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

Miguel P. Xochicale

Department of Engineering
University of Birmingham

This dissertation is submitted for the degree of
Doctor of Philosophy

December 2017

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

List of figures

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Nomenclature

Roman Symbols

F	complex function

Greek Symbols

γ	a simply closed curve on a complex plane
$\imath$	unit imaginary number $\sqrt{-1}$
π	$\simeq 3.14\ldots$

Superscripts

j	superscript index

Subscripts

0	subscript index
crit	Critical state

Other Symbols

$\oint_\gamma$	integration around a curve γ

Acronyms / Abbreviations

ALU	Arithmetic Logic Unit
BEM	Boundary Element Method
CD	Contact Dynamics
CFD	Computational Fluid Dynamics

CIF 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

Introduction

1.1 Opening hook

1.2 Context

1.3 Gap in the literature

1.4 Research Questions

1.5 Argument

1.6 Outline of logic

1.7 What is loren ipsum? Title with math σ

Lorem Ipsum is simply dummy text of the printing and typesetting industry (see Section 1.8). Lorem Ipsum [3] has been the industry's 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.

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

1.8 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.

Chapter 2

Literature Review

2.1 Source of Variability in Human Movement

2.2 Sensors

2.3 Variability within and between persons

2.4 Variability for simple and complex activities

2.5 Techniques to measure human movement variability

2.6 Reasonably long section title

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

Enumeration

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed vitae laoreet lectus. Nunc et dolor diam. Phasellus eu justo vitae diam vehicula tristique.

1. The first topic is dull
2. The second topic is duller
    (a) The first subtopic is silly

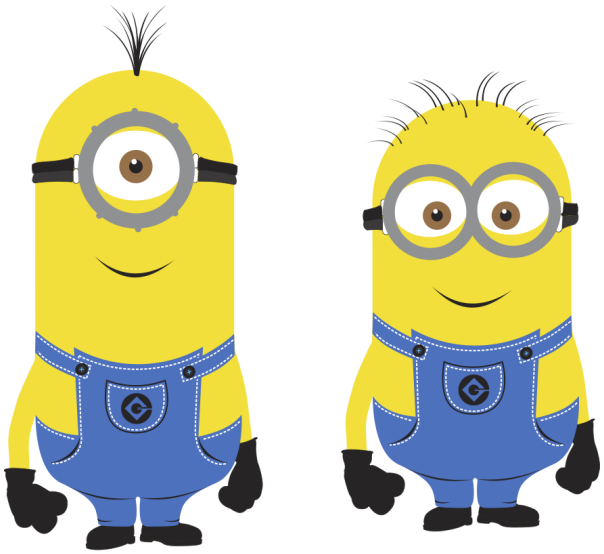


Fig. 2.1 This is just a long figure caption for the minion in Despicable Me from Pixar

(b) The second subtopic is stupid

3. The third topic is the dullest

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

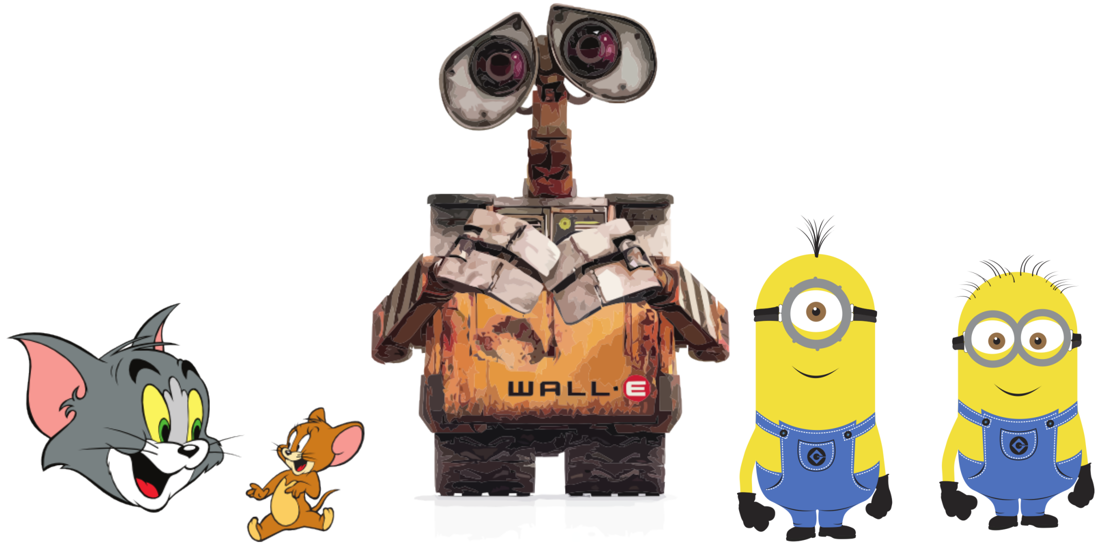
The third topic is the dullest [1]

2.7 Hidden section

Lorem ipsum dolor sit amet, *consectetur adipiscing elit*. In magna nisi, aliquam id blandit id, congue ac est. Fusce porta consequat leo.

Etiam elementum tristique lacus, sit amet eleifend nibh eleifend sed [1]. Maecenas dapibu augue ut urna malesuada, non tempor nibh mollis.

[1] My footnote goes blah blah blah! ...



(a) Tom and Jerry (b) Wall-E (c) Minions

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

Methodology

3.1 Time-domain

3.2 Frequency-domain

3.3 Nonlinear dynamics domain

3.4 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]

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 . . .

3.5 The layout of formal tables

This section has been modified from "Publication quality tables in LaTeX*" by Simon Fear.

