Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Two factor authentication in M2M

Fingerprinting of mobile devices for making a two factor authentication between the devices

Examensarbete utfört i säkra system
vid Tekniska högskolan vid Linköpings universitet
av

Anna Karlsson

LiTH-ISY-EX--15/4838--SE

Linköping 2015

Department of Electrical Engineering
Linköpings universitet
SE-581 83 Linköping, Sweden

Linköpings tekniska högskola
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Handledare: **Jonathan Jogenfors, PhD student**
ISY, Linköping university
Engineer Philip Engström
Cybercom AB

Examinator: **Jan-Åke Larsson, Ph.D**
ISY, Linköping university

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Titel
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Tvåfaktorauthentisering mellan maskiner
Two factor authentication in M2M

Författare
Author

Anna Karlsson

Sammanfattning
Abstract

If your thesis is written in English, the primary abstract would go here while the Swedish abstract would be optional.

Nyckelord
Keywords

computer security, M2M, authentication

Sammanfattning

Sammanfattning är en sammanfattning på svenska...

Abstract

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Vi tycker alla har varit så himla goa hela den här långa och tuffa tiden i våra liv.

Linköping, Januari 2020
Anna Karlsson

Contents

Notation

Notation

Notation	Meaning
G	G-force
η	
ϵ	
Θ	
ω	
$\boldsymbol{F}_C$	Coriolis force

Abbreviations

Abbreviation	Meaning
FAR	False Accept Rate
FRR	False Reject Rate
FTE	Fail To Enrollment
ICT	Information and Communication Technologies
IoT	Internet of Things
MEMS	Micro Electro-Mechanical System
M2M	Machine-to-machine
NIC	Network Interface Card
PRNU	Photo-Response Non-Uniformity noise
RFF	Radio Frequency Fingerprinting
RFID	Radio-Frequency IDentification

1

INTRODUCTION

This paper is the report for my master thesis in Computer Science and the last part of my education for become an engineer in information-technology in field of secure systems. The thesis was performed on Cybercom AB in Linköping.
This introduction chapter will give an overview of the work together with background and aims and objectives that is used as the basis for the work presented in this thesis.

1.1 Background

Cars, locks, birds, stoves, refrigerator, coffee maker, watches, cat feeder, sewing machines..., the world of connected devices is growing rapidly. For making this things connect to each other we need secure authentication methods for knowing that they are connecting to the device they are suppose to and not anything or anyone else.

For us humans it has become an everyday thing to using two factor authentication when accessing buildings, part of networks, our bank and so on. When talking about two factor authentication we usually use a combination of either three things; something you *know* like passwords, something you *have* like tag, passport, card or phone, something you *are* like iris or fingerprint. Mot about the in chapter 2.
Something you know or have is things that can be copied, stolen or modified fairly easy and without meet or know all that much about the person or thing you try to authenticate as. This compared to something you are as iris, fingerprint and DNA requires much more effort and time since you can only focus on one person at a time.

1.2 Aims & Objectives

Today most of the solutions for M2M authentication involves a certificate, token, UUID etc., from my opinion is this something the machine know or have. The area of fingerprinting a machine has been more investigated in line with the world of IoT (Internet of Things) has grown. The aim of this thesis is to look in to if the fingerprinting methods found today, can be used as something the machine *are* for two factor authentication between them. The problems I'll work to solve with this thesis is:

> Can you create a device fingerprint by using the unique hardware characteristics in a mobile device?
>
> Is this fingerprint suitable for using as a second factor for authentication between devices?

The problems above state a mobile device and not a general machine, which is one of my limitations in the area. When stating a mobile device leaves also leads to wireless network environment. The focus is also set to an authentication process where you are able to collect a set of data from the device in a database in a test environment. This means that new devices in the network has to go trough some kind of phase were collecting the unique hardware characteristics data. As the title of the thesis implies, authentication is the focus not identification. Since I'll accomplish some kind fingerprint for the mobile device software, certificates, tokens and types of ID will not be looked in to. This because I think that it's not something the device are, more something it has or knows.

