On the Deformation of Human Skin for Mechanical Counter Pressure Space Suit Development

by

Edward William Obropta Jr.

B.S., Massachusetts Institute of Technology (2013)

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

Master of Science in Aerospace Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2015

© Massachusetts Institute of Technology 2015. All rights reserved.

Author .................................................................

Department of Aeronautics and Astronautics

May 21, 2015

Certified by ............................................................... Dava J. Newman

Apollo Professor of Astronautics

Thesis Supervisor

Accepted by ................................................................. Paulo C. Lozano

Chair, Graduate Program Committee
On the Deformation of Human Skin for Mechanical Counter Pressure Space Suit Development

by

Edward William Obropta Jr.

Submitted to the Department of Aeronautics and Astronautics on May 21, 2015, in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering

Abstract

Exploration of planetary bodies requires space suits that do not inhibit astronaut mobility. Gas pressurized suits are typically bulky and stiff to operate or require unnatural human motion. Development of mechanical counter pressure (MCP) space suits can change the current space suit design paradigm.

The primary goal of this thesis is to develop methodology to quantify strain and deformation of human skin to inform how to make a MCP space suit, or second skin, that maximizes mobility and minimizes human energy expenditure. Specific emphasis was placed on joint mobility, therefore, the Lines of Non-Extension (LoNE) was investigated in detail throughout the deformation of the human elbow joint. This goal was driven by three research objectives: develop a system to measure human skin deformation and strain, develop a rigorous method to compute LoNE, and examine the variation of skin strain between multiple subjects. The contributions of this thesis are the development of a multi-camera system to measure skin deformation at 1 mm², a streamline approach for calculating LoNE, strain data at the elbow joint and a methodology moving forward to measure more sections of the human body.

The results from the six subjects showed that skin deformation can be similar in magnitude between subjects of varying anthropometrics, but the principal strain directions and LoNE maps can vary. The elbow data was flattened to 2D and normalized by anthropometrics to allow comparisons between subjects. This skin deformation data informs material selection, material placement, and suit patterning. This data is relevant to any compression garment or device that interacts with human skin.

Thesis Supervisor: Dava J. Newman
Title: Apollo Professor of Astronautics
Acknowledgments

First and foremost, I would like to thank my advisor, Professor Dava Newman. I cannot say enough wonderful things about your support, guidance, and mentorship throughout my time at MIT. Your vision, excellence, and leadership has inspired me to reach towards the stars. You have always prioritized students and provided me with wonderful opportunities in all paths of life. You have enabled me to achieve my goals and find the balance between work and life. I cannot thank Dava without mentioning Gui Trotti. Thank you Gui for providing design expertise, experience, and insights into work and life.

I would like to thank all of the professors at MIT who have helped me learn and mature my understanding of the fundamentals of engineering and science. I started at the absolute bottom of academics at MIT from 18.01 and 8.01 and I cannot believe how far I have traveled since then. Thank you Prof. Raul Radovitzsky for teaching me the beauty of solid mechanics, taking the time and having the patience to listen to some of my oddest ideas, and providing advice and direction. Thank you Prof. Tomasz Wierzbicki for enabling my research with openness to your laboratory and willingness to help. Thank you Prof. Alex Techet for being apart of the dive suit project and providing direction in the fascinating underwater world. There are too many professors to name that have helped me throughout my time at MIT.

My learning could not have been solidified without the fantastic support of various teaching assistants. Thank you Dr. Aurélie Jean and Dr. Martin Hautefeuille for all of the extra time you invested in me and extra research support.

Special thank you to the Man-Vehicle Laboratory (MVL), you are undoubtely the most-valuable lab. A cannot thank the professors, faculty, and staff enough for cultivating a fantastic learning environment for human space research. I would like to thank Prof. Larry Young, Prof. Jeff Hoffman, Prof. Leia Stirling, Prof. Chuck Oman, Dr. Andy Liu, Dr. Alan Natapoff for welcoming me into the lab and all of your insightful feedback. I want to especially thank Quentin Alexander and Liz Zotos for making the lab actually function.
I owe my industry and academic collaborators and sponsors special recognition. Thank you Dr. Tienie van Schoor, Jared Keegan, and Luke Saindon at Mide Technology for supporting my research through the Office of Naval Research and providing me opportunities to be exposed to industry and the Navy. I like to thank Jorge Martins and the MIT Portugal program for providing support and insight into the bio-medical field. I would also like to thank Prof. Guido Baroni, Dr. Matteo Serengi, and Dr. Paolo Patete for your support at Politecnico di Milano through Rocca building MITSurf.

Todd Billings, Dave Robertson, Dick Perdichizzi, Bill Litant: You guys rock. Thank you for helping me make, create, and test everything I’ve ever made in Course 16.

I cannot thank the grad and undergrad students that have worked with me and helped me through thick and thin in the MVL, Course 16, and MIT at large. Thank you Forrest Meyen, Nikhil Vadhavkar, Dustin Kendrick, Alexandra Hilbert, Conor Cullinane, Morris Vanegas, Ana Diaz, Duncan Miller, Kai Wang, Henna Jethani, Hamilton Eng, Joana Capacete, Giacomo Gatto, Luca Levrino. Quals studying: Pierre Bertrand, Kyle Kotowick – wow, seriously, thank you. Pierre, thank you for brightening my everyday with laughter. I want to especially thank Dr. Brad Holschuh who has continually been my mentor throughout undergrad and grad school. You have opened up countless opportunities for my learning. There are too many to mention, but thank you all.

To all of my friends and mentors at MIT including Course 16, Phi Sig, intramural sports, entrepreneurial ventures and SpaceX interns, too many to name, thank you for making my experience exceptionally memorable. Thomas Fronk we are an inseparable Course 16 duo. I cannot wait to continue many fishing trips with you, Bee, and Shan Shan.

