



UNIVERSITY OF THESSALY  
SCHOOL OF ENGINEERING  
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

## **Investigation of Machine Vibration Analysis System Design**

Diploma Thesis

**Vasileios Dimitriou**

**Supervisor:** Karakonstantis Georgios

Month 2022





UNIVERSITY OF THESSALY  
SCHOOL OF ENGINEERING  
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

## **Investigation of Machine Vibration Analysis System Design**

Diploma Thesis

**Vasileios Dimitriou**

**Supervisor:** Karakonstantis Georgios

Month 2022





ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

ΠΟΛΥΤΕΧΝΙΚΗ ΣΧΟΛΗ

ΤΜΗΜΑ ΗΛΕΚΤΡΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ ΚΑΙ ΜΗΧΑΝΙΚΩΝ ΥΠΟΛΟΓΙΣΤΩΝ

**Διερεύνηση Σχεδίασης Συστημάτων Ανάλυσης Δονήσεων  
Μηχανών**

**Διπλωματική Εργασία**

**Βασίλειος Δημητρίου**

**Επιβλέπων/πουνσα:** Καρακωνσταντής Γεώργιος

Μήνας 2022



Approved by the Examination Committee:

Supervisor **Karakonstantis Georgios**

Rank/position of Supervisor, Department of Electrical and Computer  
Engineering, University of Thessaly

Member **Name Surname of Member 1**

Rank/position of Member 1, Department/Institution of Member 1

Member **Name Surname of Member 2**

Rank/position of Member 2, Department/Institution of Member 2



## **DISCLAIMER ON ACADEMIC ETHICS AND INTELLECTUAL PROPERTY RIGHTS**

«Being fully aware of the implications of copyright laws, I expressly state that this diploma thesis, as well as the electronic files and source codes developed or modified in the course of this thesis, are solely the product of my personal work and do not infringe any rights of intellectual property, personality and personal data of third parties, do not contain work / contributions of third parties for which the permission of the authors / beneficiaries is required and are not a product of partial or complete plagiarism, while the sources used are limited to the bibliographic references only and meet the rules of scientific citing. The points where I have used ideas, text, files and / or sources of other authors are clearly mentioned in the text with the appropriate citation and the relevant complete reference is included in the bibliographic references section. I also declare that the results of the work have not been used to obtain another degree. I fully, individually and personally undertake all legal and administrative consequences that may arise in the event that it is proven, in the course of time, that this thesis or part of it does not belong to me because it is a product of plagiarism».

The declarant

Vasileios Dimitriou

# Diploma Thesis

## **Investigation of Machine Vibration Analysis System Design**

**Vasileios Dimitriou**

### **Abstract**

The abstract includes the scientific area and the purpose - subject of the thesis, the methodology, the main steps followed and the main results obtained. The total extent of the abstract will be up to one page. finding and conclusions to be highlighted.

A thesis written in english should include an english and a greek abstract.

### **Keywords:**

term, term, . . . , term

## Διπλωματική Εργασία

**Διερεύνηση Σχεδίασης Συστημάτων Ανάλυσης Δονήσεων Μηχανών**

**Βασίλειος Δημητρίου**

## Abstract

Η περίληψη περιλαμβάνει την επιστημονική περιοχή και το σκοπό - αντικείμενο της εργασίας, τη μεθοδολογία, τα κύρια βήματα που ακολουθήθηκαν και τέλος τα κύρια αποτελέσματα. Η συνολική έκταση της περίληψης θα είναι μέχρι μία σελίδα.

Διπλωματική εργασία γραμμένη στα ελληνικά, θα πρέπει να περιλαμβάνει ελληνική και αγγλική περίληψη.

### **Λέξεις-κλειδιά:**

όρος, όρος, . . . , όρος



# Contents

<b>Abstract</b>	<b>x</b>
<b>Abstract</b>	<b>xi</b>
<b>Contents</b>	<b>xiii</b>
<b>List of Figures</b>	<b>xv</b>
<b>Abbreviations</b>	<b>xvii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Object of the Diploma Thesis . . . . .	1
1.1.1 The Concept of Predictive Maintenance . . . . .	2
1.1.2 Contribution . . . . .	2
1.2 Structure of the Thesis . . . . .	3
<b>2 Theoretical Background</b>	<b>5</b>
2.1 Fundamentals of Bearing Fault Frequencies . . . . .	5
2.1.1 Overview . . . . .	5
2.1.2 Unfault and Fault Models . . . . .	5
2.2 Algorithms and Technologies . . . . .	8
2.2.1 Signal Processing . . . . .	8
2.2.2 Embedded Systems & IoT . . . . .	14
2.2.3 Backend & Database . . . . .	16
<b>3 System Engineering and Design</b>	<b>17</b>
3.1 System Requirements . . . . .	17

---

3.1.1	Functional Requirements . . . . .	17
3.1.2	Non-Functional Requirements . . . . .	18
3.2	Hardware Architecture . . . . .	18
3.2.1	Component Selection . . . . .	18
3.3	Software Architecture and Data Flow . . . . .	18
3.3.1	Signal Processing Pipeline . . . . .	18
3.3.2	Scalability Considerations . . . . .	19
3.3.3	Arduino sketch . . . . .	20
3.3.4	Raspberry Pi coding . . . . .	20
3.3.5	Vercel coding . . . . .	20
<b>4</b>	<b>Results</b>	<b>21</b>
4.1	Intro . . . . .	21
<b>5</b>	<b>Conclusions</b>	<b>23</b>
5.1	Σύνοψη και συμπεράσματα . . . . .	23
5.2	Μελλοντικές επεκτάσεις . . . . .	23
<b>APPENDICES</b>		<b>25</b>
<b>Appendix</b>		
<b>Τίτλος Παραρτήματος</b>		<b>27</b>
1	Δυνατότητες του L <sup>A</sup> T <sub>E</sub> X . . . . .	27
1.1	Πίνακες . . . . .	27
1.2	Διαγράμματα - Γραφικές παραστάσεις . . . . .	28
1.3	Σχήματα . . . . .	28
1.4	Αλγόριθμοι . . . . .	28
1.5	Μαθηματικές εκφράσεις . . . . .	29
1.6	Θεωρήματα, Πορίσματα, Ορισμοί, κλπ. . . . .	29
1.7	Απαριθμήσεις . . . . .	30
1.8	Είδη πηγών στις αναφορές . . . . .	30

