14853	-75.37	1.71
00:26:3E:33:1C:04	11811	-71.59	2.73
00:26:3E:33:1D:45	16185	-64.04	4.07
00:26:3E:33:1C:05	6592	-81.55	0.94
00:26:3E:32:FF:84	4300	-81.37	2.82
00:26:3E:33:44:04	15330	-67.90	1.26
00:26:3E:33:2E:04	5311	-84.44	1.08
00:26:3E:33:18:44	695	-86.14	0.89
00:26:3E:33:48:84	2551	-83.14	1.46
00:26:3E:1C:59:44	4	-87.75	0.43
00:0B:6B:DE:9E:FB	1	-79.00	0
00:26:3E:33:27:85	4	-86.25	0.83
00:26:3E:33:3A:84	1	-87.00	0

Table A.2: A table that represents the results received when sampling the signal strength against time for each access point on the eduroam BSS in test 1.

MAC Address	Samples	Mean (dB)	Standard Variation (dB)
00:26:3E:33:31:82	30527	-86.48	1.39
00:26:3E:17:15:C2	32715	-73.54	3.31
00:26:3E:33:60:42	32811	-63.89	3.01
00:26:3E:1C:62:C2	32480	-71.69	2.52
00:0B:0E:97:FA:42	29615	-84.49	1.76
00:26:3E:33:60:43	32679	-78.11	1.24
00:26:3E:1C:62:C3	32848	-67.29	2.76
00:26:3E:17:15:C3	30276	-74.63	5.47
00:26:3E:33:50:C2	6332	-90.31	0.90
00:26:3E:33:56:C2	511	-89.14	1.68
00:26:3E:33:2C:82	9	-91.00	0.67
00:26:3E:33:15:82	15	-90.80	1.05
00:26:3E:33:15:C2	87	-91.18	0.86
00:26:3E:33:3A:C2	2	-91.50	0.50

Table A.3: A table that represents the results received when sampling the signal strength against time for each access point on the CU-WiFi BSS in test 2.

MAC Address	Samples	Mean (dB)	Standard Variation (dB)
00:26:3E:33:31:80	29786	-86.73	1.40
00:26:3E:17:15:C0	32559	-73.82	3.39
00:26:3E:33:60:40	32793	-64.18	3.51
00:26:3E:1C:62:C0	32456	-72.13	2.74
00:0B:0E:97:FA:40	29395	-84.71	1.68
00:26:3E:33:60:41	32496	-78.28	1.26
00:26:3E:1C:62:C1	32835	-68.08	3.22
00:26:3E:17:15:C1	31719	-75.56	5.72
00:26:3E:33:50:C0	6129	-90.42	0.88
00:26:3E:33:56:C0	495	-89.23	1.66
00:26:3E:33:15:80	11	-90.91	0.90
00:26:3E:33:2C:80	11	-91.09	0.67
00:26:3E:33:3A:C0	4	-91.25	0.83
00:26:3E:33:57:C0	73	-91.07	0.88

Table A.4: A table that represents the results received when sampling the signal strength against time for each access point on the CU-Guest-WiFi BSS in test 2.

MAC Address	Samples	Mean (dB)	Standard Variation (dB)
00:26:3E:33:31:84	30555	-86.44	1.38
00:26:3E:17:15:C4	32757	-73.65	3.33
00:26:3E:33:60:44	32830	-63.84	2.88
00:26:3E:1C:62:C4	32556	-71.66	2.59
00:0B:0E:97:FA:44	29891	-84.44	1.75
00:26:3E:33:60:45	32618	-77.89	1.15
00:26:3E:1C:62:C5	32850	-67.53	2.82
00:26:3E:17:15:C5	29483	-74.70	5.40
00:26:3E:33:56:C4	451	-88.66	1.48
00:26:3E:33:50:C4	5900	-90.28	0.88
00:26:3E:33:15:84	11	-90.27	0.45
00:26:3E:33:2C:84	5	-91.00	0.63
00:26:3E:33:3A:C4	2	-91.50	0.50
00:26:3E:33:57:C4	42	-91.12	0.79
00:26:3E:33:31:85	1	-85.00	0.00

Table A.5: A table that represents the results received when sampling the signal strength against time for each access point on the eduroam BSS in test 2.