To my family - Mom, Dad, Alanna, Grandmom, Trent, Reed, Dave, my aunts, uncles, and cousins. I love you all. Everything I am and Everything I do comes from you and your unconditional and constant love, support, and understanding. I would be nothing without you and I am everything because of you. I am deeply thankful to
have such a wonderful family.

Finally, Juliann. You are the love of my life. MIT brought us together and we’ve been inseparable ever since freshman year. You always have supported me, my ideas and my dreams. You make me stronger, more thoughtful, and more insightful in every aspect of life. I never believed I could run more than 1 mile, but you have given me the inner strength to go forever. I am unbelievably lucky to have you in my life and I am excited for our next journey in life. Wherever the path leads, I love you and our life together.

“This is the beginning, not the end.” - Apollo 17
Contents

1 Introduction 21
   1.1 Motivation ............................................. 21
   1.2 Problem Statement ................................... 22
       1.2.1 Research Objective 1 .......................... 23
       1.2.2 Research Objective 2 .......................... 23
       1.2.3 Research Objective 3 .......................... 23
   1.3 Hypothesis ........................................... 23
       1.3.1 Hypothesis 1 .................................. 23
       1.3.2 Hypothesis 2 .................................. 24
   1.4 Contributions ....................................... 24

2 Background and Literature Review 25
   2.1 Space Suits .......................................... 25
       2.1.1 Mobility and Locomotion ....................... 31
   2.2 Pressure ............................................. 32
   2.3 Skin Physiology ..................................... 33
   2.4 Skin Deformation and Strain ....................... 33
   2.5 Digital Image Correlation ......................... 39

3 The Lines of Non-Extension 43
   3.1 Finite Strain Theory ............................... 44
       3.1.1 The Deformation Gradient ....................... 45
       3.1.2 Strain Tensors ................................ 46
3.2 Direction of Non-Extension ............................................. 47
  3.2.1 Derivation of Non-Extension Directions ............................ 48
3.3 Computing the Lines of Non-Extension ................................. 52
  3.3.1 Connection Methods ............................................. 52
  3.3.2 The Streamline Approach ....................................... 53
  3.3.3 LoNE Discussion .................................................. 57

4 Methods ................................................................. 59
  4.1 Experimental Setup .................................................. 59
    4.1.1 DIC Camera System ........................................... 60
    4.1.2 Elbow Rig ......................................................... 60
    4.1.3 Speckle Patterning ............................................. 62
  4.2 Experimental Procedure ............................................. 62
  4.3 Methods Limitations ................................................ 65

5 Data Analysis .......................................................... 67
  5.1 3D-DIC .............................................................. 67
    5.1.1 DIC Explanation ................................................. 68
  5.2 Dataset Stitching .................................................... 69
  5.3 The LoNE Calculator Version 4 ................................... 71
    5.3.1 Code Structure ................................................ 71
    5.3.2 Numerical LoNE Calculation .................................. 75
    5.3.3 The Interactive LoNE Tool .................................... 77
  5.4 Data Flattening and Normalization ................................ 77

6 Results ................................................................. 81
  6.1 Preliminary Results ................................................ 81
  6.2 Lateral Results ..................................................... 82
  6.3 Subjects A-F ......................................................... 85
  6.4 Data Normalization ................................................ 86
  6.5 Results Discussion ................................................ 89
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Buzz Aldrin wearing the A7L space suit</td>
<td>27</td>
</tr>
<tr>
<td>2-2</td>
<td>NASA advanced space suit concepts</td>
<td>27</td>
</tr>
<tr>
<td>2-3</td>
<td>The difference between MCP and gas pressurized suits</td>
<td>29</td>
</tr>
<tr>
<td>2-4</td>
<td>The Space Activity Suit developed by Annis and Webb in 197</td>
<td>30</td>
</tr>
<tr>
<td>2-5</td>
<td>The BioSuit™</td>
<td>31</td>
</tr>
<tr>
<td>2-6</td>
<td>Langer's Lines</td>
<td>34</td>
</tr>
<tr>
<td>2-7</td>
<td>The anatomy of human skin</td>
<td>34</td>
</tr>
<tr>
<td>2-8</td>
<td>A stress-strain curve of human skin taken at the abdomen</td>
<td>35</td>
</tr>
<tr>
<td>2-9</td>
<td>Iberall's skin deformation experiments</td>
<td>35</td>
</tr>
<tr>
<td>2-10</td>
<td>Iberall’s mobile pressure suit</td>
<td>37</td>
</tr>
<tr>
<td>2-11</td>
<td>A comparison of Langer’s lines and LoNE from Iberall</td>
<td>37</td>
</tr>
<tr>
<td>2-12</td>
<td>Knee LoNE visualized by connection directions of non-extension</td>
<td>38</td>
</tr>
<tr>
<td>2-13</td>
<td>Motion capture data collection and strain measurement</td>
<td>40</td>
</tr>
<tr>
<td>2-14</td>
<td>Directions of non-extension shown on the ankle for dorsiflexion movement</td>
<td>40</td>
</tr>
<tr>
<td>2-15</td>
<td>Skin deformation after bandage applied</td>
<td>42</td>
</tr>
<tr>
<td>3-1</td>
<td>The deformation of a continuum</td>
<td>46</td>
</tr>
<tr>
<td>3-2</td>
<td>The reference and the deformed configuration</td>
<td>48</td>
</tr>
<tr>
<td>3-3</td>
<td>The finite strain ellipse and Mohr’s circle</td>
<td>49</td>
</tr>
<tr>
<td>3-4</td>
<td>The strain ellipse shown in three different cases</td>
<td>49</td>
</tr>
<tr>
<td>3-5</td>
<td>Deriving the finite strain ellipse from Mohr’s circle</td>
<td>51</td>
</tr>
<tr>
<td>3-6</td>
<td>LoNE connection method developed by Wolfrum</td>
<td>53</td>
</tr>
<tr>
<td>3-7</td>
<td>LoNE connection method compared to the analytic solution</td>
<td>54</td>
</tr>
</tbody>
</table>
7-2 LoNE projected on the elbow in $90^\circ$ configuration with finite strain ellipse .................................................. 104

