

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



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

September 2018



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  
September 2018



## **Acknowledgements**

And I would like to acknowledge ...





## **Abstract**

This is where you write your abstract ...



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# Nomenclature

## Roman Symbols

$F$  complex function

## Greek Symbols

$\gamma$  a simply closed curve on a complex plane

$\iota$  unit imaginary number  $\sqrt{-1}$

$\pi$   $\simeq 3.14\dots$

## Superscripts

$j$  superscript index

## Subscripts

$0$  subscript index

crit Critical state

## Other Symbols

$\oint_{\gamma}$  integration around a curve  $\gamma$

## Acronyms / Abbreviations

ALU Arithmetic Logic Unit

BEM Boundary Element Method

CD Contact Dynamics

CFD Computational Fluid Dynamics

<i>CIF</i>	Cauchy's Integral Formula
CK	Carman - Kozeny
DEM	Discrete Element Method
DKT	Draft Kiss Tumble
DNS	Direct Numerical Simulation
EFG	Element-Free Galerkin
FEM	Finite Element Method
FLOP	Floating Point Operations
FPU	Floating Point Unit
FVM	Finite Volume Method
GPU	Graphics Processing Unit
LBM	Lattice Boltzmann Method
LES	Large Eddy Simulation
MPM	Material Point Method
MRT	Multi-Relaxation Time
PCI	Peripheral Component Interconnect
PFEM	Particle Finite Element Method
PIC	Particle-in-cell
PPC	Particles per cell
RVE	Representative Elemental Volume
SH	Savage Hutter
SM	Streaming Multiprocessors
USF	Update Stress First
USL	Update Stress Last

# Chapter 1

## Getting started

### 1.1 What is loren ipsum? Title with math $\sigma$

Lorem Ipsum is simply dummy text of the printing and typesetting industry (see Section 1.3). Lorem Ipsum [3] has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum [1, 4, 5].

The most famous equation in the world:  $E^2 = (m_0c^2)^2 + (pc)^2$ , which is known as the **energy-mass-momentum** relation as an in-line equation.

A *LaTeX class file* is a file, which holds style information for a particular *LaTeX*.

$$CIF : \quad F_0^j(a) = \frac{1}{2\pi i} \oint_{\gamma} \frac{F_0^j(z)}{z-a} dz \quad (1.1)$$

### 1.2 Why do we use loren ipsum?

It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many

web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

## 1.3 Where does it come from?

Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, *consectetur*, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet..", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham

"Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

Section 1.10.32 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo. Nemo enim ipsam voluptatem quia voluptas sit aspernatur aut odit aut fugit, sed quia consequuntur magni dolores eos qui ratione voluptatem sequi nesciunt. Neque porro quisquam est, qui dolorem ipsum quia dolor sit amet, consectetur, adipisci velit, sed quia non numquam eius modi tempora incidunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim ad minima veniam, quis nostrum exercitationem ullam corporis suscipit laboriosam, nisi ut aliquid ex ea commodi consequatur? Quis autem vel eum iure reprehenderit qui in ea voluptate velit esse quam nihil molestiae consequatur, vel illum qui dolorem eum fugiat quo voluptas nulla pariatur?"

1914 translation by H. Rackham: "But I must explain to you how all this mistaken idea of denouncing pleasure and praising pain was born and I will give you a complete

account of the system, and expound the actual teachings of the great explorer of the truth, the master-builder of human happiness. No one rejects, dislikes, or avoids pleasure itself, because it is pleasure, but because those who do not know how to pursue pleasure rationally encounter consequences that are extremely painful. Nor again is there anyone who loves or pursues or desires to obtain pain of itself, because it is pain, but because occasionally circumstances occur in which toil and pain can procure him some great pleasure. To take a trivial example, which of us ever undertakes laborious physical exercise, except to obtain some advantage from it? But who has any right to find fault with a man who chooses to enjoy a pleasure that has no annoying consequences, or one who avoids a pain that produces no resultant pleasure?"

Section 1.10.33 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "At vero eos et accusamus et iusto odio dignissimos ducimus qui blanditiis praesentium voluptatum deleniti atque corrupti quos dolores et quas molestias excepturi sint occaecati cupiditate non provident, similique sunt in culpa qui officia deserunt mollitia animi, id est laborum et dolorum fuga. Et harum quidem rerum facilis est et expedita distinctio. Nam libero tempore, cum soluta nobis est eligendi optio cumque nihil impedit quo minus id quod maxime placeat facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum hic tenetur a sapiente delectus, ut aut reiciendis voluptatibus maiores alias consequatur aut perferendis doloribus asperiores repellat."