# List of Figures

2.1	Fault and unfault spectrum graphs [?]. . . . .	6
2.2	Fault tree analysis diagram showing the relationship between machine conditions and specific fault frequencies. . . . .	8
2.3	Recursive decomposition using even-odd splitting. . . . .	13
2.4	The Internet of Things paradigm as a result of the convergence of different visions. Source: [?]. . . . .	15
2.5	Hierarchical IoT data flow from Sensor to Cloud Integration. . . . .	15
3.1	Hardware architecture with signal flow . . . . .	19
3.2	End-to-end data flow with protocols . . . . .	19
.1	Κλιμάκωση χρόνου εκτέλεσης για διάφορες υποδιαιρέσεις του καννάβου .	28
.2	Παράδειγμα σχήματος με εντολές του πακέτου TikZ . . . . .	29



# Abbreviations

$\beta\lambda\pi$	$\beta\lambda\acute{\epsilon}\pi\varepsilon$
$\kappa.\lambda\pi.$	και λοιπά
Κ.Ο.Κ	και ούτω καθεξής
TEI	Τεχνολογικό Εκπαιδευτικό Ίδρυμα
BPF	Band Pass Filter



# Chapter 1

## Introduction

Motivation and description. Points:

- Importance of maintenance
- Predictive maintenance
- Object of my thesis
- Contribution of my thesis

Εδώ αυτή κάνουμε μια γενική περιγραφή του χώρου εφαρμογής της διπλωματικής. Αναφέρουμε τα χαρακτηριστικά του χώρου και καταλήγουμε στα γενικότερα προβλήματα που αντιμετωπίζει ο χώρος. Η συζήτηση των προβλημάτων θα πρέπει να προϊδεάζει τον αναγνώστη για το τι θα προσπαθήσει να αντιμετωπίσει η διπλωματική, χωρίς ακόμα να αναφερόμαστε συγκεκριμένα στο αντικείμενο της διπλωματικής.

### 1.1 Object of the Diploma Thesis

Elaboration on a system that predicts the failure of mechanical components based on historical data. This thesis focuses on resolving the issue of unplanned shutdowns due to corrective maintenance of machines that have bearings. Εδώ αναφερόμαστε συγκεκριμένα στο τι θα κάνει η διπλωματική. Αναφέρουμε λεπτομερώς α) τα προβλήματα που θα λύσει (και που ήδη έχουν περιγραφεί γενικά στην προηγούμενη ενότητα), και β) πώς σκοπεύει να τα λύσει. Είναι σημαντικό κάποιος που θα διαβάσει την ενότητα αυτή να καταλάβει σε σημαντικό βαθμό τον σκοπό της διπλωματικής σας και τις τεχνικές δυσκολίες της, χωρίς

να είναι αναγκαίο να δει όλα τα άλλα κεφάλαια. Η ενότητα αυτή θέλει πολύ προσοχή και καλύτερα να τη γράψετε αφού έχετε γράψει όλα τα υπόλοιπα κεφάλαια.

### **1.1.1 The Concept of Predictive Maintenance**

Getting a good grasp on the upcoming required maintenance activities and being aware of what is of utmost importance is vital for the operation of a plant. A grasp on Periodical status checks of different machines is crucial for the maintenance engineers, since this could yield a clear understanding of what priority is at that instance of time. Therefore the prediction of an upcoming machine failure would constitute an invaluable tool.

- Good condition readings
- Periodical readings
- Readings analysis
- online board

### **1.1.2 Contribution**

Εδώ παραθέτουμε αριθμητικά συγκεκριμένες ενέργειες/λύσεις/μεθοδολογίες που παρουσιάζει η διπλωματική και λύνουν τα προβλήματα που υποσχεθήκαμε στην προηγούμενη ενότητα ότι θα λύσει η διπλωματική. Συνήθως η υποενότητα αυτή έχει την παρακάτω μορφή:

Η συνεισφορά της διπλωματικής συνοψίζεται ως εξής:

1. Μελετήθηκαν συστήματα κ.λ.π.
2. Υλοποιήθηκαν τρεις αλγόριθμοι υπολογισμού κ.λ.π.
3. Αξιολογήθηκε η επίδοση των αλγορίθμων και βρέθηκε ότι κ.λ.π.
4. Ενσωματώθηκαν οι αλγόριθμοι σε πρότυπο σύστημα κ.λ.π.
5. ...

## 1.2 Structure of the Thesis

Εδώ περιγράφουμε τα κεφάλαια της διπλωματικής: μία πρόταση για το τί θα έχει κάθε κεφάλαιο. Συνήθως η ενότητα αυτή έχει την παρακάτω μορφή (δεν θα σας πάρει πάνω από μία μεγάλη παράγραφο):

Εργασίες σχετικές με το αντικείμενο της διπλωματικής παρουσιάζονται στο Κεφάλαιο 2. Το Κεφάλαιο ... συζητά θέματα μοντελοποίησης. Στο Κεφάλαιο ... αναπτύσσουμε κ.λ.π.

Για την τελική οργάνωση του κειμένου σας, συμβουλευθείτε τον επιβλέποντα της εργασίας.



# Chapter 2

## Theoretical Background

### 2.1 Fundamentals of Bearing Fault Frequencies

#### 2.1.1 Overview

The most significant challenge that the authors had to deal with is that of the faulty cases detection. For this reason, fault and unfault models have been developed, and series of comparisons between the actual model generated by apparatus measurements and these two situational models are being executed. This development constitutes a real challenge since this is the main criterion that identifies the state of the motor.

#### 2.1.2 Unfault and Fault Models

As previously mentioned, the authors make use of a model-based approach, which entails that the main concept is comparison-oriented. Specifically, there is the unfault model, which contains a high-amplitude peak at the shaft rotating frequency  $F_\omega$ . In addition to that, it can be noticed in Figure 2.1 that some other patterns distinct themselves from the previously-mentioned unfault model. Regarding the unbalance model, it is obvious that the amplitude at the first tone is much greater. In the case of the misalignment model, it can be noticed that the tone at  $2F_\omega$  has a much greater amplitude while the amplitude at the tone of the shaft speed  $F_\omega$  remains at a high level. In the case of looseness, there are some more tones prevailing on the spectrum, among the tones related to the shaft speed. To top it all off, the most important vibration spectrum is that of the bearing failure (Refer to Figure 2.2). Every bearing is characterized by four critical frequencies, given by its manufacturer, and these

frequencies are associated with the four bearing components (inner and outer ring, balls, and cage):

- BPFO (Ball Pass Frequency Outer) - outer race failure
- BPFI (Ball Pass Frequency Inner) - inner race failure
- BSF (Ball Spin Frequency) - rolling element failure
- FTF (Fundamental Train Frequency) - cage failure

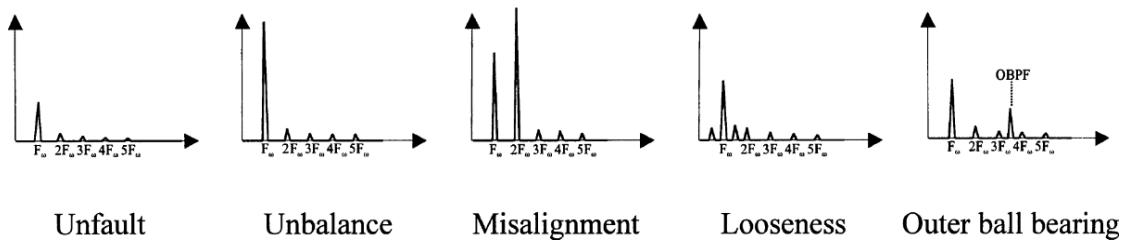


Figure 2.1: Fault and unfault spectrum graphs [?].