There are different point of views to this work and can be summed up to the objectives:

> **Explore different unique hardware characteristics of a mobile device**
> Mobile devices today are equipped with a lot of sensors and since they like other hardware has some noise that may be unique enough to differ from a device of the same model. Measurements from the microphone-, speaker-, gyroscope-, accelerometer- and camera-sensor will be collected and valuated from the view as fingerprints. RFF (Radio Frequency Fingerprinting) is another perspective that also will be measured from the noise of the mobile devices in a wireless environment and compared together with the sensors.
>
> **Combining M2M, two factor and biometric authentication**
> Biometric authentication has ways of measure and compare fingerprints, this measurements and methods will be used to make the two factor authentication between the devices.

1.3 Thesis Outline

This introduction chapter including background, aims and objectives will give a quick view of what the thesis is about. The chapters that following is divided in

different parts that maps to the different objectives listed above.

Ch.1: This will give an introduction to the work done in the thesis and motivation for doing it.

Ch.2: How authentication is made today between machines, two factor and in biometric.

Ch.3: The different unique hardware characteristics of a mobile device that has been found today and how they are collected.

Ch.4: Result of the collected unique hardware characteristics of a mobile device together with comparison and evaluation on if they can be used as mobile fingerprints or not. This chapter also presents the demo the made from the test result.

Ch.5: Conclusion will except conclusions also include ethical aspects and further work.

1.4 Related Work

TODO! or to be removed and covered in the next two chapters...

2

COMMUNICATION & AUTHENTICATION

Since every device connected to some network that is in almost all of the cases connected to Internet is they in a untenanted or malicious environment. Everything connected to the Internet is very likely to be hacked. Thus, authentication is needed for remote sensing devices to communicate. Ren et al. [2013]
In this chapter will show ways of authentication (two factor, M2M and biometric) that is in the area of this thesis. The biometric part is in the area because it has good ways of measure strength in a biometric trait (especially fingerprint) that will be used when comparing strength of my tests of characteristic noise in the mobile device.

2.1 Two factor authentication

There are more ways to authenticate a user than password, however it is the most common. There are three different types of authentication;

- Something the authenticator *have* like a key, card, passport and so on
- Something the authenticator *knows* for example password
- Something the authenticator *are*, known as biometrics such as fingerprint or iris pattern

[Anderson, 2008, p. 31]
Authentication in two factor means a combination of two of the three types of authentication above. An example can be use of a credit card (you have) in combination with a PIN-code (you know) to collect the money from an ATM. Something the authenticator have and knows is the most common combination. The third one, cost is the biggest reason form that biometrics isn't that common yet. [Anderson, 2008, p. 47]

2.2 M2M (Machine-to-machine)

Information that is exchanged via a communication network between machines has to establish conditions for doing so, that is where M2M is used. M2M is often a short synonym for M2M communication, meaning the communication conditions between devices. M2M communication is only the communication made between machines without any human behind it. A mobile device interacting with a call center application is not M2M, cause there is a human behind the mobile device calling. Often is M2M involving similar devices in the same M2M area network, interacting with an application. This makes it possible for devices to access public networks as well, via a gateway or router. Devices are not a new thing, but when we have a growing world of IoT devices with very specific characteristics is growing. Thus makes the area of M2M more important to make these devises talk without a human behind. This affecting the requirements on the application and networks dealing with the devices. Characteristics of this devices is listed blow;

Multitude, they say that connected devise not directly interacting with humans, the big part of IoT is soon to be significant more than the ones which interact directly with humans. This will put more pressure on application and networks dealing with all devices.

Variety of connected devices with requirements like data exchange rate, form factor, computing, or communication capabilities. M2M applications have to be built, in order to define and develop common enabling capabilities.

Invisibility meaning that the device has virtually zero human control. The more invisibly the less likely for error caused by humans.

Criticality devices that can harm humans like voltage. Therefor reliability is an important factor.

Intrusiveness many of the increasing connected devices raise the privacy question like refrigerators, stoves, doors, etc.