1914 translation by H. Rackham: "On the other hand, we denounce with righteous indignation and dislike men who are so beguiled and demoralized by the charms of pleasure of the moment, so blinded by desire, that they cannot foresee the pain and trouble that are bound to ensue; and equal blame belongs to those who fail in their duty through weakness of will, which is the same as saying through shrinking from toil and pain. These cases are perfectly simple and easy to distinguish. In a free hour, when our power of choice is untrammelled and when nothing prevents our being able to do what we like best, every pleasure is to be welcomed and every pain avoided. But in certain circumstances and owing to the claims of duty or the obligations of business it will frequently occur that pleasures have to be repudiated and annoyances accepted. The wise man therefore always holds in these matters to this principle of selection: he rejects pleasures to secure other greater pleasures, or else he endures pains to avoid worse pains."



# Chapter 2

## My second chapter

### 2.1 Reasonably long section title

I'm going to randomly include a picture Figure 2.1.

If you have trouble viewing this document contact Krishna at: [kks32@cam.ac.uk](mailto:kks32@cam.ac.uk) or raise an issue at <https://github.com/kks32/phd-thesis-template/>

### Enumeration

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Fig. 2.1 This is just a long figure caption for the minion in Despicable Me from Pixar



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1. The first topic is dull
2. The second topic is duller
  - (a) The first subtopic is silly
  - (b) The second subtopic is stupid
3. The third topic is the dullest

Morbi bibendum est aliquam, hendrerit dolor ac, pretium sem. Nunc molestie, dui in euismod finibus, nunc enim viverra enim, eu mattis mi metus id libero. Cras sed accumsan justo, ut volutpat ipsum. Nam faucibus auctor molestie. Morbi sit amet eros a justo pretium aliquet. Maecenas tempor risus sit amet tincidunt tincidunt. Curabitur dapibus gravida gravida. Vivamus porta ullamcorper nisi eu molestie. Ut pretium nisl eu facilisis tempor. Nulla rutrum tincidunt justo, id placerat lacus laoreet et. Sed cursus lobortis vehicula. Donec sed tortor et est cursus pellentesque sit amet sed velit. Proin efficitur posuere felis, porta auctor nunc. Etiam non porta risus. Pellentesque lacinia eros at ante iaculis, sed aliquet ipsum volutpat. Suspendisse potenti.

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## Itemize

- The first topic is dull
- The second topic is duller
  - The first subtopic is silly
  - The second subtopic is stupid
- The third topic is the dullest

## Description

**The first topic** is dull

**The second topic** is duller

**The first subtopic** is silly

**The second subtopic** is stupid

**The third topic** is the dullest

## 2.2 Hidden section

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<sup>1</sup>My footnote goes blah blah blah! ...



Fig. 2.2 Best Animations

## Subplots

I can cite Wall-E (see Fig. 2.2b) and Minions in despicable me (Fig. 2.2c) or I can cite the whole figure as Fig. 2.2

# Chapter 3

## My third chapter

### 3.1 First section of the third chapter

And now I begin my third chapter here ...

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

#### 3.1.1 First subsection in the first section

...and some more

#### 3.1.2 Second subsection in the first section

...and some more ...

##### First subsub section in the second subsection

...and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

#### 3.1.3 Third subsection in the first section

...and some more ...

##### First subsub section in the third subsection

...and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it and some more and some more and some more and some more and some more and some more and some more ...

### Second subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

## 3.2 Second section of the third chapter

and here I write more ...

## 3.3 The layout of formal tables

This section has been modified from “Publication quality tables in L<sup>A</sup>T<sub>E</sub>X<sup>\*</sup>” by Simon Fear.

The layout of a table has been established over centuries of experience and should only be altered in extraordinary circumstances.

When formatting a table, remember two simple guidelines at all times:

1. Never, ever use vertical rules (lines).
2. Never use double rules.

These guidelines may seem extreme but I have never found a good argument in favour of breaking them. For example, if you feel that the information in the left half of a table is so different from that on the right that it needs to be separated by a vertical line, then you should use two tables instead. Not everyone follows the second guideline:

There are three further guidelines worth mentioning here as they are generally not known outside the circle of professional typesetters and subeditors:

3. Put the units in the column heading (not in the body of the table).
4. Always precede a decimal point by a digit; thus 0.1 *not* just .1.
5. Do not use ‘ditto’ signs or any other such convention to repeat a previous value. In many circumstances a blank will serve just as well. If it won't, then repeat the value.