The procedure to calculate critical frequencies involves two steps: first computing the bearing frequency factors, then deriving the vibration frequencies. The following analysis covers the case where the inner race rotates while the outer race remains stationary.

$$F_{OR} = \frac{Z}{2} \left( 1 - \frac{d}{D} \cos \alpha \right) \quad (\text{Outer Race Fault}) \quad (2.1)$$

$$F_{IR} = \frac{Z}{2} \left( 1 + \frac{d}{D} \cos \alpha \right) \quad (\text{Inner Race Fault}) \quad (2.2)$$

$$F_{FTF} = \frac{1}{2} \left( 1 - \frac{d}{D} \cos \alpha \right) \quad (\text{Cage Frequency, Inner Race Rotating}) \quad (2.3)$$

$$F_{BS} = \frac{D}{d} \left[ 1 - \left( \frac{d}{D} \right)^2 \cos^2 \alpha \right] \quad (\text{Ball Spin Frequency}) \quad (2.4)$$

Then, the aforementioned factors when multiplied with shaft speed ( $f$ ) give specific critical bearing vibration frequencies:

$$\text{BPFO} = f \times F_{OR} \quad (2.5)$$

$$\text{BPFI} = f \times F_{IR} \quad (2.6)$$

$$\text{BSF} = f \times F_{BS} \quad (2.7)$$

$$\text{FTF} = f \times F_{FTF} \quad (2.8)$$

where:

$f$	: Shaft rotational speed (Hz)
BPFI	: Ball pass frequency, inner race
BPFO	: Ball pass frequency, outer race
FTF	: Fundamental train frequency
BSF	: Ball spin frequency
$Z$	: Number of rolling elements
$D$	: Pitch circle diameter of the bearing (mm)
$d$	: Rolling element (ball) diameter (mm)
$\alpha$	: Contact angle ( $^{\circ}$ )

It is also worth noting that the bearing frequency factors can be obtained through:

- Manufacturer-provided values
- Direct calculation using the above equations (2.1)–(2.4)
- Reverse calculation from measured vibration frequencies (2.5)–(2.8)

To summarize the preceding analysis, Figure 2.2 provides a clear visualization of the fault diagnosis procedure. When analysis reveals elevated frequency tones, a systematic approach must be followed to identify the source of these dominant frequencies. This process essentially involves mapping characteristic vibration patterns to specific machine faults on a frequency spectrum plot.

It must be that a fault-emulation method can be used in such cases to simulate the faulty models. This entails that additional tones can be stressed, and crucial spectra modifications may take place for research and comparison purposes.

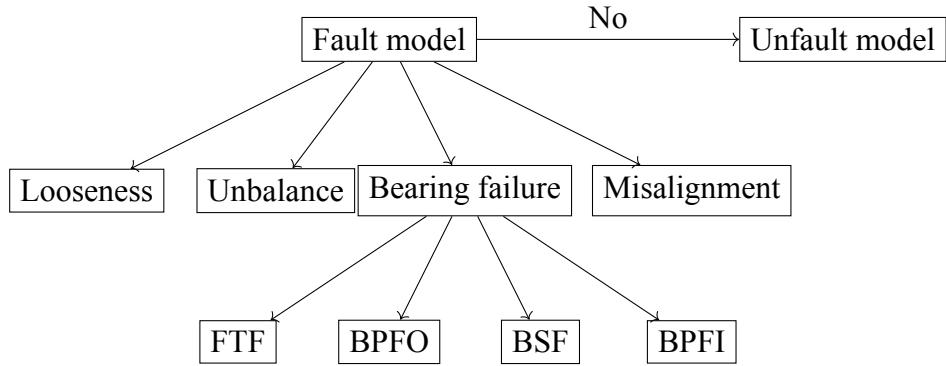


Figure 2.2: Fault tree analysis diagram showing the relationship between machine conditions and specific fault frequencies.

## 2.2 Algorithms and Technologies

### 2.2.1 Signal Processing

#### Fourier Analysis

In this section a deeper elaboration on Fourier Analysis and Transform is going to take place.

Serafeimidou explains in detail the theoretical background of the Fourier Analysis [?]. For an arbitrary finite range  $[-L, L]$  there is a family of functions, which meet the Dirichlet condition, and these functions can be expressed as a trigonometric sequence:

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos(n\pi\omega x) + b_n \sin(n\pi\omega x)), \quad (2.9)$$

where  $\omega = \frac{\pi}{L}$ .

In addition its constants can be expressed as follows:

$$a_n = \frac{1}{L} \int_{-L}^L f(u) \cos(n\omega u) du \quad (2.10)$$

$$b_n = \frac{1}{L} \int_{-L}^L f(u) \sin(n\omega u) du \quad (2.11)$$

The equation (2.9) needs to be expressed as a valid form within the whole  $x \in \mathbb{R}$ . For this reason the trigonometric integral (which is called Fourier integral) can be expressed as follows:

$$F(x) = \int_0^\infty [A(\omega) \cos(\omega x) + B(\omega) \sin(\omega x)] d\omega \quad (2.12)$$

where:

$$A(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} f(u) \cos(\omega u) du \quad (2.13)$$

$$B(\omega) = \frac{1}{\pi} \int_{-\infty}^{\infty} f(u) \sin(\omega u) du \quad (2.14)$$

Assuming that there exist real functions  $f(x)$  defined in  $\mathbb{R}$  meeting the following points:

- $f(x)$  and its derivative  $f'(x)$  are continuous in the range  $[-L, L] \subset \mathbb{R}$ .
- $f(x)$  is integrable in  $\mathbb{R}$ :

$$\int_{-\infty}^{\infty} |f(x)| dx < \infty.$$

Hence, given that the aforementioned conditions are met,  $A(\omega)$  (see Eq. (2.13)) and  $B(\omega)$  (see Eq. (2.14)) tend to attain a real value for  $\omega$ , which implies that  $A(\omega)$  and  $B(\omega)$  are defined for every  $\omega \in \mathbb{R}$ . In addition to this, the integral of the equation (2.12) tends to attain a real value for  $x$ , which ensues that  $F(x)$  is defined for every  $x \in \mathbb{R}$ .