All this devices with no human control is like told above very different, but many of them is similar in some ways, such that the functionality is limited, low-powered, embedded and have long life cycles. The fact that they often are embedded makes it hard to separate between M2M communication and machine-to-human or human-to-human communication. [Boswarthick et al., 2012, p. 2-4]

2.2.1 Difference between M2M and IoT

Internet-of-Things, meaning to making everything connected to everything in the Internet. IoT is now in its starting pits and ready to start the race. Machine-to-machine communication is a part of that, but it also covers other areas and IoT some that M2M doesn't. The common denominator is according to Polsonetti

remote device access, where the embedded hardware modules in a machine that communicate wireless or not is M2M applications. Remote device access for IoT has a much more wider perspective that not only including same device communication but also passive and other low-power sensors that not can be motivated as a M2M hardware module. Polsonetti [2014]
In this thesis is M2M a subset of IoT, since it always one mobile device that wants to authenticate then it can communicate with other deceives.

2.2.2 M2M authentication

There are no standardized way of authenticate in M2M, but effort is done in the area. An example is He [2012] where he based authentication on a machines fingerprint. But this fingerprint isn't of the same character as the one this thesis is focusing on. In his article the fingerprint consist of hardware message of computers, such serial number of CPU, MAC address of network card, Machine ID etc. These things have through the years been proven to bee pretty easy to spoof. There are hundreds of guides of how to do that in many platforms like mobile devices (iPhone **?** and Android **?**) that is the thesis area.
Like Ren et al. [2013] that states in their article that "...traditional methods such as "what you know and who you are" may not be applied". But the aim in section 1.2 is to do precisely that and with the advantage that using "regular" authentication that is more tried and tested. Thus the next section will be about biometric systems and how they authentication which is used for who you are.

2.3 The biometric process

This section will be about the biometric authentication process that is implemented in to mobile device instead of a user in section 5.2.

"A biometric system measures one or more behavioral characteristics...information of an individual to determine or verify his identity." [Jain et al., 2011, p. 3]

2.3.1 Recognition

As said before is biometric something you *are* and the person who wants to be recognized to the system. Buy, showing his or her biometric identifier (fingerprint, iris, DNA, etc.) to the biometric system, thus seen as a *user* of the system. The strength in biometrics is also the fact that it knows if a user is known to the system even if the user denies it. [Jain et al., 2011, ch. 1]

2.3.2 Biometric systems

There are some blocks for building a biometric systems, which can measure characteristics of a user. In biometric these characteristics is called *traits*, *indicators*, *identifiers*, *or modalities*, but for for the aim of this thesis will it still be called

characteristics. For designing, implementation and evaluation when building a biometric system there are some steps that has to be done;

The first step is to collect biometric data and store it in a database with the users identity. The recognition is then done by again collect biometric data from the user and compared to the database. This is the so called *enrollment and recognition phase*. The raw biometric data is often destroyed after enrollment and the recognition is all about pattern matching. This matching is done in four steps;

1. *Sensor* - to collect the raw biometric samples, that can be a image, amplitude signal, online signature, odor or chemical-based.
2. *Feature extractor* - first has to make the raw biometric samples comparable, mostly done in three pre-process operations;
    - Quality assessment, is the sample good enough?
    - Segmentation, remove background noise from sample
    - Enhancement, by using an algorithm to improve the sample
3. *Database* - that has the data from the enrollment phase together with some identity data (like name orID). This database should having a access control mechanism for security reasons.
4. *Matcher* - where the sample from the enrollment is compared with the sample in recognition, to see if it's a match or not. This is done by having a match score to decide how close the enrolled and recognition sample is. The score is counted in different way depending on the characteristics that is used in the system.