A frequently seen mistake is to use ‘`\begin{center}`’ ... ‘`\end{center}`’ inside a figure or table environment. This center environment can cause additional vertical space. If you want to avoid that just use ‘`\centering`’

Table 3.1 A badly formatted table

	Species I		Species II	
Dental measurement	mean	SD	mean	SD
I1MD	6.23	0.91	5.2	0.7
I1LL	7.48	0.56	8.7	0.71
I2MD	3.99	0.63	4.22	0.54
I2LL	6.81	0.02	6.66	0.01
CMD	13.47	0.09	10.55	0.05
CBL	11.88	0.05	13.11	0.04

Table 3.2 A nice looking table

Dental measurement	Species I		Species II	
	mean	SD	mean	SD
I1MD	6.23	0.91	5.2	0.7
I1LL	7.48	0.56	8.7	0.71
I2MD	3.99	0.63	4.22	0.54
I2LL	6.81	0.02	6.66	0.01
CMD	13.47	0.09	10.55	0.05
CBL	11.88	0.05	13.11	0.04

Table 3.3 Even better looking table using booktabs

Dental measurement	Species I		Species II	
	mean	SD	mean	SD
I1MD	6.23	0.91	5.2	0.7
I1LL	7.48	0.56	8.7	0.71
I2MD	3.99	0.63	4.22	0.54
I2LL	6.81	0.02	6.66	0.01
CMD	13.47	0.09	10.55	0.05
CBL	11.88	0.05	13.11	0.04





# Chapter 4

## My 4 chapter

### 4.1 Reasonably long section title

#### Enumeration

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1. The first topic is dull
2. The second topic is duller
  - (a) The first subtopic is silly
  - (b) The second subtopic is stupid
3. The third topic is the dumbest

Morbi bibendum est aliquam, hendrerit dolor ac, pretium sem. Nunc molestie, dui in euismod finibus, nunc enim viverra enim, eu mattis mi metus id libero. Cras sed accumsan justo, ut volutpat ipsum. Nam faucibus auctor molestie. Morbi sit amet eros a justo pretium aliquet. Maecenas tempor risus sit amet tincidunt tincidunt. Curabitur dapibus gravida gravida. Vivamus porta ullamcorper nisi eu molestie. Ut pretium nisl eu facilisis tempor. Nulla rutrum tincidunt justo, id placerat lacus laoreet et. Sed cursus lobortis vehicula. Donec sed tortor et est cursus pellentesque sit amet sed velit. Proin efficitur posuere felis, porta auctor nunc. Etiam non porta risus. Pellentesque lacinia eros at ante iaculis, sed aliquet ipsum volutpat. Suspendisse potenti.

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## Itemize

- The first topic is dull

- The second topic is duller
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## Description

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**The first subtopic** is silly

**The second subtopic** is stupid

**The third topic** is the dullest

## 4.2 Hidden section

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# Chapter 5

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#### Enumeration

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2. The second topic is duller
  - (a) The first subtopic is silly
  - (b) The second subtopic is stupid
3. The third topic is the dumbest

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## Description

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**The second topic** is duller

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## 5.2 Hidden section

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<sup>1</sup>My footnote goes blah blah blah! ...



# Chapter 6

## My 6 chapter

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<sup>1</sup>My footnote goes blah blah blah! ...

# References

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# **Appendix A**

## **Inertial Measurement Units**

### **Inertial Measurement Units**

**Accelerometer**

**Angular rate gyroscope**

**Magnetometer**

### **Inertial Sensor Signal**

**The IMU signal**

**Kinematic Parameters**

**Coordinate Systems**

### **Benchmark**

#### **Shimmer3 (Dublin, Ireland)**

BtStream firmware program is used for shimmer configuration and data capture over Bluetooth. The Shimmer unit is within Bluetooth range of the PC (<12m approximately).

rechargeable Lithium Polymer battery 3.7V 450mAh

#### **Capabilities**

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

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

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

Wide Range Accelerometer SM303DLHC device from STMicro

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

The gyroscope on the MPU-9150 chip from Invensense

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

magnetometer LSM303DLHC device from STMicroelectronics

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

Noise performance when varying signal bandwidths . the sampling rate for each case was 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:  $\pm 2 / 4 / 8g$  (14 bit resolution). Range setting Convert to g Dynamic range 2 divide by 16384  $\pm 2g$  4 divide by 8192  $\pm 4g$  8 divide by 4096  $\pm 8g$

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:  $\pm 1\mu T$  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.