$F(x)$  is identical to  $f(x)$  whenever  $f(x)$  is a continuous function. There are some special cases when  $f(x)$  is not a continuous function, and to deal with these cases, we define:

$$F(x) = \frac{1}{2} \left[ \lim_{x \rightarrow x^+} f(x) + \lim_{x \rightarrow x^-} f(x) \right] \quad (2.15)$$

This ensures that  $F(x)$  is properly handled even in cases of discontinuity.

All things considered the Fourier Transform  $F(\omega) = \mathcal{F}\{F(x)\}$  can be mathematically expressed as follows:

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \quad (2.16)$$

where the frequency can derive from the following form:  $\omega = \frac{2\pi j k}{N}$ .

In practice, the Discrete Fourier Transform (DFT) boasts an extremely wide variety of applications, facilitating the Fourier Transform when applied to sampled signals.

Hence, the mathematical formulation for determining the amplitude of each frequency, given a waveform  $x_0, x_1, \dots, x_{n-1}$  consisting of real values, is structured as follows:

$$X(j) = \sum_{k=0}^{n-1} x(k) e^{-\frac{i2\pi j k}{n}}, \quad \text{for } j = 0, 1, \dots, n-1. \quad (2.17)$$

## Fast Fourier Transform (FFT)

The Fast Fourier Transform (FFT) is an efficient algorithm for computing the Discrete Fourier Transform (DFT), expressed by the equation (2.17) and its inverse. One of the most prominent FFT algorithms, the Cooley-Tukey algorithm [?], employs a divide-and-conquer approach to reduce the computational complexity from  $\mathcal{O}(n^2)$  (for the naive DFT) to  $\mathcal{O}(2n \log n)$ , enabling significant speedups for large amount of data.

This reduces complexity from  $\mathcal{O}(n^2)$  (naive DFT entails direct implementation of the equation (2.17)) to less than  $\mathcal{O}(2n \log n)$  (a Fast Fourier Transform implementation), enabling major time savings for complex and large-scale transforms. It is also worth articulating that the complexity can be interpreted as the number of operations executed [?], [?].

Both algorithms are implemented in major numerical packages including MATLAB and NumPy's routines [?]. What is highlighted by Singeleton is that the Cooley-Tukey approach is considerably faster and decently performing especially when coupled with some additional practices so as to execute the Fast Fourier Transform [?].

The computation time according to the aforementioned article decreases drastically by making use of the Cooley-Tukey algorithm. In addition, this very algorithm performs and adapts better to different applications compared to Good's, Danielson's and Goertzel's approaches.

Cooley and Tukey proved that the sample length can be composite size where it is preferable to make use of sample points sized as power of 2, especially when it comes to personal computers with binary arithmetic system. In addition to this the authors have proven that the power of 3 is formally the most efficient approach, however in the context of the fast Fourier Analysis the so-called Radix-2 implementation is the prominent one [?].

$$N = 2^m \quad (2.18)$$

It is hereby worth it elaboration on the Fast Fourier Transform algorithm [?]. The indices of the equation (2.17) can be expressed as follows:

$$\begin{aligned} j &= j_{m-1} \cdot 2^{m-1} + j_{m-2} \cdot 2^{m-2} + \cdots + j_1 \cdot 2 + j_0, \\ k &= k_{m-1} \cdot 2^{m-1} + \cdots + k_1 \cdot 2 + k_0, \end{aligned} \quad (2.19)$$

where  $j_v$  and  $k_v$  are the contents of the respective bit positions within the binary representation, which ensues that they are equal to 0 or 1.

The aforementioned set-up (see eq. (2.17)) leads to the following equation (2.21), encompassing twiddle factors expressed as:

$$W = e^{-2\pi i/N} \quad (2.20)$$

And the Fast Fourier Transform:

$$X(j_{m-1}, \dots, j_0) = \sum_{k_0} \sum_{k_1} \dots \sum_{m-1} x(k_{m-1}, \dots, k_0) \cdot W^{j \cdot k_{m-1} \cdot 2^{m-1} + \dots + j \cdot k_0} \quad (2.21)$$

where as per the first step:

$$W^{j \cdot k_{m-1} \cdot 2^{m-1}} = W^{j_0 \cdot k_{m-1} \cdot 2^{m-1}} \quad (2.22)$$

Furthermore, in the context of the first calculation, the first array can be expressed as follows:

$$x_1(j_0, k_{m-2}, \dots, k_0) = \sum_{\mathbf{k}_{m-1}} x(\mathbf{k}_{m-1}, \dots, \mathbf{k}_0) \cdot W^{j_0 \cdot \mathbf{k}_{m-1} \cdot 2^{m-1}} \quad (2.23)$$

And hereunder can be contemplated that proceeding to the next innermost-successive sum:

$$W^{j \cdot k_{m-1} \cdot 2^{m-1}} = W^{(j_{l-1} \cdot 2^{l-1} + \dots + j_0) \cdot k_{m-l} \cdot 2^{m-l}} \quad (2.24)$$

followed by the calculation of the arrays:

$$x_l(j_0, \dots, j_{l-1}, k_{m-l-1}, \dots, k_0) = \sum_{\mathbf{k}_{m-l}} x_{l-1}(j_0, \dots, j_{l-2}, \dots, k_{m-l}, \dots, k_0) \cdot W^{(j_{l-1} \cdot 2^{l-1} + \dots + j_0) \cdot k_{m-l} \cdot 2^{m-l}} \quad (2.25)$$

for  $l = 1, 2, \dots, m$

And this could constitute a recursive procedure obtaining the successive arrays. And last but not least, this finally could lead to the calculation of X spectrum. It can be contemplated that from the Equation (2.25), there is at all times two consecutive values, the even and the odd value that can be stored at a specific location corresponding to an index of:

$$(j_0 2^{m-1} + \dots + j_{l-1} 2^{m-l} + k_{m-l-1} 2^{m-l-1} + \dots + k_0) \quad (2.26)$$

It is also worth it recalling that  $m$  is defined by  $N = 2^m$ . Since bit positions  $2^{(m-l)}$ , meaning the  $j$  and  $k$  coefficients, can only get the values 0 and 1, which ensues that there is multiple-storage locations that can be calculated simultaneously.