[Jain et al., 2011, ch. 1]

2.3.3 Biometric authentication

Biometrics authentication, is sometimes also called verification that answers the question "Are you the one you say you are?". There is also biometric identification that answers "Are you someone known to the system?" but that is not what this thesis aim to answer. The practical difference between authentication and identification is that the user has to give the system some kind of information (username, passport, email etc.) on who they claim to be. But in identification the user just give the sample to the system, which then looks if the user is known to the system or not. The identification look-up takes longer time since you look for all samples in the database and compare them, in authentication you only look for the claimed identity. [Jain et al., 2011, ch. 1]

2.3.4 Measurements

Biometric measurements is a bit more tricky than in a password-based system where the answer just is 'match' or 'no match'. The accuracy of the biometric system must be consider when you choose characteristics. This is measured by two

rates (False Reject Rate) that is the probability that two samples from the same user is not a match and (False Accept Rate) is the probability that two samples from different users is a match. A match is decided authentic between two samples from the same user is high enough and as a *impostor* is there is similarity between two samples from different users.
There are a threshold η that is used to decide the FRR and FAR. The proportion of authentic scores (ω_1)) that are less than η is defined as FRR and the impostor score (ω_0)) that are greater than or equal to η is FAR. Which can be described mathematical as;

$$FAR(\eta) = p(s \geq \eta|\omega_0) = \int_{\eta}^{\infty} p(s|\omega_0)ds,$$

$$FRR(\eta) = p(s \geq \eta|\omega_1) = \int_{-\infty}^{\eta} p(s|\omega_1)ds,$$

where $p(s \geq \eta|\omega_x)$ us the probability density function of the authentic respective impostor score. [Jain et al., 2011, p. 18]

2.3.5 Design a biometric system

When designing a biometric system it is done in a five activity cycle. Depending on the outcome of one activity, the next step could be forward or redoing earlier activity. The design cycle is represented as a flow-chart below (from page 27 in Jain et al. [2011]), followed by a description of the five activities.

Understand nature of application - is about deciding functionality type and classified based on how well the system fits this six different behaviors; cooperative, overt, habituated users, attended, untenanted operation, controlled operation and open system. The first is if the user will be *cooperative* or not, like if the user wants to access something it is likely to cooperate. *Overt* is if the user knows that it is object for biometric recognition. If the user interacts with the system a lot it is likely that the user will be *habituated*. The enrollment and recognition operations can either be *attended* by a human or not. The environment of the operations may have to be *controlled* in terms of temperature, pressure, etc. in order to work. Last there are also the question if the system will be closed or *open*, such if the database of biometric data will be shared between applications or be in one closed application.)

Choose biometric characteristics - is also classified, based on seven different factors. The thing with biometrics is that it will never be completely solid, thus all the factors can't be perfect. Counted to this is that the factors will have different value for different systems.

1. *Universality*, the fail-to-enrollment (FTE) rate should be low.

2. If the *uniqueness* of the characteristics is high will the rate of FAR be low.

3. The characteristic should be high in terms of *permanence* and not be changing significantly over time.
4. *Measurability* from the user perspective in terms of collecting characteristics, should convenient.
5. The time of the authentication is measured in *performance*.
6. User should have a high *acceptability* in present their characteristics to the system.
7. *Circumvention*, in terms of how easy it is to malicious fake the characteristics.

Collect biometric data - is apart from the collecting also includes factors of time, cost and size of the equipment.

Choose features and matching algorithm - is a critical step since this is the heart of the system and has to bee done with a great deal of knowledge if the selected characteristics and the data extracted from it.

Evaluate the biometric system - by asking different questions. There are no framework for doing this and it has to account different perspective as require experts of different field such psychology, business, computer science and statistics. There exists no framework for these types of evaluation but Jain et al. [2011] propose doing it in three evaluation-stages technology, scenario and operational.

