Thesis submitted to obtain the title of
Doctor of Philosophy

Doctoral School of Engineering Science
Field: Computer Science

Real-time Soft Tissue Modelling on GPU for Medical Simulation

Prepared by Olivier Comas at
INRIA Lille, Shaman Team and CSIRO ICT Brisbane, EAHRC

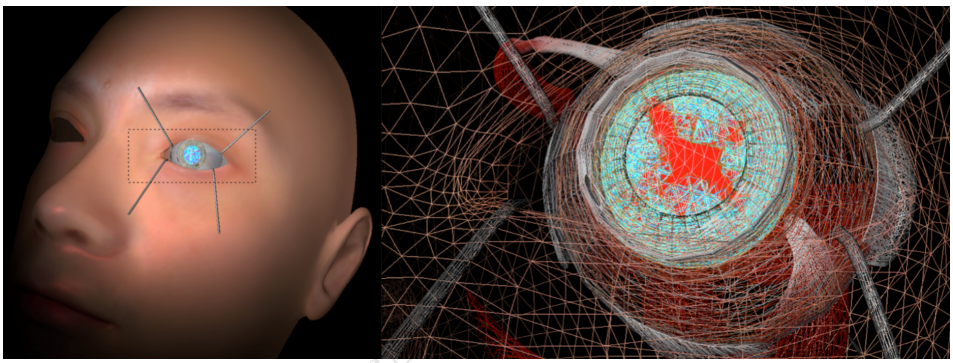
Defended on the 00^{th} of December 2010

Jury:

Reviewers:	Bernard	-	INRIA (Shaman)
	Bernard	-	INRIA (Shaman)
Advisor:	Stéphane Cotin	-	INRIA (Shaman)
President:	Bernard	-	INRIA (Shaman)
Examinators:	Bernard	-	INRIA (Shaman)
	Bernard	-	INRIA (Shaman)

University of Lille 1 - Doctoral School of Engineering Science
Thesis submitted to obtain the degree of Doctor of Philosophy in Computer Science

Real-time Soft Tissue Modelling on GPU for Medical Simulation



Prepared by Olivier Comas at
INRIA Lille, Shaman Team and CSIRO ICT Brisbane, EAHRC

Defended on the 00^{th} of December 2010

Jury:

Reviewers:	Bernard	-	INRIA (Shaman)
	Bernard	-	INRIA (Shaman)
Advisor:	Stéphane Cotin	-	INRIA (Shaman)
President:	Bernard	-	INRIA (Shaman)
Examinators:	Bernard	-	INRIA (Shaman)
	Bernard	-	INRIA (Shaman)

Contents

Contents i

I Introduction 1

1 Medical simulation 3
1.1 General context and goal: medical training, patient-specific planning and per-operative guidance . . . 3
1.2 Challenges (trade-off between accuracy and real-time) . . . 3

2 One key point in medical simulation: soft-tissue modelling 5
2.1 Necessary background in continuum mechanics . . . 5
2.1.1 Deformation tensor and strain tensor . . . 5
2.1.2 Stress and constitutive laws . . . 5
2.2 Tissue characterisation . . . 5
2.2.1 Material models for organs (non-linear, visco-elastic and anisotropic) . . . 5
2.2.2 Measure/estimation of model parameters . . . 5

3 Main principles of Finite Element Method (or how to solve equations of continuum mechanics from previous section) 7
3.1 Discretisation . . . 7
3.2 Derivation of element equations . . . 7
3.3 Assembly of element equations . . . 7
3.4 Solution of global problem . . . 7

II Solid organs modelling 9

4 State of art: FEM 11

5 Linear not accurate => Non-linear FEM => Introduction of TLED 13
5.1 Differences with classic FEM and reasons of its efficiency . . . 13
5.2 Visco-elasticity and anisotropy added (MICCAI 2008; MedIA 2009) . 13

6 GPU implementation of TLED 15
6.1 What is GPGPU . . . 15
6.2 Re-formulation of the algorithm for its Cg implementation . . . 15
6.3 CUDA implementation/optimisations (ISBMS 2008a) . . . 15

7 Implementation in SOFA **17**
7.1 Presentation of SOFA project and architecture 17
7.2 Implementation in SOFA and TLED released in open-source 17

III Hollow organs modelling **19**

8 State of art: hollow structures **21**
8.1 Non-physic approaches (computer graphics stuff) 21
8.2 Physically accurate approches (plates/shells) 21

9 Colonoscopy simulator project **23**
9.1 Project introduction 23
9.2 Mass-spring model for colon implemented on GPU (ISBMS 2008b) . 23

10 More accurate: a co-rotational triangular shell model (ISBMS 2010) **25**
10.1 Model description 25
10.2 Validation 25
10.3 Application to implant deployment simulation in cataract surgery . . 25

11 'Shell meshing' technique (MICCAI 2010) **27**
11.1 State of art: reconstruction/simplification 27
11.2 Our method 27

12 Applications to medical simulation **29**
12.1 Nice medical stuff to show 29
12.2 Interaction solid/hollow organs 29

IV Conclusion **31**

References **33**

Part I

Introduction

Chapter 1

Medical simulation

1.1 General context and goal: medical training, patient-specific planning and per-operative guidance

1.2 Challenges (trade-off between accuracy and real-time)

Chapter 2

One key point in medical simulation: soft-tissue modelling

2.1 Necessary background in continuum mechanics

2.1.1 Deformation tensor and strain tensor

2.1.2 Stress and constitutive laws

2.2 Tissue characterisation

2.2.1 Material models for organs (non-linear, visco-elastic and anisotropic)

2.2.2 Measure/estimation of model parameters

Chapter 3

Main principles of Finite Element Method (or how to solve equations of continuum mechanics from previous section)

3.1 Discretisation

3.2 Derivation of element equations

3.3 Assembly of element equations

3.4 Solution of global problem

Part II

Solid organs modelling

Chapter 4

State of art: FEM

Chapter 5

Linear not accurate => Non-linear FEM => Introduction of TLED

5.1 Differences with classic FEM and reasons of its efficiency

5.2 Visco-elasticity and anisotropy added (MICCAI 2008; MedIA 2009)

Chapter 6

GPU implementation of TLED

6.1 What is GPGPU

6.2 Re-formulation of the algorithm for its Cg implementation

6.3 CUDA implementation/optimisations (ISBMS 2008a)

Chapter 7

Implementation in SOFA

7.1 Presentation of SOFA project and architecture

7.2 Implementation in SOFA and TLED released in open-source

Part III

Hollow organs modelling

Chapter 8

State of art: hollow structures

8.1 Non-physic approaches (computer graphics stuff)

8.2 Physically accurate approches (plates/shells)

Chapter 9

Colonoscopy simulator project

9.1 Project introduction

9.2 Mass-spring model for colon implemented on GPU (ISBMS 2008b)

Chapter 10

More accurate: a co-rotational triangular shell model (ISBMS 2010)

10.1 Model description

10.2 Validation

10.3 Application to implant deployment simulation in cataract surgery

Chapter 11

'Shell meshing' technique (MICCAI 2010)

11.1 State of art: reconstruction/simplification

11.2 Our method

Chapter 12

Applications to medical simulation

12.1 Nice medical stuff to show

12.2 Interaction solid/hollow organs

Part IV

Conclusion

References