7-3 A conceptual sketch of second skin garment ............................................. 106

B-1 MCP pressure production ........................................................................ 117

B-2 LoNE Uncertainty .................................................................................... 117
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>MCP space suit engineering requirements</td>
<td>32</td>
</tr>
<tr>
<td>4.1</td>
<td>Subject Anthropometrics</td>
<td>63</td>
</tr>
<tr>
<td>6.1</td>
<td>Range of Principal Strain</td>
<td>85</td>
</tr>
<tr>
<td>6.2</td>
<td>Strain error results</td>
<td>92</td>
</tr>
<tr>
<td>7.1</td>
<td>Mesh Area Info</td>
<td>102</td>
</tr>
<tr>
<td>A.1</td>
<td>Subject All Anthropometrics</td>
<td>111</td>
</tr>
</tbody>
</table>
List of Acronyms

3D-DIC three dimensional digital image correlation.

CAD computer aided design.

DIC digital image correlation.

EMU Extravehicular Mobility Unit.

EVA Extravehicular Activity.

LoNE Lines of Non-Extension.

MCP mechanical counter pressure.

NASA National Aeronautics and Space Administration.
Chapter 1

Introduction

1.1 Motivation

Exploration is core to our human-nature. Since the beginning of humankind, we’ve looked towards the heavens out of curiosity and in the hopes of discovery. Perhaps we are continually driven to seek out new beginnings and build an understanding of the unknown. With the Wright Brother’s first flights a little over a century ago and with Sputnik 1, the first man-made object sent to space, half a century ago, we’ve developed technology that has enabled us to move outwards to the stars. Space exploration revolves around the grandest questions: the origins of the Universe and the history of our very own solar system. More practically speaking, space exploration can lead to technological innovation, nationalistic pride, and the development of new economic markets. The astronaut element in space exploration systems can provide adaptability to changing situations, synthesis of diverse information, and provide the human narrative.

According to the National Aeronautics and Space Administration (NASA) Strategic Plan 2014, a primary objective of the agency is to “Expand human presence into the solar system and to the surface of Mars to advance exploration, science, innovation, benefits to humanity, and international collaboration.” In the next two decades NASA hopes to develop the technologies and capabilities to send humans to Mars [2]. Robotics and satellites have been the initial pioneers: their images and data are
painting a picture of what to expect. In order to bring clarity to this picture we must experience space first hand by human space exploration. In order to experience space first hand, we need space suits to protect us from the extreme environment.

The current space suits are problematic for planetary exploration because they limit astronaut mobility and cause fatigue and exhaustion[27]. The National Research Council (NRC), developed space technology roadmaps to outline technologies that currently need further research to enable exploration. Within the Human Health, Life Support, and Habitation Systems (TA06), the NRC specifically pointed out that space suit mobility, technically referred to as Extravehicular Activity (EVA) mobility, is a major challenge that requires research and development[1]. Historically, all human spaceflight programs that required EVA have used gas-pressurized space suits. In order to improve mobility various joint design techniques have been developed. NASA has been transitioning to hard components in the Z-2 suit, the most recent advanced suit for planetary exploration, with strategically placed rotary bearings for mobility[43]. An alternative concept for space suit design is mechanical counter pressure, where the body is pressurized through direct material contact with the skin. This thesis extends the research in mechanical counter pressure space suits in order to maximize mobility and minimize astronaut energy expenditure.

1.2 Problem Statement

The primary goal of this thesis is to develop methodology to quantify strain and deformation of human skin to inform how to make a mechanical counter pressure (MCP) space suit, or second skin, that maximizes mobility and minimizes human energy expenditure. Specific emphasis was placed on joint mobility, therefore, the Lines of Non-Extension (LoNE) was investigated in detail throughout the deformation of the human elbow joint. The concept of LoNE is important for joint mobility because it provides a theory for how the body can have pressure applied to the skin without sacrificing mobility. Quantifying LoNE patterning will provide insight into how to create the patterning of a MCP suit. The goal of developing a methodology
to quantify strain and deformation was driven by three research objectives.

1.2.1 Research Objective 1

Develop a system and methodology to quantify skin strain and deformation at a spatial resolution less than 1 cm$^2$. This requirement is driven by the previous resolution limitations that prohibited accurate determination of Lines of Non-Extension.

1.2.2 Research Objective 2

Determine a mathematically rigorous method to compute the LoNE throughout a progressive deformation.

1.2.3 Research Objective 3

Examine the variation of skin deformation, strain, and the LoNE between multiple subjects.

1.3 Hypothesis

This thesis follows the narrative of developing strain measurement techniques and mathematical tools to analyze the strain data. Subsequently, multiple subjects were tested and compared. This breakdown lent itself to two main hypotheses.

1.3.1 Hypothesis 1

Digital image correlation (DIC) can be used to measure skin strain at a spatial resolution less than 1 cm$^2$ at joints and a mathematically rigorous method can be used to compute the Lines of Non-Extension from the collected strain data. DIC has been shown to measure strain at sub-pixel resolution [49] and has been shown to work on skin [7, 29, 34, 37, 62].
1.3.2 Hypothesis 2

The LoNE will be quantitatively similar between subjects due to deformation of human skin being largely influenced by rigid body motion of limbs. This rigid body motion is similar between most humans.

