

# **Towards the Analysis of Movement Variability in the context of Human-Humanoid Imitation**



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This dissertation is submitted for the degree of  
*Doctor of Philosophy*

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I would like to dedicate this thesis to my loving parents ...



## **Declaration**

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Miguel P. Xochicale  
December 2017



## **Acknowledgements**

And I would like to acknowledge ...





## **Abstract**

This is where you write your abstract ...



# Table of contents

<b>List of figures</b>	<b>xiii</b>
<b>List of tables</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Opening hook . . . . .	1
1.2 Context . . . . .	1
1.3 Gap in the literature . . . . .	1
1.4 Research Questions . . . . .	1
1.5 Argument . . . . .	1
1.6 Outline of logic . . . . .	1
<b>2 Movement Variability</b>	<b>3</b>
2.1 Source of Variability in Human Movement . . . . .	3
2.2 Sensors . . . . .	3
2.3 Variability within and between persons . . . . .	3
2.4 Variability for simple and complex activities . . . . .	3
<b>3 Techniques to measure human movement variability</b>	<b>5</b>
3.1 Time-domain . . . . .	5
3.2 Frequency-domain . . . . .	5
3.3 Nonlinear dynamics domain . . . . .	5
<b>4 Experiments</b>	<b>7</b>
4.1 Dancing Salsa . . . . .	7
4.2 Simple movements . . . . .	7
4.3 Human-Humanoid Imitation . . . . .	7
4.4 Group Activity in Human-Humanoid Imitation . . . . .	7

<b>5</b>	<b>Automatic Classification</b>	<b>9</b>
5.1	Convolutional Neural Networks . . . . .	9
5.2	Convolutional Neural Networks Using time-series . . . . .	9
<b>6</b>	<b>Conclusion</b>	<b>11</b>
6.1	Short title . . . . .	11
	<b>References</b>	<b>13</b>
	<b>Appendix A Inertial Measurement Units</b>	<b>15</b>
A.1	benchmark . . . . .	20
	<b>Appendix B How to install L<sup>A</sup>T<sub>E</sub>X</b>	<b>23</b>
	<b>Appendix C Installing the CUED class file</b>	<b>25</b>

## **List of figures**



## **List of tables**





# Chapter 1

1

## Introduction

2

### 1.1 Opening hook

3

### 1.2 Context

4

### 1.3 Gap in the literature

5

### 1.4 Research Questions

6

### 1.5 Argument

7

### 1.6 Outline of logic

8

Lorem Ipsum is simply dummy text of the printing and typesetting industry (see Section [1.2](#)).

9

Lorem Ipsum [\[3\]](#) has been the industry's Ipsum [\[1, 4, 5\]](#).

10



## **Chapter 2**

1

## **Movement Variability**

2

### **2.1 Source of Variability in Human Movement**

3

### **2.2 Sensors**

4

### **2.3 Variability within and between persons**

5

### **2.4 Variability for simple and complex activities**

6



## **Chapter 3**

1

# **Techniques to measure human movement variability**

2

3

### **3.1 Time-domain**

4

### **3.2 Frequency-domain**

5

### **3.3 Nonlinear dynamics domain**

6

And now to cite some more people Read [\[6\]](#), Ancey et al. [\[2\]](#)

7



## **Chapter 4**

1

## **Experiments**

2

### **4.1 Dancing Salsa**

3

### **4.2 Simple movements**

4

### **4.3 Human-Humanoid Imitation**

5

### **4.4 Group Activity in Human-Humanoid Imitation**

6





## **Chapter 5**

1

## **Automatic Classification**

2

### **5.1 Convolutional Neural Networks**

3

### **5.2 Convolutional Neural Networks Using time-series**

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# Chapter 6

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## Conclusion

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### 6.1 Reasonably long section title

3

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed vitae laoreet lectus. Donec lacus quam, malesuada ut erat vel, consectetur eleifend tellus.

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# References

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# Appendix A

1

## Inertial Measurement Units

2

### Inertial Measurement Units

3

#### Accelerometer

4

#### Angular rate gyroscope

5

#### Magnetometer

6

### Inertial Sensor Signal

7

#### The IMU signal

8

#### Kinematic Parameters

9

#### Coordinate Systems

10

### Benchmark

11

#### Shimmer3 (Dublin, Ireland)

12

BtStream firmware program is used for shimmer configuration and data capture over Bluetooth.

13

The Shimmer unit is within Bluetooth range of the PC (<12m approximately).