The array calculated gives the desired Fourier sums:

$$X(j_{m-1}, \dots, j_0) = A_m((j_0, \dots, j_{m-1})) \quad (2.27)$$

At this point there is a need to simplify the Fast Fourier Transform algorithm. It is mandatory to recall the (2.21) so as to depict the algorithm.

The calculations workload can be reduced, by decomposing the original input sequence  $X[k]$ , of length  $N$ , into two subsequences:

- A sequence consisting of elements at even-numbered indices:  $X_{\text{even}}[k]$
- A sequence consisting of elements at odd-numbered indices:  $X_{\text{odd}}[k]$

By processing these smaller sequences independently, the algorithm substantially reduces the computational workload. The FFT is applied recursively to each half, and this decomposition continues until each subproblem has length 1, at which point the computation becomes trivial (the amplitude value corresponding to a specific frequency). Furthermore, the results from the smaller FFTs are recombined using twiddle factors (see Equation (2.20)).

An significant property of this algorithm is that that, in the case of  $j > \frac{n}{2}$ , the values are repeated due to the sinusoidal property of  $\exp$ , which is known as the symmetry identity. This entails that for the values  $j = 0, 1, \dots, n/2 - 1$ :

$$X_{\text{even}}(j + n/2) = X_{\text{even}}(j) \quad \text{and} \quad X_{\text{odd}}(j + n/2) = X_{\text{odd}}(j) \quad (2.28)$$

The evens and odds decomposition:

$$X_{\text{even}}(j) = \sum_{k=0}^{n/2-1} x(2k)e^{-\frac{i2\pi j k}{n/2}}, \quad \text{for } j = 0, 1, \dots, n/2 - 1. \quad (2.29)$$

$$X_{\text{odd}}(j) = \sum_{k=0}^{n/2-1} x(2k+1)e^{-\frac{i2\pi j k}{n/2}}, \quad \text{for } j = 0, 1, \dots, n/2 - 1. \quad (2.30)$$

So from the Equation (2.21):

$$X(j) = X_{\text{even}}(j) + e^{-\frac{i2\pi j}{n}} X_{\text{odd}}(j) \quad (2.31)$$

And this procedure is scalable since each and every  $X_{even}$  and  $X_{odd}$  can be depleted into a subsequent set of  $X_{eve}$  and  $X_{odd}$  to the point that the length 1 is reached.

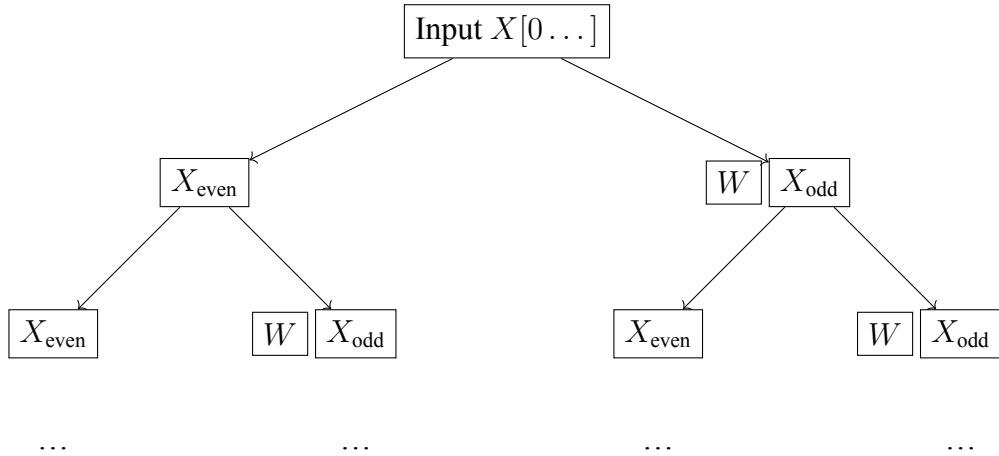
Last but not least, the symmetry identity as described by the Equation (2.28), leads to the following set of equations (see also (2.31)):

$$X(j + n/2) = X_{even}(j) + e^{-\frac{i2\pi(j+n/2)}{n}} X_{odd}(j) \quad (2.32)$$

For the values  $j = 0, 1, \dots, n/2 - 1$ .

The objective of this algorithm is to get to the point that the length is of the sums is 1, meaning that the sums of the Equations (2.29) and (2.30) are applicable for  $k=0$ . The only remaining exponential terms  $e^{-\frac{i2\pi j}{n}}$  in the Equation (2.31) - as previously described by Equation (2.25).

The aforementioned procedure can be further repeated, by breaking the branches problem into sub-branches. The radix-2 DIT algorithm to be formulated as follows on Figure 2.3, depicting the concept of narrowing down the problem.



## 2.2.2 Embedded Systems & IoT

The ultimate objective of this project is to create a set-up that is well-rounded and has a real-time monitoring and assessment competency. Two of the most prominent technologies that are being incorporated by Internet of Things (IoT) is the cloud computing and the wireless communication. It is also worth mentioning that, Internet of things encompasses interconnection of physical devices and applications making the most of sensors, networks and data analysis.

An extremely accurate definition of the *Internet of Things* is given by Gubbi et al [?], articulating that:

“Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. This is achieved by seamless ubiquitous sensing, data analytics and information representation with Cloud computing as the unifying framework.”

Hardware-sensor breakouts are critically important, as they serve as the primary means of data collection in IoT systems. Middleware and computing tools for data analytics are equally invaluable, as they enable the processing of raw sensor data into actionable insights. Finally, visualization tools and dashboards play a key role in user interaction with the IoT environment, while also providing stakeholders with an intuitive and accessible representation of the data [?].

As regards the approach of Atzori et al, there is given a different definition by considering two different approaches, the "Internet"-oriented approach and the "Things"-oriented approach [?]. The "Things"-oriented approach targets mainly at Big Data applications, since according to Atzori et al the time, the place and multiple recipients are the most important factors of this approach. In essence the "Things" that contribute to this perspective are the Radio-Frequency Identification (RFID), Near Field Communications (NFC) and Wireless Sensor and Actuator Networks (WSAN) among others.

As regards the "Internet"-oriented vision,

The whole concept of most of the projects requires a semantic approach so as to set some thresholds and yield some feedback or take some action over something. In addition to this the semantic vision according to Atzori et al expresses the need for a representation of the

collected data [?].