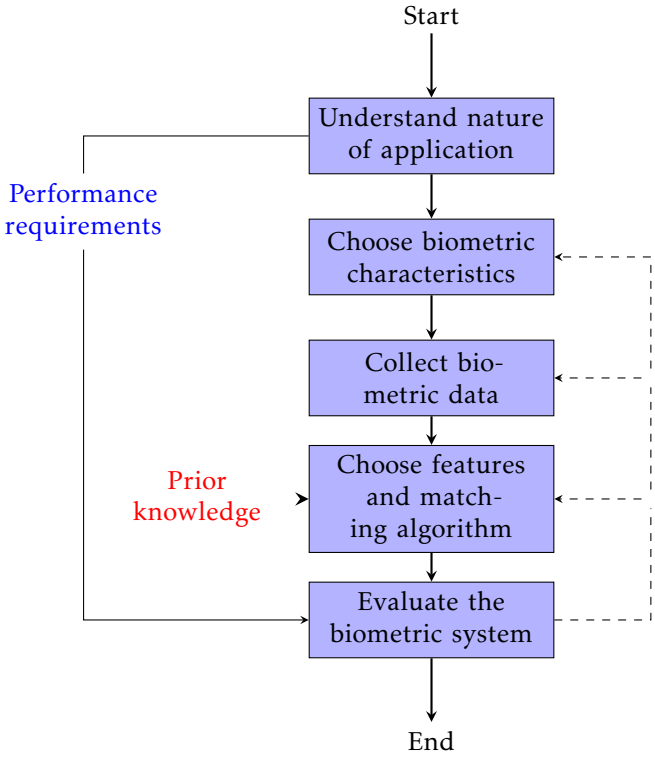

Figure 2.1: *The design cycle of a biometric system*

3

UNIQUE HARDWARE CHARACTERISTICS OF A MOBILE DEVICE

In the hardware of a device there are some features that can be used to distinguish devices from each other. In the pyramid below (from Das et al. [2014]) showing features from a mobile device that can be used for fingerprinting a device. This chapter will cover explanation on why and how this can be done for the sensors and radio signal. The clock skew rate will not be covred in this thesis

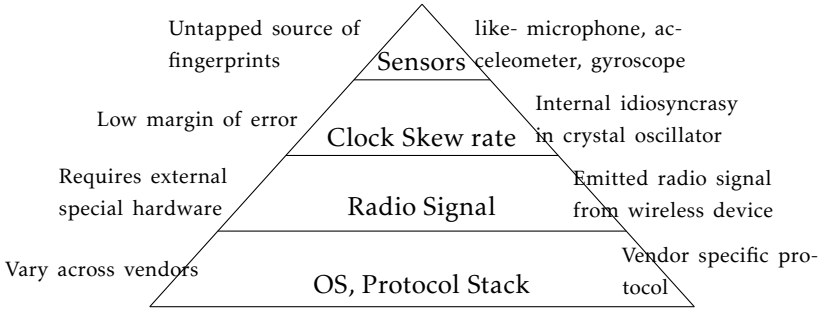

Figure 3.1: *The pyramid of features in a mobile device that can be used for fingerprinting.*

because it is proven REFERENSER!! not to be unique enought for authentication purposes.The bottom layer of the pyramid, OS and protocol stack will not be coverd since it vary across vendors and has vendor specific protocols that will be out of the time frame to look in to.

3.1 Sensors

As seen above in figure 3.1 are sensors an untapped source of fingerprints in mobile devices and example of sensors are microphone, accelerometer, barometer, speakers and gyroscope. In this chapter will accelerometer, gyroscope, microphone and speaker sensors in mobile devices be presented and how collecting characteristic noise from them is done.

3.1.1 Accelerometer

The accelerometer is the sensor that detect movement on a mobile device, like when you changing orientation on your device. Acceleration is measured by sensing how much pressure the device has in terms of force. A mobile device in rest relative to the surface of the earth has about 1G (gravitational-force). Rodriguez and Shala [2011]
In mobile devices is done using a micro-electro-mechanical system (MEMS) that translates electrical property-changes (as voltage) and translated into signals. Processing is then done by software in the mobile device. Mobile devices today uses three different accelerometers; *micro-electromechanical system* that reacts when forces affect them which is changing an electrical property. *Capacitive accelerometer* reacts when a net force is applied on the mechanical system, that is resulting a change in capacitance. The *piezoelectric accelerometer* uses as the name implies the structures of piezoelectric crystals. These are crystals that reacts on forces applied to the mobile device trough creating electrical charges that generate voltage. `http://www.techopedia.com/definition/24430/accelerometer`