14

rechargeable Lithium Polymer battery 3.7V 450mAh

15

#### Capabilities

16

According to the User Guide, the output data of the sensors are approximate values

17

1 Low Noise Accelerometer A KXRB5-2042 device from Kionix is used

- 2 • Zero-output: 1.5 V.
- 3 • Full scale range:  $\pm 2.0$  g.
- 4 • Sensitivity: 600 mV/g.

5 Wide Range Accelerometer SM303DLHC device from STMicro

- 6 • Full scale range:  $\pm 2.0$  g;  $\pm 4.0$  g;  $\pm 8.0$  g;  $\pm 16.0$  g.
- 7 • Sensitivity (LSB/g): 1000 ( $\pm 2.0$  g); 500 ( $\pm 4.0$  g); 250 ( $\pm 8.0$  g); 83.3 ( $\pm 16.0$  g).
- 8 • Output: 16 bits

9 The gyroscope on the MPU-9150 chip from Invensense

- 10 • Full scale range (deg/sec):  $\pm 250$ ;  $\pm 500$ ;  $\pm 1000$ ;  $\pm 2000$ .
- 11 • Sensitivity (LSB/(deg/sec)): 131 ( $\pm 250$ ); 65.5 ( $\pm 500$ ); 32.8 ( $\pm 1000$ ); 16.4 ( $\pm 2000$ ).
- 12 • Output: 16 bits.

13 magnetometer LSM303DLHC device from STMicroelectronics

- 14 • Full scale range (Ga):  $\pm 1.3$ ;  $\pm 1.9$ ;  $\pm 2.5$ ;  $\pm 4.0$ ;  $\pm 4.7$ ;  $\pm 5.6$ ;  $\pm 8.1$ .
- 15 • Sensitivity (X,Y/Z) (LSB/Ga): 1100/980 ( $\pm 1.3$ ); 855/760 ( $\pm 1.9$ ); 670/600( $\pm 2.5$ );  
16 450/400 ( $\pm 4.0$ ); 400/355( $\pm 4.7$ ); 330/295 ( $\pm 5.6$ ); 230/205 ( $\pm 8.1$ ).
- 17 • Output: 16 bits

18 Noise performance when varying signal bandwidths . the sampling rate for each case was  
19 500 Hz with a low-pass filter for the variation of the bandwidth.



Bandwidth (Hz)	50	100	250
Low Noise Accelerometer			
RMS noise ( $m/s^2$ )	$3.51 \times 10^{-3}$	$5.09 \times 10^{-3}$	$8.12 \times 10^{-3}$
Wide Range Accelerometer			
RMS noise ( $m/s^2$ )	$18.6 \times 10^{-3}$	$27.5 \times 10^{-3}$	$37.2 \times 10^{-3}$
Gyroscope			
RMS noise (deg/s)	0.0322	0.0481	0.0785
Magnetometer			
RMS noise (normalised local flux)	0.005	0.0081	0.0129

For further information, please refer to the manufacturer's datasheets.

## 9 Degrees of Freedom - Razor IMU

### Capabilities

triple-axis Digital accelerometer ADXL345 device from Analog Devices.

- Full scale range:  $\pm 2.0$  g;  $\pm 4.0$  g;  $\pm 8.0$  g;  $\pm 16.0$  g.
- Sensitivity (LSB/g): Min232, Typ256, Max286 ( $\pm 2.0$  g); Min116, Typ128, Max143 ( $\pm 4.0$  g); Min58, Typ64, Max71 ( $\pm 8.0$  g); Min29, Typ32, Max36 ( $\pm 16.0$  g).
- Output: User-selectable resolution: 10-bit or 13-bit

Noise Performance x,y-Axes. Data rate = 100 Hz for  $\pm 2$  g, 10-bit. <1.0 LBS rms z-Axes.

Data rate = 100 Hz for  $\pm 2$  g, 10-bit. <1.5 LBS rms

The gyroscope on the ITG-3200 chip from Invensense

- Full scale range (deg/sec):  $\pm 2000$ .
- Sensitivity (LSB/(deg/sec)): 14.375 ( $\pm 2000$ ).
- Output: 16-bit

Gyro Noise performance

Total RMS noise. 100Hz LPD (DLPFCFG=2). 0.38 deg/sec-rms

Rate Noise Spectral Density. At 10Hz. 0.03 deg/sec  $\sqrt{Hz}$

magnetometer. HMC5883L device from Honeywell

• Full scale range (Gauss):  $\pm 8$ .