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

Experiments

4.1 Dancing Salsa

4.2 Simple movements

4.3 Human-Humanoid Imitation

4.4 Group Activity in Human-Humanoid Imitation

4.5 Reasonably long section title

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Chapter 5

Automatic Classification

5.1 Convolutional Neural Networks

5.2 Convolutional Neural Networks Using time-series

Chapter 6

Conclusion

6.1 Reasonably long section title

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References

[1] Abramovich, Y. A., Aliprantis, C. D., and Burkinshaw, O. (1995). Another characterization of the invariant subspace problem. *Operator Theory in Function Spaces and Banach Lattices.* The A.C. Zaanen Anniversary Volume*, Operator Theory: Advances and Applications*, 75:15–31. Birkhäuser Verlag.

[2] Ancey, C., Coussot, P., and Evesque, P. (1996). Examination of the possibility of a fluid-mechanics treatment of dense granular flows. *Mechanics of Cohesive-frictional Materials*, 1(4):385–403.

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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 tot he 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: ±2.0 g.
- Sensitivity: 600 mV/g.

Wide Range Accelerometer SM303DLHC device from STMicro

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

The gyroscope on the MPU-9150 chip from Invensense

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

magnetometer LSM303DLHC device from STMicroelectronics

- Full scale range (Ga): ±1.3; ±1.9; ±2.5; ±4.0; ±4.7; ±5.6; ±8.1.
- 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).
- 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)	3.51×10^{-3}	5.09×10^{-3}	8.12×10^{-3}
Wide Range Accelerometer RMS noise (m/s^2)	18.6×10^{-3}	27.5×10^{-3}	37.2×10^{-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: ±2.0 g; ±4.0 g; ±8.0 g; ±16.0 g.
- Sensitivity (LSB/g): Min232, Typ256, Max286 (±2.0 g); Min116, Typ128, Max143 (±4.0 g); Min58,Typ64, Max71 (±8.0 g); Min29,Typ32, Max36 (±16.0 g).
- Output: User-selectable resolution: 10-bit or 13-bit

Noise Performance x-,y-Axes. Date rate = 100 Hz for ±2 g, 10-bit. <1.0 LBS rms z-Axes. Date rate = 100 Hz for ±2 g, 10-bit. <1.5 LBS rms

The gyroscope on the ITG-3200 chip from Invensense

- Full scale range (deg/sec): ±2000.
- Sensitivity (LSB/(deg/sec)): 14.375 (±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): ±8.
- Sensitivity (LSB/Gauss): Min230,Max1370 (±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: ± 2 / 4 / 8g (14 bit resolution). Range setting Convert to g Dynamic range 2 divide by 16384 ± 2g 4 divide by 8192 ± 4g 8 divide by 4096 ± 8g

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

Magnetometer: ± 1uT steps (1 mGs, milli-gauss). (16 bit resolution) The range of the sensor is ± 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 booth as a disadvantage and adtange.

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 (±2 / ±4 / ±8 / ±16 g). 3-axis gyroscope with selectable full-scale range (±250 / ±500 / ±1000 / ±2000 dps) 3-axis magnetometer ±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 BluetoothTM 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 : ± 2000 dps - Triple axis 16-bit accelerometer : ± 16 g - Triple axis 13-bit magnetometer : ± 1200 uT

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

user-programmable gyro full-scale range of ±250, ±500, ±1000, and ±2000°/sec (dps) Gyro sensitivity (LSB/°/sec) N/A Gyro Rate Noise (dps/ Hz) 0.005

a user-programmable accelerometer full-scale range of ±2 g, ±4 g, ±8 g, and ±16 g, Accel Sensitivity (LSB/g) N/A and compass with a full scale range of ±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: ± 2 g Sensitivity: 256 LSB/g ADCs: 10-bit	Full-scale region: ±2000 dps Sensitivity: 14.375 LSB/dps ADCs: 16-bit	Full-scale region: ±8 Gauss Sensitivity: 230 to 1370 LSB/gauss ADCs: 12-bit	50	–	–	C++ Android ROS
myAHRS+	£69.52	USB,UART,I2C	Full-scale Range: ±16 g Sensitivity: (2048 LSB/g) ADCs: 16-bit	Full-scale region: ±2000 dps Sensitivity: 16.4 LSB/dps ADCs: 16-bit	Full-scale Range: ± 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 ≈ £291	Bluetooth 2.1	Full-scale range: ± 2/ 4/8/16 g	Full-scale range: ± 250/ 500/1000/2000 dps	Full-scale range: ±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	± 2/4/8g Resolution: 14-bit	± 250/500/2000 Resolution: 16-bit	Range ± 1mT Resolution: 16-bit	1 to 400	0 - 65°C	6h	C# iOS App
Shimmer3	503.07 euro ** ≈ £381	USB,Bluetooth 2.1	± 2/4/8/16 g Sensitivity: 1000(2g) /500(4g)/250(8g)/ 83.3(16g) LSB/g ADCs: 16-bit	Range: ± 250/500/ 1000/2000 Sensitivity: 131(250) / 65.5 (500) 32.8(1000) / 250 (2000)LBS/g ADCs: 16-bit ADCs: 16-bit	Range: ±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)	Matlab LabVIEW C# Android

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

Appendix B

How to install LaTeX

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 - TeX distribution

1. Download Basic-MiKTeX(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 - TeX editor

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

Mac OS X

MacTeX - TeX 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 - TeX editor

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

Unix/Linux

TeXLive - TeX 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

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 TeXinstallation. 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 LaTeXsystem is reinstalled and/or upgraded.

It is recommended that the user create a subdirectory <texmf>/tex/latex/CUED for all CUED related LaTeXclass and package files. On some LaTeXsystems, the directory look-up tables will need to be refreshed after making additions or deletions to the system files. For TeXLive systems this is accomplished via executing "texhash" as root. MIKTeXusers can run "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 LaTeX.

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