Measure the error characteristics from the accelerometer is done by taking the long term average of the output when the accelerometer is in rest. That is the biggest error source in the accelerometer and it grows quadratically over time, but when the accelerometer is in rest the error $epsilon$ can be calculated as a function of time t;

$$s(t) = \epsilon * \frac{t^2}{2}$$

Woodman [2007]

3.1.2 Gyroscope

The gyroscope is sensing how the device is moving in terms of angles, for maintaining or measure the orientation. This is originally a mechanical system based on the principle of conservation of angular momentum. The most popular Gyroscope for devices today is a MEMS that is using silicon micro-mechanical techniques. Coriolis effect is measured with vibrating elements in the MEMS gyroscope. Coriolis effect is a change of moving objects direction when looking at it from a rotating reference system. The difference from the accelerometer is that

the gyroscope measures relative to the device body rather than relative to earth. The equations of Coriolis force;

$$\boldsymbol{F}_C = -2\,m\,(\omega * v)$$

Where m is the mass of the particle, ω the angular velocity and v the velocity of the particle in the rotating system. Woodman [2007]

The MEMS sensors is common used because has many pros such small (like a hair), light, cheap, low powered, etc. The MEMS gyro is also known for high reliability but it has some error characteristics like constant bias, white noise, bias instability, calibration error and temperature effects. One of these error characteristics that can be tested by reading the output from a gyroscope in rest is the *constant bias*. That is bias of the gyroscope output when not having any rotation on it. This constant error ϵ of the bias over time t leads to an angular error that grows linear;

$$\theta(t) = \epsilon * t$$

If take the long term average output from the gyro in rest, the constant error of a rate gyro can be estimated.

3.1.3 Microphone & Speaker

A microphone or speaker on a mobile device is like accelerometer and gyroscope a MEMS. Today mobile devices has one, two or three MEMS microphone. When a sound reaches the microphone sets a diaphragm in motion by the pressure from the sound wave. The motion causes capacitive change and that leads to a change of voltage. In short terms is the pressure of the sound converted to electrical signals. Das et al. [2014]
A normalized output gain over a given frequency range is the response from a microphone that has specification in a frequency response graph.The range should ideally be the same as for the speaker. In the real world however the response curve varies between different frequencies, depending on the design of the mobile device. Bojinov et al. [2014]

The error characteristics in the microphone or speaker due to inconsistent in the manufacturing. This inconsistencies does that not even microphones of the same model are identical. Every manufacturer of microphones and speaker specifies a tolerance for these errors and it is typical ±2db. Bojinov et al. [2014]

3.1.4 Camera

The digital camera of a mobile device also includes sensors and other hardware that can be used as fingerprinting characteristics. The basic is that light travels trough a lens and hits a imaging sensor which contains pixels that has a filter array in front. The filter is for gives each pixel a detected color. The pixels is then put together again to a resulting signal which is send to some final post

processing (color correction, white balance, etc.) steps before the image is written to the memory card. In this process there are different kind of noise that effects the image;

Shot noise - the amount of photons hitting the sensor and each pixel varies a random amount

Fixed pattern noise - there is a small electric current that leaks from photodiodes in each pixel, caused by dark current

Photo-response non-uniformity noise (PRNU) - is a noise that is not affected by temperature or humidity. When manufacturing sensors the silicon gets imperfection which causes that pixels aren't equally sensitive to light. This is the main source of pattern noise and makes it really unlikely for two cameras to have the same pattern.

The three types of noise can be described as a mathematical model for getting the output of the sensor y_{ij}:

$$y_{ij} = f_{ij}(x_{ij} + \eta_{ij}) + c_{ij} + \epsilon_{ij}$$

where f_{ij} is a multiple factor close to one that captures PRNU noise, x_{ij} is the number of photons hitting the sensor, η_{ij} the shot noise, c_{ij} the dark current and ϵ_{ij} the additive random noise. The key for a unique fingerprint of the camera (in the mobile device) is to finding f. Jenkins [2009]

3.2 Clock skew rate

Mobile devices today have a lot of clocks both in hardware and software. These clocks isn't all that synced as you may think and have what is called a clock skew rate between them, which is the time difference between them. This could be a thing to measure as unique characteristics if the clocks always is equally wrong. Lanze et al. [2012]

Measuring the clock skew rate remotely is done by comparing different clocks from the device with a more correct clock, like an atomic clock. In the paper Lanze et al. [2012] and... LÄGG TILL FLER KÄLLOR!! they conclude that the clock skew rate isn't unique enough for fingerprinting device. Due to that it's proven not completely unique it will not be good enough for a fingerprint and something the mobile devise *are* in two-factor authentication purpose.