1.4 Contributions

This thesis makes several contributions to the field of human movement, human skin strain measurement and the development of mechanical counter pressure space suits. A three dimensional digital image correlation (3D-DIC) system was developed and validated to quantify skin strain at the elbow joint at a spatial resolution of 1 mm². LoNE have been continually suggested in the literature as an essential element to the development of mobile MCP suits and compression garments, but they were never rigorously quantified [9,17,18,31,41,60,61]. This thesis shows that streamlines are one way to rigorously describe LoNE. The streamline approach is used to compare the elbow strain field for multiple subjects.

In pursuit of the three research objectives, a multiple-camera digital image correlation system to measure strain in 3D on objects that have complicated geometry, such as the joints of the human body was created. In addition to the hardware system setup and layout, a complete software pipeline was developed to visualize strain data, interactively compute LoNE maps, and export data to computer aided design (CAD) software. This was a complete overhaul of the previous LoNE calculator tool in order to accommodate the DIC data and LoNE streamline methodology. This novel system and pipeline can be used to assess the deformation of the remaining joints of the human body. It can also be used to study the variation of skin deformation between and within subjects. Now that strain and LoNE maps have been made exportable to CAD, strain data can begin to drive the development of textile patterning, material properties, and material selection of MCP space suits, compression garments, or any wearable device where skin contact is a critical design factor.
Chapter 2

Background and Literature Review

2.1 Space Suits

Space suits have been made for three purposes, namely, intravehicular (IVA), extravehicular (EVA), and intra/extravehicular (IEVA). IVA suits are used to keep astronauts alive inside spacecraft in the event of a cabin depressurization or if the air becomes contaminated. EVA suits are used to go outside of the spacecraft environment to perform mission critical tasks. IEVA suits can be worn both inside and outside of the spacecraft [56].

Space suits were initially modified, high-altitude pressure suits developed for pilots to counteract decreased atmospheric pressure, oxygen supply, and temperatures. The Mercury astronauts wore IVA suits and never left the pressurized capsule environment. The first EVA was performed by cosmonaut Alexey Leonov on March 18, 1965 and the first US EVA was performed by astronaut Ed White on June 3, 1965. When Neil Armstrong and Buzz Aldrin stepped outside the Lunar Module on July 20, 1969 wearing their A7L space suits they performed the first EVA on the moon during Apollo 11. The Apollo A7L suit, shown in Figure 2-1, was a IEVA suit made by the International Latex Corporation (ILC) who currently makes the Extravehicular Mobility Unit (EMU) space suit. The EMU is used during space walks onboard the International Space Station and was originally designed for Space Shuttle EVAs. Various advanced space suits have been developed for future planetary exploration.
The most recent suits in testing at NASA are the ILC Mark III and Z-Series suits designed under the NASA Advanced Exploration System program, which are shown in Figure 2-2.

In *US Spacesuits*, Kenneth Thomas and Harold McMann identify eight main challenges of space suit development, which are reiterated here [56]:

- Space vacuum vs the human need for surrounding pressure
- The dynamics of a pressure enclosure and effects on joint mobility
- Pressure selection, and decompression
- Thermal and radiation protection and control
- Human-friendly spacesuit environments
- Protection from direct sunlight in space
- Space debris
- The cost of space hardware

Each of these challenges have engineering solutions that could be optimized and improved, as with all engineering products, but this thesis focuses on pressure production and its relation to joint mobility.

The current space suits are problematic for planetary exploration because they limit astronaut mobility and cause fatigue and exhaustion [27]. Despite their bulkiness they have proven to be reliable. In the 1950s, Arthur Iberall researched ways to develop mobile pressurized space suits [25]. He was inspired by the deformation and motion of human skin and developed the concept of Lines of Non-Extension, which he described as contours along the human body where the skin does not stretch. Iberall developed theories of space suit mobility and created prototypes that used a restraint mesh over the pressure bladder [26]. The David Clark Company began to develop space suits around the same time and developed a mesh restraint system with a material called Link-net. It is still debated whether these similar methodologies developed independently or were the result of Iberall’s and Clark’s relations [56]. David Clark received the patent on this technology [13] and went on to produce many suits for the military and NASA.
Figure 2-1: Buzz Aldrin walking on the moon during Apollo 11 wearing the A7L space suit. A reflection of Neil Armstrong can be seen in Aldrin’s visor. Photo credit: NASA

Figure 2-2: NASA Advanced Suit Concepts for planetary exploration: Mark III (left), Z-1 (middle), and Z-2 concept (right). Each suit features a suit-port, which is the concept that the space suit is directly mounted to the spacecraft and continually pressurized. Photo credit: [http://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp_index=1794](http://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp_index=1794) (left) and [http://jscfeatures.jsc.nasa.gov/z2/](http://jscfeatures.jsc.nasa.gov/z2/) (middle and right).
There are two main techniques to provide pressure to the body: gas pressure and mechanical counter pressure. In gas pressurized suits, the gas directly applies the pressure to the body equivalent to how the atmosphere applied pressure to our body on Earth. MCP is when a material presses on the body and applies a pressure through a contact force. MCP can be applied by inflating a tube around the body that expands and presses against the body. MCP can also be applied by stretching an elastic material around the body. The curvature in addition the tension in the fabric can apply a normal pressure. The difference between MCP suits and gas pressurized suits is illustrated in Figure 2-3. In the MCP concept, the stress in the fabric applied about a radius of curvature applies a stress traction normal to the skin. This stress traction is called mechanical counter pressure. The amount of stress required to produce counter pressure about a cylinder can be calculated using the assumption of a thin-walled pressure vessel. The mechanical counter pressure, $P$, is related to the hoop stress, $\sigma_h$, multiplied by the fabric thickness, $t$, divided by the cylinder’s radius, $R$, as follows:

$$P = \frac{\sigma_h t}{R}. \quad (2.1)$$

For an MCP suit various limbs, such as the arms, legs, torso, and fingers can be assumed to be cylinders and fabric is most often much thinner in thickness compared to it’s planar dimensions. This maintains the thin-walled assumption. One important consideration is that MCP may not be evenly distributed if friction is not properly managed. High friction materials could cause the fabric to stick in places and not evenly distribute pressure.