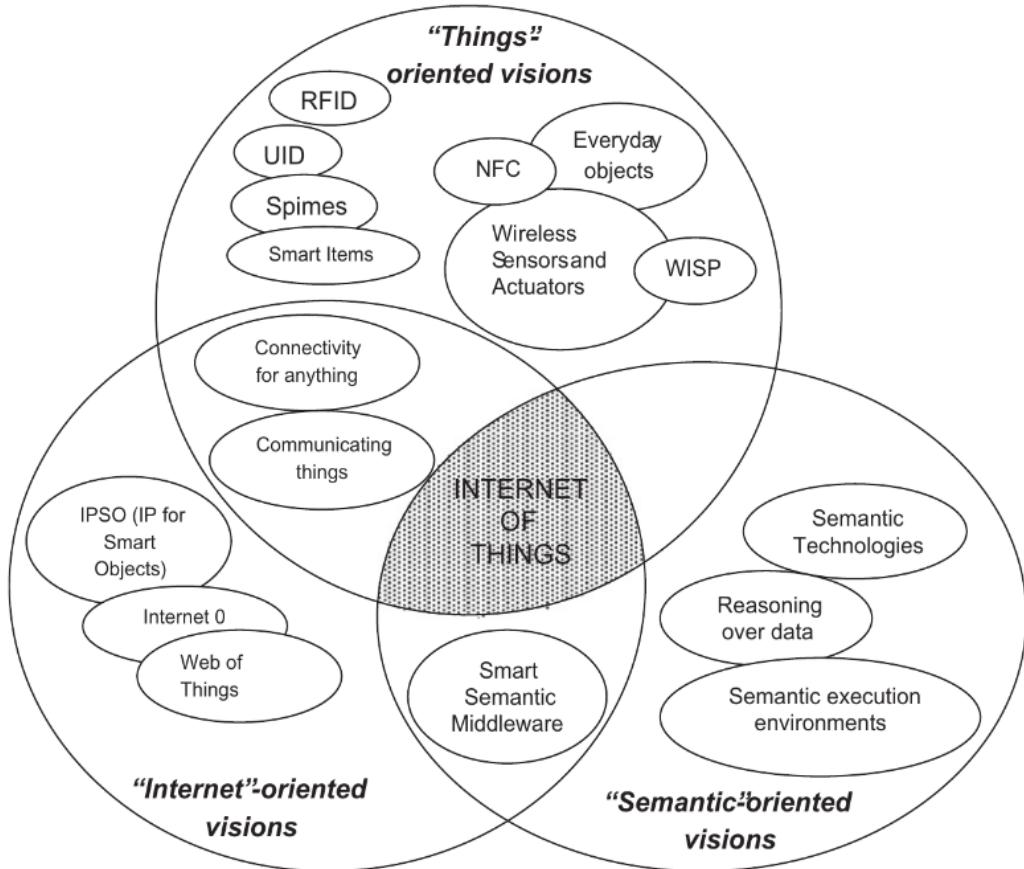


Figure 2.4: The Internet of Things paradigm as a result of the convergence of different visions.

Source: [?].

All in all Atzori defines Internet of Things (IoT) as follows:

a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols

The sensing unit of this project's application collects physical data and connects to the microcontroller through a specific interface like analog input. There are also other communication interface options such as digital input, **SPI** (Serial Peripheral Interface), **UART** (Universal Asynchronous Receiver-Transmitter), and **I<sup>2</sup>C** (Inter-Integrated Circuit) [?].



Figure 2.5: Hierarchical IoT data flow from Sensor to Cloud Integration.

## **ADXL335 Sensor**

The ADXL335 is a 3-axis accelerometer that measures acceleration using analog voltage outputs. This section discusses its interfacing with an Arduino and signal processing.

- **Sensor Breakout Board** A breakout board simplifies the connection of the ADXL335 by providing necessary components (e.g., voltage regulation, filtering capacitors) and standardized pin headers. This avoids the need for complex PCB design when prototyping.
- **Analog Signal Transmission** The ADXL335 outputs analog voltages proportional to acceleration. Unlike digital signals (discrete values), analog signals are continuous and susceptible to noise. The Arduino's ADC (Analog-to-Digital Converter) reads these voltages for processing.
- **Signal Conditioning & Processing** Since analog signals degrade over long wires, techniques like filtering (RC low-pass) and amplification may be needed. Calibration (mapping voltage to g-forces) is also essential for accurate readings.

## **Arduino Microcontroller**

UART serial communication sending data to RPi. To elaborate on this protocol

- what serial protocol is
- what Arduino is

## **Raspberry Pi 4**

RPi receiving data using a script and posing HTTP Post data to a supabase api. Elaborate on this

- how to collect data and analyse
- what Raspberry Pi 4 is

### 2.2.3 Backend & Database

#### Supabase

- PostgreSQL.
- APIs
- what http post is

#### Vercel and Next.js

- nextjs
- vercel



# Chapter 3

## System Engineering and Design

### 3.1 System Requirements

The system is designed for low-cost, real-time vibration monitoring of rotating machinery. This set-up encompasses components that are of major importance and its aim is to collect data within a specific - prerequired range, store data safely at a database and finally process data.

The following sections include more detailed overview of the system requirements. Hereunder, more details will be elaborated.

#### 3.1.1 Functional Requirements

The most commonly rotating speed of machinery goes up to 1500 [rpm] corresponds to 25 [Hz]. This relationship is defined by the following equation:

$$f [\text{Hz}] = \frac{r [\text{RPM}]}{60} \quad (3.1)$$

The aforementioned relationship entails that the rotational speed of a machine can be interpreted in frequency, which in turn is of great help when related to Fourier Transform applications.

All in all, the functional requirements are highlighted hereunder:

- **Frequency Range:** 0–300 Hz (covers common machine faults like imbalance, misalignment).
- **Real-Time Processing:** On-the-fly FFT computation for immediate fault detection.

- **Scalability:** Modular design for multi-sensor deployments.

### 3.1.2 Non-Functional Requirements

- **Cost:** Minimize BOM cost (justifies Arduino + RPi4 over industrial PLCs).
- **Power:** Optimize for continuous operation (e.g., no active cooling).
- **Accuracy:** ADXL335's  $\pm 3g$  range suffices for industrial vibrations (cite datasheet).

## 3.2 Hardware Architecture

### 3.2.1 Component Selection

- **ADXL335 Accelerometer:**
  - Analog output simplifies Arduino ADC interfacing.
  - 300Hz bandwidth meets requirements (vs. digital sensors like MPU6050 needing I2C).
- **Arduino Uno:**
  - Handles analog sampling at 600Hz (Nyquist-compliant for 300Hz signals).
  - Low-latency preprocessing (e.g., DC removal, windowing).
- **Raspberry Pi 4:**
  - Runs Python-based FFT (e.g., NumPy) and SQLite for local storage.
  - WiFi/Bluetooth enables cloud integration (e.g., AWS IoT, InfluxDB).