• Sensitivity (LSB/Gauss): Min230,Max1370 ( $\pm 8$ )

• Output: 12-bit ADC

Noise Floor (Field resolution) VDD=3.0V, GN=0, No measurement average, Standard Deviation 100 samples. Typ: 2 milli-gauss. <https://www.sparkfun.com/products/10736>

## IMU WAX9 sensor from axivity (Newcastle, UK)

The devices are £149.00 each (excluding VAT). plus delivery charge of £9.99

Physical Parameter: Dimensions 23x32.5x7.6 (mm) Weight 7g

### Typical Capabilities

Accelerometer:  $\pm 2 / 4 / 8$  g (14 bit resolution). Range setting Convert to g Dynamic range 2 divide by 16384  $\pm 2$ g 4 divide by 8192  $\pm 4$ g 8 divide by 4096  $\pm 8$ g

Gyro:  $\pm 250 / 500 / 2000$  dps (16 bit resolution) Range setting Convert to deg/sec Dynamic range 250 multiply by 0.00875  $\pm 250$  dec/sec 500 multiply by 0.01750  $\pm 500$  dec/sec 2000 multiply by 0.07000  $\pm 2000$  dec/sec

Magnetometer:  $\pm 1$ uT steps (1 mGs, milli-gauss). (16 bit resolution) The range of the sensor is  $\pm 20,000$  (2 mT or 0.2 Gs).

Temperature Range: 0 - 65 °C (0.1°C resolution) Pressure: 30-110 kPa (1Pa resolution)

Battery Life: Hibernate 56 days LE Connected (50Hz stream) 6 Hours

Sample rate: The data rate is set by the RATEX variable in samples per second (default 50 Hz).

The sensors on the WAX9 are all digital sensors with their own independent sample clocks.

The sensors each have their own independent internal sample rates because of the sampling scheme described above. Variable Values Effect Accelerometer rate 12 50 100 200 400 800 Internal rate Hz Accelerometer range 2 4 8 Range in +/-g Gyroscope rate 100 200 400 800 Internal rate Hz Gyroscope range 250 500 2000 Range in dps Magnetometer rate 5 10 20 40 80 Internal rate Hz

<http://axivity.com/userguides/wax9/technical/>

WAX9 has different operating sample frequencies which is considered to be both as a disadvantage and advantage.

**IMU EXL-S3 sensor from exel (Bologna, Italy)**

EXLs3 1 to 9 pieces for Euros 230 each. EXLs3KIT1 1 to 9 pieces for 384

**\*Features**

Module size 54 mm x 33 mm x 14 mm Module weight 22 g 32-bit MCU, Cortex-M3 @72 MHz 3-axis accelerometer with selectable full-scale range ( $\pm 2$  /  $\pm 4$  /  $\pm 8$  /  $\pm 16$  g). 3-axis gyroscope with selectable full-scale range ( $\pm 250$  /  $\pm 500$  /  $\pm 1000$  /  $\pm 2000$  dps) 3-axis magnetometer  $\pm 1200$  dps Orientation estimation with Kalman filtering and quaternion output. Sampling rate up to 200 Hz for raw data and 100 Hz for orientation data. Various data packet format available Bluetooth<sup>TM</sup> 2.1 class 1. Up to 7 nodes at the same time can stream data to the same host. 1GB Flash Memory (USB Mass Storage) for data storage Docking station with micro-USB connector for battery recharging and log-file downloading. Battery operating time 3h

**SAMPLE RATE**

200 Hz (100 Hz if a packet with orientation is chosen) 100 Hz 50 Hz 33.33 Hz 25Hz 20Hz 16.67 Hz 12.5 Hz 10 Hz 5 Hz 300 Hz (No magnetometer data, 100 Hz if a packet with orientation is chosen)

**Odroid myAHRS+**

£69.52 Ex Tax: £57.93 We offer free shipping (delivery up to 5 working days) to all UK destinations.

myAHRS+ is a high performance AHRS(Attitude Heading Reference System).

the following connectivity options are available: - USB : Virtual COM PORT - UART : Standard baud rates up to 460800 bps - I2C : up to 1kHz

Unfortunately we are unable to offer technical support on the ODROID range of products. Clive - Lilliput UK

\* Sensors - Triple axis 16-bit gyroscope :  $\pm 2000$  dps - Triple axis 16-bit accelerometer :  $\pm 16$  g - Triple axis 13-bit magnetometer :  $\pm 1200$  uT