Various pressure suit concepts were tested in the early days of space flight. Most suits used gas pressurization and various military G-suits used the inflated MCP concepts. Annis and Webb provided a creative exception in space suit development history. They developed the Space Activity Suit (SAS), as shown in Figure 2-4, the first MCP space suit that used material elasticity to pressurize the body. They tested this concept in 1971, but gas pressurized suits were more technologically feasible at
the time. The following quote from Annis and Webb summarizes the difficulties they faced developing the SAS.

Its [The SAS’s] problems are primarily mechanical in nature. Improvements are needed in methods for donning and closing the garments. Through the use of special fabrics combined with the application biomechanical analysis of joint function, it is felt that mobility can be further improved and the energy cost of activity further lowered [7].

This thesis provides insight into the biomechanical analysis of joint function and motion to inform the design of MCP suits.

In 2001, the BioSuit™ System, a fully MCP space suit design, reemerged at MIT. Professor Dava Newman led the development of the BioSuit™ with inspiration from Iberall, Annis, and Webb [35,36,40]. The BioSuit™, shown in Figure 2-5, is currently the most advanced MCP space suit concept and is still continually researched at the MIT Man-Vehicle Laboratory. To produce pressure various prototypes were constructed. There was a concept to produce pressure using detached elastic bands and a continuous elastic band wrapped around the skin where each band was stretched a different amount depending on the local radius of the limb [50]. Partial pressure
Figure 2-4: The Space Activity Suit developed by Annis and Webb in 1971 is shown. The suit allowed a human subject to breathe oxygen at 170 mm of Hg in a chamber pressurized to 20 mm of Hg using multiple layers of elastic material.

commendations were also researched where a varying number of tubes were inflated inside of an elastic garment. The inflation would press the material against the skin. A foam composite prototype was also constructed where an open cell foam would be inflated and press the garment against the skin. More recently the focus has been shifted from fundamental pressure production to the challenges of donning and doffing systems. Anderson designed an inflatable device that can pull the MCP garment off of the wearer. Various concepts of using active materials were suggested since the first publications on the BioSuit\textsuperscript{TM} as a way to produce compression and allow donning and doffing. Holschuh was the first to actually create MCP suit prototypes that incorporate active materials, many of which use shape memory alloy combined with 3D printing. Shape memory polymer has also been explored as an active material for use in space suits. The requirements for MCP suits are shown in Table 2.1. The pressure requirement will be reviewed Section 2.2.

The concepts of MCP have also been applied to different components of space suits, such as gloves that have been tested by Clapp, Tanaka et al., and Waldie et al. MCP gloves have been compared to the EMU glove and have been shown to provide increased mobility with only minor edema in the palms of the
Figure 2-5: The BioSuit™ shown in conceptual stages and actual prototypes. The lines on the prototype illustrate the Iberall LoNE concept [35, 36, 40].

hands. The body’s concavities are often challenges for pressure production. Various techniques to provide pressure in these areas involve adding a gas bladder or padding with foam to create convexity.

2.1.1 Mobility and Locomotion

The energy required to arbitrarily deform a space suit can be expressed as:

\[ \Delta W = \Delta W_p + \Delta W_b + \Delta W_s, \]  

(2.2)

where the work required to change the gas pressure and volume of the suit is \( \Delta W_p \), the work to bend the suit’s material is \( \Delta W_b \), and the work required to stretch the suit’s material is \( \Delta W_s \) [26]. Gas pressurized suits cause fatigue because they are difficult to move and bend primarily because of work done to change the pressure-volume, \( \Delta W_p \). Contrarily, MCP suits eliminate this term. This makes the mobility of MCP suits
Table 2.1: Summary of MCP space suit engineering requirements adapted from Sim

<table>
<thead>
<tr>
<th>Function</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Production</td>
<td>For elastic-only suits, apply at least 29.7 kPa (225 mm of Hg, 4.3 psi) of average pressure at body surface</td>
</tr>
<tr>
<td></td>
<td>No more than 1.6 kPa (± 12 mm of Hg) spatial variation in pressure</td>
</tr>
<tr>
<td></td>
<td>Locally expose no more than 1 mm² skin surface area to vacuum</td>
</tr>
<tr>
<td>Mobility</td>
<td>Permit wearer to initiate and maintain deep knee squat without undue discomfort, using only body weight.</td>
</tr>
<tr>
<td>Operations</td>
<td>Don and doff in less than 10 minutes without assistance</td>
</tr>
</tbody>
</table>

directly dependent on the mechanical deformation of the suit’s material \[10\]. If the material is designed to deform similarly to the skin of the human body it is feasible that these factors can be minimized to make MCP suits have superior mobility. This is a challenging issue because the surface of the body undergoes a wide range of large, complex motions and deformations, which makes it difficult to model, engineer, and manufacture a MCP suit that maximizes mobility.

2.2 Pressure

The human body requires pressure to be continually and evenly applied. Everyday on Earth the atmosphere applies 101.325 kPa (1 atmosphere at sea-level) to the surface of the human body. In the vacuum of space, pressure must be applied using a pressurized capsule or space suit. The safe minimum pressure is limited by breathing pure oxygen at a pressure of 25.33 kPa \[39, 6\]. However this low pressure requires a long pre-breathe time when transitioning from an atmoshpere with inert gases to avoid decompression sickness, the “bends”, when inert gas bubbles, typically nitrogen, evolve within soft tissues. This places an operational constraint on pre-breathe time. Ideally suits would have a pressure of 101.325 kPa to allow zero-prebreathe time, but that makes traditional space suits too stiff to move.
2.3 Skin Physiology