Appendix B

Circuit Diagram

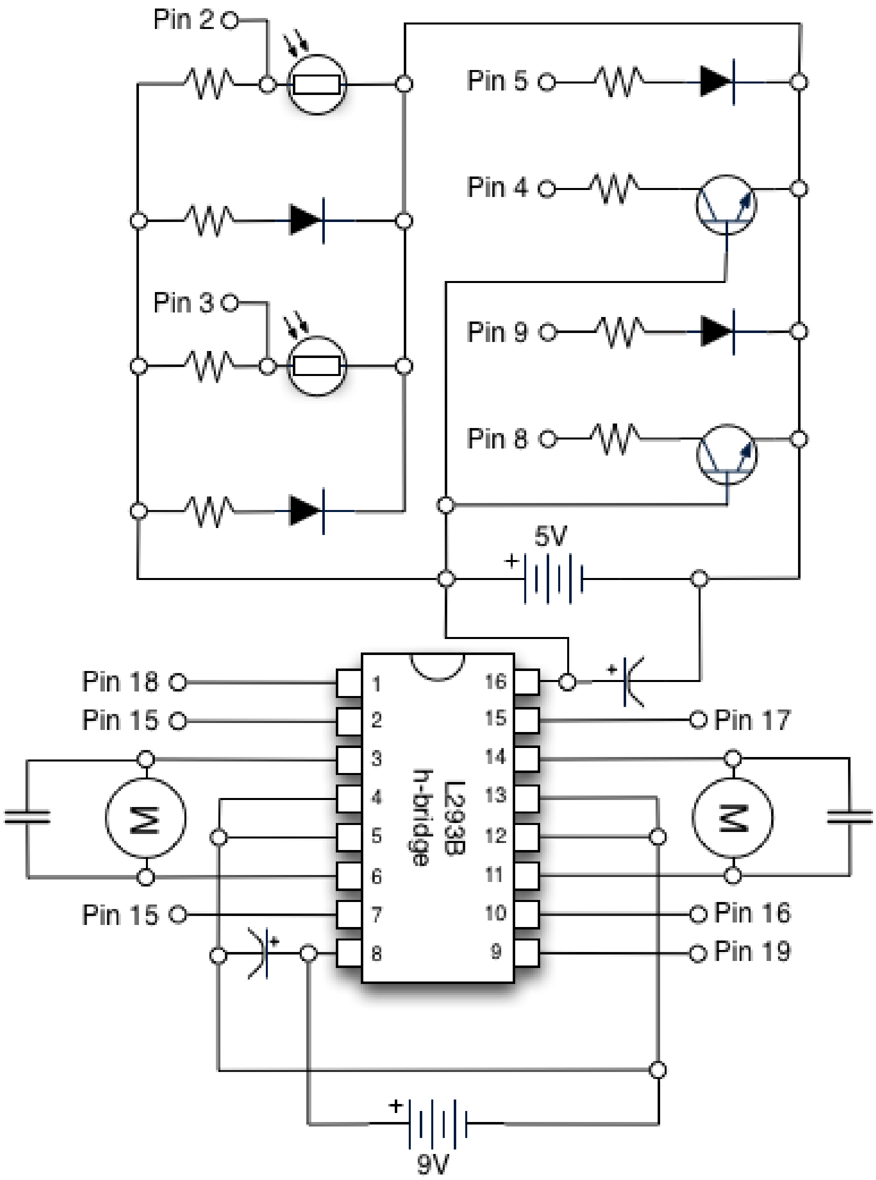

Figure B.1: Complete circuit diagram of the autonomous system, which is able to correct its position to avoid obstacles and calculate its travelled distance.