\* On board software - Extended Kalman filter - max 100 Hz output rate Attitude : Euler angle, Quaternion Sensor : acceleration, rotation rate, magnetic field

user-programmable gyro full-scale range of  $\pm 250$ ,  $\pm 500$ ,  $\pm 1000$ , and  $\pm 2000^\circ/\text{sec}$  (dps) Gyro sensitivity (LSB/ $^\circ/\text{sec}$ ) N/A Gyro Rate Noise (dps/ Hz) 0.005

a user-programmable accelerometer full-scale range of  $\pm 2$  g,  $\pm 4$  g,  $\pm 8$  g, and  $\pm 16$  g, Accel Sensitivity (LSB/g) N/A and compass with a full scale range of  $\pm 1200$  uT.

## **<sub>1</sub> A.1 benchmark**

## A.1 benchmark

21

Sensor	Price*	Connectivity	ACC	GYR	MAG	Sample rate Hz	Temp.	battery time	API
9 DOF Razor	£59.99	USB,Bluetooth 2.1, LE	Full-scale range: $\pm 2$ g Sensitivity: 256 LSB/g ADCs: 10-bit	Full-scale region: $\pm 2000$ dps Sensitivity: 14.375 LSB/dps ADCs: 16-bit	Full-scale region: $\pm 8$ Gauss Sensitivity: 230 to 1370 LSB/gauss ADCs: 12-bit	50	-	-	C++ Android ROS
myAHRS+	£69.52	USB,UART,I2C	Full-scale Range: $\pm 16$ g Sensitivity: (2048 LSB/g) ADCs: 16-bit	Full-scale region: $\pm 2000$ dps Sensitivity: 16.4 LSB/dps ADCs: 16-bit	Full-scale Range: $\pm 1200$ T Sensitivity: 0.3 T/LSB ADCs: 13-bit	max 100	-40 to +85°C Res: 340 LSB/°C	-	C++ Python ROS
EXLs3	384 euro $\approx$ £291	Bluetooth 2.1	Full-scale range: $\pm 2/4/8/16$ g	Full-scale range: $\pm 250/500/1000/2000$ dps	Full-scale range: $\pm 1200$ dps	5, 10, 12.5, 16.67, 20, 25, 33.33, 50, 100, 200, 300	-	3h	-
WAX9	£178.8	Bluetooth 2.1 and LE	$\pm 2/4/8$ g Resolution: 14-bit	$\pm 250/500/2000$ Resolution: 16-bit	Range $\pm 1$ mT Resolution: 16-bit	1 to 400	0 - 65°C	6h	C# iOS App
Shimmer3	503.07 euro ** $\approx$ £381	USB,Bluetooth 2.1	$\pm 2/4/8/16$ g Sensitivity: 1000(2g)/ 500(4g)/250(8g)/ 83.3(16g) LSB/g ADCs: 16-bit	Range: $\pm 250/500/1000/2000$ Sensitivity: 131(250) / 65.5 (500) 32.8(1000) / 250 (2000)LSB/g ADCs: 16-bit	Range: $\pm 1.3/1.9/2.5/4.0/4.7/5.6/8.1$ Ga Sensitivity (X,Y,Z) (LSB/Ga): 1100/980(1.3), 855/760(1.9) 670/600(2.5), 450/400(4.0) 400/355(4.7), 330/295(5.6) 230/205 (8.1) ADCs: (16 bits)	10.24 to 1024	-	14h15m (@51.2Hz) C# Android	

\*Incl. Tax. \*\* Incl. shipping \*\*\* g is the acceleration due to gravity



## Appendix B

1

## How to install L<sup>A</sup>T<sub>E</sub>X

2

### Debian/Ubuntu:

3

```
sudo apt-get install texlive texlive-latex-extra
```

4

```
sudo apt-get install psutils
```

5





## Appendix C

1

### Installing the CUED class file

2

$\text{\LaTeX}$ .cls files can be accessed system-wide when they are placed in the `<texmf>/tex/latex` directory, where `<texmf>` is the root directory of the user's  $\text{\TeX}$  installation. On systems that have a local texmf tree (`<texmflocal>`), which may be named “texmf-local” or “localtexmf”, it may be advisable to install packages in `<texmflocal>`, rather than `<texmf>` as the contents of the former, unlike that of the latter, are preserved after the  $\text{\LaTeX}$  system is reinstalled and/or upgraded.

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