Human skin is a heterogeneous tissue composed of three layers: the epidermis, papillary, and reticular dermis. The different components of skin are illustrated in Figure 2-7. Research on skin deformation and physiology dates back to the mid-1800s with one of the earliest publications by Karl Langer [28]. Langer studied the skin of cadavers and created diagrams that shows the direction in which the skin deforms when punctured. The directions and lines are known as Langer Lines or cleavage lines, which are shown for the arm in Figure 2-6. Collagen and elastin are the two main proteins that give skin it’s mechanical characteristics [38]. Collagen gives skin its tensile strength and elastin contributes to skin’s elasticity [38]. Skin is characterized as anisotropic, viscoelastic, and highly non-linear. The anistropy of skin also varies by anatomical location on the body [6, 14, 45]. Figure 2-8 shows a stress-strain curve of human skin and how its material properties at different locations on the body. Skin is a living tissue composed of cells so it is also continually growing, adapting, and potentially healing. Wrinkles develop as skin ages and it’s properties change, which was researched by Daly in 1979 [15]. Skin is difficult to model due to these various mechanical complexities. Because it is difficult to model skin, empirical data on skin deformation is the most relevant to understand how develop skin-tight garments such as a MCP space suit.

2.4 Skin Deformation and Strain

Arthur Iberall was the first person to use knowledge about skin deformation to design and make a space suit. In his pursuit, to create a mobile pressure suit, he studied human movement and skin deformation. Iberall assessed skin deformation by using a technique called the finite strain ellipse, which can be described in four steps.

1. Stamp a small circle on the skin in a initial static pose (reference configuration)
2. Move subject into the desired position (deformed configuration). The initial circle deforms approximately into an ellipse, smaller circle, or larger circle.
Figure 2-6: Langer’s cleavage lines on the arm. Langer punctured skin and analyzed how the pre-stress in the skin was relaxed by examining the shape of the puncture hole [28].

Figure 2-7: The anatomy of human skin. Skin is a heterogeneous tissue with various layers and components [3].
3. While in the deformed configuration, stamp the original circle on top of the deformed circle, preferably in a different color.

4. Assess the circle pair in the reference and deformed configuration

The finite ellipse method creates a circle and ellipse pair that can be analyzed. If the reference circle and deformed circle intersect they form a pair of directions of non-extension. The finite strain ellipse will be discussed further in Chapter 3. Iberall determined the directions of non-extension and connected them together forming somewhat of a contour map that he called the LoNE. This process is shown in Figure 2-9.

Iberall stated,
Experimental study of the intrinsically limited motion at each joint verifies that this system of lines of non-extension will be essentially the same for all deformations [26].

which shows that he noticed that the LoNE was not exactly the same for each deformation, but were very similar during human motion. LoNE is a small misnomer, because some deformation occurs throughout a deformation, which is quantified in Chapter 3.

Iberall used LoNE to create a grid of non-extensible elements as the restrain layer to a mobile pressure suit. By using the LoNE geometry he hoped to minimize the pressure-volume work required to deform the suit. The suit is shown in Figure 2-10.

Kristen Bethke completed the first experiments to quantify Iberall’s lines of non-extension. She painted subject’s legs with a black paint and placed markers on the legs. The locations of the markers were measured in 3D using a laser scanner at the US Army Natick Soldier Research Development and Engineering Center (NSRDEC) in a standing pose and a knee bent pose. She created a MATLAB code to analyze the data, known as the LoNE Calculator. She determined that the surface area and volume of the leg did not significantly change between poses. Using a strain gauge rosette method she calculated the strain field of the skin along with the principal strain directions and directions of non-extension. Figure 2-11 illustrates the strain data collected and how it compares to the work of Langer and Iberall. Spatial resolution of the data was roughly 5-15 cm² and required significant manual input to label the markers [9]. In 2006, Nina Wolfrum came up with a method to automatically label the markers using a special color scheme and marker layout. She also decided to use the Green-Lagrange strain tensor as a non-linear strain measurement to take into account large deformations and rotations. LoNEs were also visualized by connecting the directions of non-extension together and smoothed, which is shown in Figure 2-12 [61].

Sara Marreiros performed skin strain analysis on the ankle joint to develop an ankle orthotic in 2010. She related the finite strain ellipse to Mohr’s circle. She developed a separate code from the LoNE Calculator developed by Bethke. This code preprocessed
Figure 2-10: Iberall’s mobile pressure suit. The LoNE geometry was used to create a grid of in-extensible elements that make up the restraint layer of the pressure suit. The figures show various views of the suit \[26\].

Figure 2-11: A comparison of Langer’s and Iberall’s lines with longitudinal strain data and the directions of non-extension determined through quantitative measurements \[9\].
Figure 2-12: LoNE visualized by connecting the directions of non-extension together. This is the posterior view of the knee. The right image with the blue lines are a smoothing of the red lines shown in the left figure [61].

data from a motion capture system (Qualisys, Gothenburg, Sweden) and created a triangular mesh. The mesh and the displacement information was imported into ABAQUS, which calculated the strain field for each element in the mesh. The strain data was re-imported into MATLAB to analyze the principal strain directions and directions of non-extension. The mesh was made smaller by dividing up each element. This did not add data, but only allowed better visualizations. The LoNE lines were then drawn by hand by closely examining the directions of non-extension. The data resolution was approximately 4 cm² [31].