## 3.3 Software Architecture and Data Flow

### 3.3.1 Signal Processing Pipeline

The Arduino samples data at 600Hz, which is extremely high and constitutes a sufficient sample rate for this project. Additionally, another consideration is receiving data from the

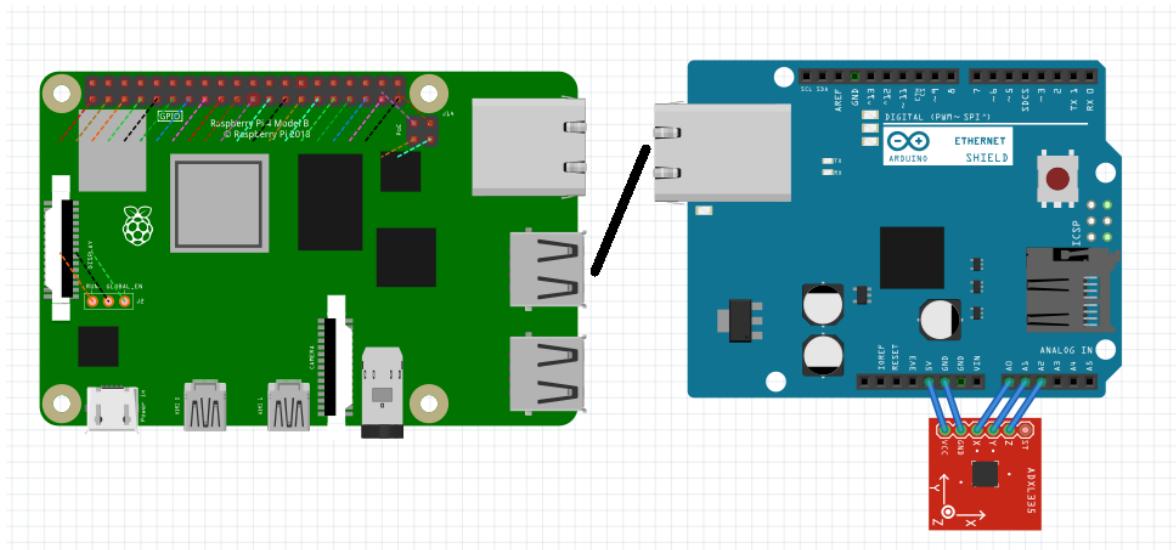


Figure 3.1: Hardware architecture with signal flow

ADXL335 sensor breakout, which could potentially make this procedure slower. The highest data volume over a predefined time span achieved for this project is 300Hz.

In essence, a batch of data is received through this procedure by a Raspberry Pi 4, which in turn processes and analyzes these samples.

### 3.3.2 Scalability Considerations

- **Multi-Threading:** RPi4 handles concurrent sensor inputs (e.g., 4x Arduino nodes).
- **Data Compression:** FFT bin reduction (0–300Hz only) minimizes cloud costs.

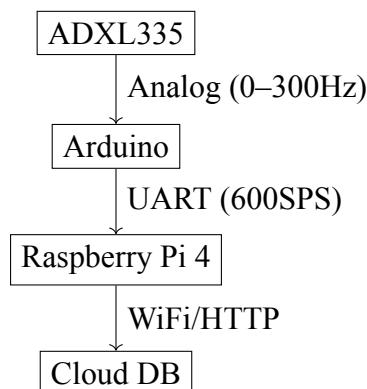


Figure 3.2: End-to-end data flow with protocols

### **3.3.3 Arduino sketch**

Elaboration on (including the whole code):

- Description of sketch and cpp files
- elaborate on how it shares data via UART
- Analyse the possibility of translating Voltage into g or m/s<sup>2</sup>

### **3.3.4 Raspberry Pi coding**

Elaboration on (including some parts of the code):

- Description of the whole program
- how it posts data via HTTP
- Data stored on database , and database setup

### **3.3.5 Vercel coding**

Elaboration on (including some parts of the code):

- page file that prints data
- how it is coupled with supabase

# **Chapter 4**

## **Results**

### **4.1 Intro**

- depict data dashboard
- analyse alarm cases
- database - stored data



# **Chapter 5**

## **Conclusions**

Εδώ εξηγούμε ότι θα συνοψίσουμε την μελέτη που εκπονήθηκε στα πλαίσια της διπλωματικής.

- summarize how it decides if a bearing is defective
- how it collects data
- how data is analysed and at what stages it is analysed

### **5.1 Σύνοψη και συμπεράσματα**

Εδώ συνοψίζουμε τα αποτελέσματα της διπλωματικής και περιγράφουμε τα συμπεράσματα που προέκυψαν, αρνητικά και θετικά. Επιβεβαιώνουμε την συνεισφορά της διπλωματικής στα προβλήματα που αναφέραμε στην εισαγωγή.

### **5.2 Μελλοντικές επεκτάσεις**

Εδώ δίνουμε ιδέες για επέκταση της διπλωματικής.



## **APPENDICES**



# Appendix

## Τίτλος Παραρτήματος

Τα παραρτήματα περιλαμβάνουν συνοδευτικό, υποστηρικτικό υλικό (πίνακες, φωτογραφίες, ερωτηματολόγια, στατιστικά στοιχεία, αποδείξεις, περιγραφές λογισμικών προγραμμάτων, παραδείγματα, περιγραφές πολύπλοκων διαδικασιών, λίστα με πρωτογενή στοιχεία, λεπτομερής περιγραφή και προδιαγραφές εξοπλισμού, οδηγίες εγκατάστασης λογισμικού, κ.λπ.), ή αλλιώς ό,τι θεωρείται χρήσιμο να περιγραφεί, αλλά δεν συνηθίζεται να εντάσσεται μέσα στο κυρίως κείμενο της Εργασίας. Στο κυρίως κείμενο της Εργασίας πρέπει να γίνονται οι κατάλληλες παραπομπές προς τα παραρτήματα, όπου το κείμενο σχετίζεται με υλικό που περιλαμβάνεται σε αυτά. Ένα παράρτημα, αναλόγως με το περιεχόμενό του, μπορεί να είναι ενιαίο, ή να χωρίζεται σε ενότητες.