## **A.1 benchmark**

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 $\pm 1mT$ 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-bit	10.24 to 1024	–	14h15m (@51.2Hz)	Matlab LabVIEW C# Android

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



# Appendix B

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

### Windows OS

#### TeXLive package - full version

1. Download the TeXLive ISO (2.2GB) from  
<https://www.tug.org/texlive/>
2. Download WinCDEmu (if you don't have a virtual drive) from  
<http://wincdemu.sysprogs.org/download/>
3. To install Windows CD Emulator follow the instructions at  
<http://wincdemu.sysprogs.org/tutorials/install/>
4. Right click the iso and mount it using the WinCDEmu as shown in  
<http://wincdemu.sysprogs.org/tutorials/mount/>
5. Open your virtual drive and run setup.pl

or

#### Basic MikTeX - T<sub>E</sub>X distribution

1. Download Basic-MiK<sub>T</sub>E<sub>X</sub>(32bit or 64bit) from  
<http://miktex.org/download>
2. Run the installer
3. To add a new package go to Start » All Programs » MikTeX » Maintenance (Admin)  
and choose Package Manager

4. Select or search for packages to install

## **TexStudio - T<sub>E</sub>X editor**

1. Download TexStudio from  
<http://texstudio.sourceforge.net/#downloads>
2. Run the installer

## **Mac OS X**

### **MacTeX - T<sub>E</sub>X distribution**

1. Download the file from  
<https://www.tug.org/mactex/>
2. Extract and double click to run the installer. It does the entire configuration, sit back and relax.

### **TexStudio - T<sub>E</sub>X editor**

1. Download TexStudio from  
<http://texstudio.sourceforge.net/#downloads>
2. Extract and Start

## **Unix/Linux**

### **TeXLive - T<sub>E</sub>X distribution**

#### **Getting the distribution:**

1. TexLive can be downloaded from  
<http://www.tug.org/texlive/acquire-netinstall.html>.
2. TexLive is provided by most operating system you can use (rpm,apt-get or yum) to get TexLive distributions



## Installation

1. Mount the ISO file in the mnt directory

```
mount -t iso9660 -o ro,loop,noauto /your/texlive####.iso /mnt
```

2. Install wget on your OS (use rpm, apt-get or yum install)
3. Run the installer script install-tl.

```
cd /your/download/directory  
./install-tl
```

4. Enter command 'i' for installation
5. Post-Installation configuration:  
<http://www.tug.org/texlive/doc/texlive-en/texlive-en.html#x1-320003.4.1>
6. Set the path for the directory of TexLive binaries in your .bashrc file

### For 32bit OS

For Bourne-compatible shells such as bash, and using Intel x86 GNU/Linux and a default directory setup as an example, the file to edit might be

```
edit ~/.bashrc file and add following lines  
PATH=/usr/local/texlive/2011/bin/i386-linux:$PATH;  
export PATH  
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;  
export MANPATH  
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;  
export INFOPATH
```

### For 64bit OS

```
edit ~/.bashrc file and add following lines  
PATH=/usr/local/texlive/2011/bin/x86_64-linux:$PATH;  
export PATH  
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;  
export MANPATH
```

```
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;  
export INFOPATH
```

**Fedora/RedHat/CentOS:**

```
sudo yum install texlive  
sudo yum install psutils
```

**SUSE:**

```
sudo zypper install texlive
```

**Debian/Ubuntu:**

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

# Appendix C

## Installing the CUED class file

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

It is recommended that the user create a subdirectory  $\langle\text{texmf}\rangle/\text{tex}/\text{latex}/\text{CUED}$  for all CUED related  $\text{\LaTeX}$  class and package files. On some  $\text{\LaTeX}$  systems, the directory look-up tables will need to be refreshed after making additions or deletions to the system files. For  $\text{\TeX}$ Live systems this is accomplished via executing “ $\text{texhash}$ ” as root.  $\text{MikTeX}$  users can run “ $\text{initexmf -u}$ ” to accomplish the same thing.

Users not willing or able to install the files system-wide can install them in their personal directories, but will then have to provide the path (full or relative) in addition to the filename when referring to them in  $\text{\LaTeX}$ .



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