Ashley Wessendorf focused on the knee joint and created a way to measure skin strain at various points in time throughout a deformation rather than just at two extreme poses. This was accomplished using motion capture (Vicon) rather than the marker and laser scanning system similar to Marreiro’s approach. Bethke’s original LoNE Calculator was modified to accept motion capture data from Vicon instead of the laser scanning data. The same strain calculation procedure from Bethke was used. This code produced movies of skin strain rather than one singular image. However the LoNE section of the code was not completed to visualize LoNEs throughout the motion. Figure 2-13 highlights how the strain was measured from motion capture.
data and visualized by showing the data in a 2D space. The resolution of the data was roughly 1-5 cm²

Rita Domingues furthered Marreiros’ work on the ankle. She implemented the strain field calculation in MALAB to eliminate exportation to ABAQUS. The strain field calculation was based on finite elements and uses a pseudoinverse to calculate the deformation gradient. Domingues used motion tracking to acquire data, but also used a point tracking tool to touch similar locations on the skin after they deformed. Domingues proposed a method to draw the LoNEs using a connectivity algorithm. The algorithm looks to see if nearby elements have directions of non-extension in similar directions and if this is true for 8 elements in a row a line is drawn. This method is not mentioned in her thesis. The data resolution remained approximately 4 cm²

Another contribution provided by Marecki, used multiple view imaging to reconstruct skin deformation at the knee for development of lower limb prothesis. His work showed that strain measurement is not limited to motion capture systems or laboratory settings, but could potentially be accomplished using low cost camera equipment

2.5 Digital Image Correlation

Digital image correlation is a non-contact optical technique to measure shape and deformation. Although digital images became primitively available in the 1960s and 1970s, it wasn’t until the 80s that solid mechanics research used digital images to measure deformation in two dimensions. In the late 90s, three dimensional digital image correlation (3D-DIC) was developed using stereoscopic vision. Now, various commercial and university software exists to perform DIC to measure shape and deformation.

DIC has been applied to soft tissues and specifically on skin. Bethke actually noted in her thesis that DIC techniques existed when she was collecting strain data using laser-scanning. She chose not to pursue this methodology because it was limited to
Figure 2-13: The left figure shows the process from motion capture data collection, to strain computation, and a visualization of the Lines of Non-Extension. The right figure visualizes the magnitude of the longitudinal strain data [60].

Figure 2-14: Directions of non-extension shown on the ankle for dorsiflexion movement. The top and bottom row show the anterior and posterior view. The right column shows the data after increasing the resolution [16,18].
in-plane measurements, which were not suitable for full body measurements [9, 34]. In the past decade advancements in 3D-DIC software and increased digital image resolution has enable strain measurements on large areas and curved geometries. Marcellier was the first to measure skin deformation using 2D-DIC [29]. The motion of skin in various facial expressions have been analyzed using DIC techniques [37]. The aging of facial skin has been analyzed using 2D-DIC with results that show the elasticity in skin decreases exponentially [4,51]. In a study using high speed imaging, the skin deformation leading to wrinkle formation around eyes was measured during blinking [34]. In 2011, Wong in collaboration with an industrial partner, Neodyne Biosciences, collected skin strain using 3D-DIC to determine deformation around scars [62]. These studies show that 3D-DIC is a promising measurement technique to acquire high resolution strain maps of skin. However these tests only focus on small sections of the body that do not experience large rigid body motions. This thesis further develops 3D-DIC skin techniques to measure larger sections of the body at joints with a novel application to MCP space suit design.
Figure 2-15: Wong studied how skin deformation changed after the application of a stress-shielding device (bandage in compression) for various anatomical regions. He used a grid to visualize and validate measurements used by 3D-DIC. The top two rows are the grid method and the bottom two rows are the images used by the DIC system and the results of the strain analysis \cite{62}. 
Chapter 3

The Lines of Non-Extension

In the pursuit of developing a maximally mobile pressure suit, Iberall studied the deformation of human skin. He found that skin has unique contours that do not extend during human motion, which he called the Lines of Non-Extension (LoNE) \[26\]. There is a significant amount of speculation about the lines of non-extension and how they should be used in garment development. This chapter attempts to clear up confusion regarding the concept of LoNE. The last section of this chapter contributes a rigorous analysis and mathematical expression of LoNE as streamlines.

The following list of statements regarding LoNE are to provide clarity and to alleviate any misconceptions of LoNE.

1. There are an infinite number of LoNEs. The ones displayed are only the ones chosen to be displayed.
2. LoNEs may not remain an exactly constant length throughout a deformation, therefore “LoNE” is a slight misnomer
3. LoNEs are not unique to a particular material, such as skin
4. The anisotropy of a material does not cause LoNE, isotropic material can have LoNE in the way LoNE has been mathematically defined

Regarding Statement 1: The LoNE maps presented in this thesis and previous works only show a finite number of LoNEs, but in fact an infinite number of LoNEs can be drawn between the LoNEs depicted. They should be thought of as a contour
map, but not in the way that a topographical contour map has isolines that do not intersect.

Regarding Statement 2: Iberall stated, “Experimental study of the intrinsically limited motion at each joint verifies that this system of lines of non-extension will be essentially the same for all deformations.” In fact, for a given deformation, LoNEs can appear to exist, but because deformations occur progressively, the specific LoNEs may extend at other states of the deformation. For skin, at least at one degree of freedom joints, the skin deforms similarly throughout motion and the magnitude continues to increase resulting in similar LoNE maps for each deformation. In Chapter 6 data will be shown to explain and support this phenomenon. For this reason, LoNE is technically a misnomer, but because the LoNEs are similar throughout human motion these contours can be thought of as not extending much. For human skin LoNEs can sometime change length on the order of 5 percent.

Regarding Statement 3: A common misconception is that LoNE is a property of human skin. The specific and interesting LoNE contours found on skin are unique to skin, but the concept of LoNE can be applied to any deformation. LoNE is only a function of the principal strain, which can be determined for any deformation regardless of material. LoNEs will only exist if the principal strains are opposite in sign. Something not fully considered is if LoNE can exist in 3D. The present mathematical definition has only been considered for 2D deformations or deformations of surfaces that are locally 2D.

Regarding Statement 4: Similar to statement 2, material properties do not cause LoNE. Interesting material properties can lead to interesting LoNE patterns, but it is not fundamental to its description.