3.3 Radio signal

Wireless devices that want to connect to another device sends radio signals. This signals can be used for fingerprinting the device by passively analyzing radio-frequency (RF) in IEEE 802.11 and finding the source network interface card

(NIC) . Where you can find characteristic errors for each device due to transmitter-specific imperfections in the signal. There are different artifacts that can be taken into account for fingerprinting. This is known as radio frequency fingerprinting (RFF). Brik et al. [2008]

ish funkar Padilla et al. [2007] , Franklin et al. [2006], Brik et al. [2008]

följt av ett stycke om hur man mäter bruset.

4

TEST & DESIGN

In this chapter the methods used for testing the mobile devices for different characteristics is described.

4.1 Accelerometer & Gyroscope

I decided to collect the data via a web-page since JavaScript can access gyroscope and accelerometer data without any permission or knowledge from the user Block and Popescu [2011]. This only require that the device has Internet and a browser installed, no additional installations and completely cross-platform.

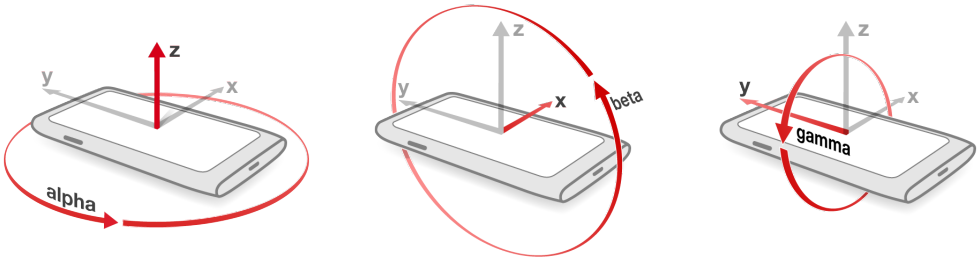

Figure 4.1: *The device axes for the JavaScript* `DeviceOrientation` *and* `DeviceMotion`

4.1.1 Accelerometer

For the measurements of the accelerometer a event listener is added:

```
if(window.DeviceMotionEvent) {
```

```
  window.addEventListener('devicemotion', function(event) {
    x = event.acceleration.x;
    y = event.acceleration.y;
    z = event.acceleration.z;
    r = event.acceleration.rotationRate;
  });
}
```

In JavaScript there are two types of acceleration with and without gravity, which according to Mozilla means that `accelerationIncludingGravity` is acceleration made by the device. In context to `acceleration` not depending on influence of gravity only by the acceleration made on the device. But as I see it that acceleration is made because of gravity so it is just different point of views. Since without gravity gives no difference in scene of meters above sea level, I'll use that one. The accelerometer also comes with the nice feature of `rotationRate` which is the acceleration made from the axes in alpha, beta and gamma direction, see Figure 4.1. Mozilla [2015]

The recording of the accelerometer is done by taking 1000 accelerator-data samples during a few seconds and saved in a CSV for analyzing. Since there are six different measurements that gives a 6-by-1000 matrix for each device as a base for accelerometer characteristics. When gather all devices together in a six-dimension space that includes clusters of all device samples. For knowing the distance between this measurements MATLAB is used. To know the difference between measurements from the devices, the Euclidean norm value is calculated. Norm is a function that gives a size to a vector. The norm for one vector is calculated like;

$$\|\boldsymbol{x}\| := \sqrt{x_1^2 + \cdots + x_n^2}.$$

This is done for each of the six measurement-vectors. And then summed up like

$$(abs(V_x)^6 + abs(V_y)^6 + abs(V_z)^6 + abs(V_alpha)^6 + abs(V_beta)^6 + abs(V_gamma)^6)^(1/6)$$

In MATLAB this looks like:

```
motion = importdata(motion.csv);
norm = norm(motions.data, 6);
```

A nearest neighbor algorithm called `pdist2` that calculates the pairwise euclidean distance between two sets of observations;

```
D = pdist2(X,Y,'euclidean');
```

Where X us an x-by-n matrix and Y is an y-by-n matrix.