## 1 Δυνατότητες του L<sup>A</sup>T<sub>E</sub>X

Καθώς το παρόν αποτελεί ένα πρότυπο συγγραφής διπλωματικών εργασιών, στην ενότητα αυτή επιδεικνύονται ορισμένες από τις δυνατότητες το L<sup>A</sup>T<sub>E</sub>Xοι οποίες μπορούν να αξιοποιηθούν στο κείμενο μιας διπλωματικής εργασίας (μια καλή πηγή για τη διερεύνηση των δυνατοτήτων του L<sup>A</sup>T<sub>E</sub>Xείναι η ιστοσελίδα [https://www.overleaf.com/learn/latex/Main\\_Page](https://www.overleaf.com/learn/latex/Main_Page)).

### 1.1 Πίνακες

Ο Πίνακας .1 είναι ένα παράδειγμα πίνακα σχεδιασμένου με εντολές του περιβάλλοντος `tabular`.

Table .1: Παράμετροι πειραμάτων

Πλήθος κελιών καννάβου $c \times c$	$50 \times 50, 100 \times 100, 200 \times 200, \mathbf{250 \times 250},$ $500 \times 500, 1000 \times 1000$
Τυπική απόκλιση $\sigma$	25m, 50m, 75m, <b>100m</b> , 150m, 200m
Αριθμός εγγύτερων γειτόνων $k$	1, 2, <b>3</b> , 4, 5, 10, 20
Πιθανοτικό κατώφλι $\theta$	50%, 60%, 70%, <b>75%</b> , 80%, 90%, 99%

## 1.2 Διαγράμματα - Γραφικές παραστάσεις

Στο Σχήμα .1, παρουσιάζεται ένα παράδειγμα γραφικής παράστασης σχεδιασμένης με το Gnuplot.

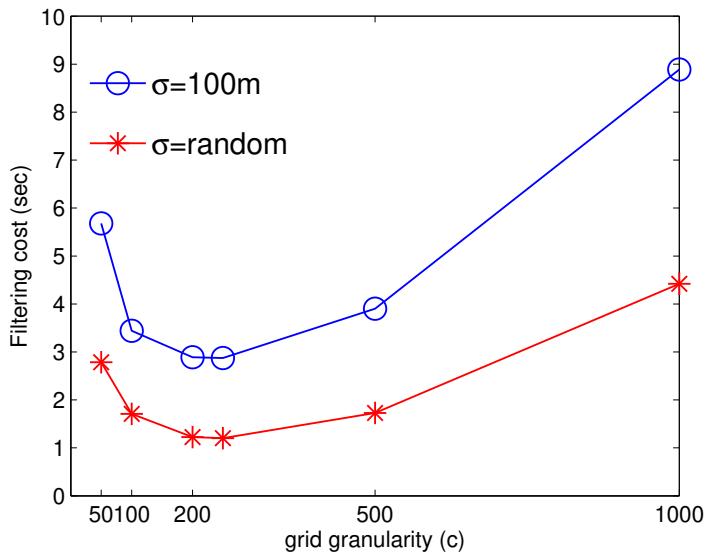


Figure .1: Κλιμάκωση χρόνου εκτέλεσης για διάφορες υποδιαιρέσεις του καννάβου

## 1.3 Σχήματα

Ακολουθεί στο Σχήμα .2 ένα παράδειγμα σχήματος φτιαγμένου με εντολές του πακέτου TikZ.

## 1.4 Αλγόριθμοι

Ακολουθεί ο Αλγόριθμος 1, ο οποίος είναι μορφοποιημένος με τα πακέτα algorithm και algorithmic.

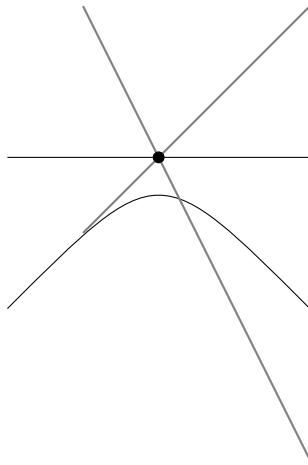


Figure .2: Παράδειγμα σχήματος με εντολές του πακέτου TikZ

---

#### Algorithm 1 Probabilistic $k\theta NN$ Monitoring

---

```

1: Procedure VerifyCandidate (focal query point  $q$ , threshold  $\theta$ , object  $o$ , list of auxiliary objects  $P$ ,  
distance  $kMAXDIST$ )
2: if  $\Phi(o, kMAXDIST) \geq \theta$  and  $L_2(q, o) \leq L_2(q, P.\text{top}())$  then
3:    $P.\text{pop}();$       //Replace the most extreme element in  $P$ , since candidate  $o$  ...
4:    $P.\text{push}(o);$     //... has enough probability and has its mean closer to focal  $q$ 
5: end if
6: End Procedure

```

---

## 1.5 Μαθηματικές εκφράσεις

Ακολουθούν παραδείγματα μαθηματικών εκφράσεων.

$$\hat{I}(x, u, t) = dist(y(t_f), \Gamma) + \int_t^{t_f} \mathcal{L}(y(s), u(s), s) ds \quad (1)$$

$$\frac{d}{dx} \left( \int_0^z f(u) du \right) = f(x).$$

## 1.6 Θεωρήματα, Πορίσματα, Ορισμοί, κλπ.

Ακολουθεί παράδειγμα θεωρήματος από την ιστοσελίδα [https://www.overleaf.com/learn/latex/Theorems\\_and\\_proofs](https://www.overleaf.com/learn/latex/Theorems_and_proofs)

**Theorem 5.1.** *Let  $f$  be a function whose derivative exists in every point, then  $f$  is a continuous function.*

## 1.7 Απαριθμήσεις

Μια απαρίθμηση (itemized list) βοηθά στην παρουσίαση μιας σειράς περιπτώσεων με σαφήνεια. Ακολουθεί παράδειγμα.

Η εκπαίδευση στην Ελλάδα διακρίνεται σε:

- Πρωτοβάθμια
- Δευτεροβάθμια
- Τριτοβάθμια

## 1.8 Είδη πηγών στις αναφορές

Στο references.bib μπορεί να δει κανείς πώς γράφονται διάφορα είδη πηγών (Βιβλία Ξενόγλωσσα [?], Βιβλία Ελληνικά [?], Άρθρα σε επιστημονικά περιοδικά [?], Άρθρα σε επιστημονικά συνέδρια [?], Ιστοσελίδες [?], Πτυχιακές Εργασίες [?], Διπλωματικές Εργασίες [?], Μεταπτυχιακές Διπλωματικές Εργασίες [?], Διδακτορικές Διατριβές [?], Τεχνικές Αναφορές [?], Διπλώματα Ευρεσιτεχνίας [?]), Κεφάλαια σε συλλογικούς τόμους [?].