4.1.2 Gyroscope

For the measurements of the gyroscope another event listener is added:

```
if(window.DeviceOrientationEvent) {
  window.addEventListener('deviceorientation', function(event) {
    alpha = event.alpha;
```

```
    beta = event.beta;
    gamma = event.gamma;
  }, false);
}
```

The `DeviceOrientation` is using the same axes as the accelerometer but the gyroscope is measuring how much the device is rotating along the `alpha, beta` and `gamma` axes in degrees (Figure 4.1). The `alpha` is between 0 and 360 degrees, `beta` -180 to 180 degrees and `gamma` -90 to 90 degrees. Block and Popescu [2011]

4.2 Sound

For distinguish these error characteristics for fingerprinting Bojinov et al. [2014] used an application in the mobile device. The application played a sound from the speakers, recorded by the microphone that send its output back to the application. This were applied in a quiet environment due to minimizing signal noise.

4.3 Camera

e basic algorithm for linking a camera to an image is quite simple. First we calculate the camera reference patterns (essentially an approximation to f), then we look for a correlation between each of these patterns and the noise of an image. e easiest way to calculate an approximation to the camera reference pattern is to average multiple images. To speed up this process we can first remove the scene content using a denoising filter and then average the noise residuals instead. Based on experimentation, Lukáš et al. found a wavelet-based filter gave the best results as it removed the most traces of the scene. e technique also works better with uniformly lit images with no features so we only get noise from the sensor. e larger the number of images we average over, the more we suppress random noise and the impact of any scene data; a minimum of 50 images is recommended. Once we have established this reference pattern, we can see if there is a correlation with the noise of a particular image. To find the noise, we employ the same trick as before: Use the denoising filter to approximate the noise-free image and subtract this (on a pixel-wise basis) from the original, leaving only the noise residual. We then find the correlation between this noise n and a particular reference pattern r using the standard formula: By experimentally determining the distribution of this correlation for images taken with a camera and images not taken with that camera we can find a threshold for acceptance and estimate the false rejection rate, subject to an upper bound on the false acceptance rate. [Jenkins, 2009, p.2]

4.4 Gyroscope Accelerometer

TIPS TESTMETOD: In this section we describe a technique known as Allan Variance, which can be used to detect and determine the properties of such processes.

We then apply this technique to the accelerometer and gyroscope signals emitted from an Xsens Mtx device Woodman [2007]
ACC KANSKE SKA ANVÄNDA DENNA: Bojinov et al. [2014]

Testa först: Hämta data från acc o gyro när mobilen ligger stilla och data från vibration.

4.5 Radio signal

PARADIS ?

5

RESULT

TODO!

5.1 Result of the test for characteristics in mobile device

TODO!

5.1.1 Result of sensor tests

TOpresent!

5.1.2 Result of clock skew rate test

TOpresent!

5.1.3 Result of radio signal test

TOpresent!

5.1.4 Comparing of characteristics

TOcompare!

5.2 Implementation

toBeImplemented!

6

CONCLUSIONS

6.1 Conclusions

TODO!

6.2 Ethical aspects

TODO!

6.3 Further work

TODO!

Appendix

A

Trista saker

Långa beräkningar brukar bli rätt trista…

Detta är ett appendix-kapitel. Jämför med appendixet i chapter 5.

A.1 Bädda sängen

Den här beräkingen är så trista att vi kallar den *att bädda sängen*.

A.2 Diska

Den här beräkingen är så trista att vi kallar den *att diska*.

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Index