### 3.1 Finite Strain Theory

To understand LoNE in the context of human skin, this explanation begins at the fundamentals of solid mechanics deformation. In most structural engineering courses, strain is always considered to be “small” such that higher order terms can be ne-
neglected. This is often true for most engineering materials such as metal or carbon fiber composites, but is not the case for soft biological tissues such as skin. In order to handle large deformations and rotations we need to use more general measurements of deformation [19].

Notation: Tensorial notation is being used. Repeated indices represents a summation (i.e. \( x_{ii} = x_{11} + x_{22} + x_{33} \)) and derivatives with respect to the global coordinate system are indicated with a comma (i.e. \( \frac{du_i}{dx_j} = u_{i,j} \)).

We consider deformation as the mapping of the reference state, \( X \), to a deformed state, \( x \) by the function \( \phi \) which is expressed as

\[
x = \phi(X)
\]

An illustration of this deformation is shown in Figure 3-1.

From an engineering point of view the concept of displacement, \( u \), as the new position subtracted from the reference position, where \( u_i = x_i - X_i \). Then strain, \( \epsilon \) is computed as \( \epsilon_{ij} = \frac{1}{2}(u_{ij} + u_{ji}) \). This is true for small strain where we consider the change in an infinitesimal length, \( ds \), \( \epsilon = \frac{ds - dS}{dS} \), but for large deformations we need to consider the change in the squares of the lengths \( E = \frac{ds^2 - dS^2}{dS^2} \) [19]. Instead of using displacement, it is simpler to use the mapping \( x = \phi(X) \) to understand the deformation. We then consider the deformation gradient instead of derivatives with respect to displacement.

### 3.1.1 The Deformation Gradient

The deformation gradient, \( F \) is the gradient of the mapping from the deformed frame to the reference frame,

\[
F_{ij} = \frac{dx_i}{dX_J} = \begin{bmatrix}
\frac{\partial x_1}{\partial X_1} & \frac{\partial x_1}{\partial X_2} & \frac{\partial x_1}{\partial X_3} \\
\frac{\partial x_2}{\partial X_1} & \frac{\partial x_2}{\partial X_2} & \frac{\partial x_2}{\partial X_3} \\
\frac{\partial x_3}{\partial X_1} & \frac{\partial x_3}{\partial X_2} & \frac{\partial x_3}{\partial X_3}
\end{bmatrix}
\]
A polar decomposition of $F$ can be performed where $U$ corresponds to the right stretch tensor and $R$ corresponds to the rotation matrix shown as,

$$F = RU$$  \hspace{1cm} (3.3)

The eigenvalues of $U$ are known as the principal stretches, $\lambda_i$,

$$F \cdot \nu = \lambda \cdot \nu$$  \hspace{1cm} (3.4)

### 3.1.2 Strain Tensors

After computing $F$, the Green-Lagrange and Euler-Almansi strain tensors can be computed. The Green-Lagrange strain, $E$, is with respect to the reference geometry

$$E = \frac{1}{2}(F^T F - I)$$  \hspace{1cm} (3.5)

and the Euler-Almansi strain, $e$, is with respect to the deformed geometry

$$e = \frac{1}{2}((I - (FF^T)^{-1})$$  \hspace{1cm} (3.6)
These two strain tensors actually are equal to $\epsilon$ if the strain is small. However in the case of large deformations and rotations depending on what you want to visualize or compute the selection of the proper strain tensor will significantly affect your result. Figure 3-2 illustrates the difference between the reference configuration and deformed configuration. The angle from a line is denoted by $\phi$, but in the deformed configuration this angle changes to $\theta$.

You can decompose $E$ and $e$ into their eigenvalues and eigenvectors as follows,

$$ E \cdot \nu = \lambda \cdot \nu $$

(3.7)

The eigenvalues represent the principal strain magnitudes and the eigenvectors show which direction the principal magnitudes are oriented. The principal strain magnitudes are referred to with only one index, $E_1$ and $E_2$. Principal strains are essential to understanding the maximum and minimum amount of compression or tension in a material.

### 3.2 Direction of Non-Extension

Similarly to how the principal directions point in the directions of minimum and/or maximum strain, there can exist directions of non-extension. When referring to the directions of non-extension we assume that the material is locally two-dimensional. The concept of directions of non-extension in three-dimensional deformation is plausible, but will not be evaluated in this thesis. Along the directions of non-extension there is no extensional strain (however shear strain maybe present).

In Iberall’s description of LoNEs he states, “The twoâ€”fold extended mapping of such diameters are principal shear lines, here to be called 'lines of non-extension.' Along these two lines we may lay strands of "infinite modulus" (i.e., there is no stretch) [26].” This technique is also found in geology. Ramsay et al. quantifies the lines of non-extension directions [42].
The angle from a line is denoted as $\phi$ in the reference configuration, but as the material deforms the line creates the angle $\theta$.

From the principal strain directions the directions of non-extension can be calculated by Equation 3.8 where $\phi$ is the angle from the principal strain direction.

$$\phi = \tan^{-1}\left(\sqrt{-\frac{E_1}{E_2}}\right) \quad (3.8)$$

It is important to note that the angle $\phi$ will be numerically different if you use Green strain or Almansi strain representing the difference between reference and deformed configurations highlighted by Figure 3-2. To conceptually understand the Equation 3.8 we refer to the Finite Strain Ellipse and Mohr’s Circle in Figure 3-3.\[17,18,31,32\].

Note that directions of non-extension only exist if compression and tension are both present. Mathematically this is when the principal strains, $E_1$ and $E_2$, have opposite signs. This is illustrated by Figure 3-4 by three cases of deformation that can occur when considering the strain ellipse.

### 3.2.1 Derivation of Non-Extension Directions

The derivation shown here will relate the finite strain ellipse and Mohr’s circle. The derivation shows that the LoNE directions do not occur at the maximum shear di-
Figure 3-3: The Finite Strain Ellipse (a) and Mohr’s Circle (b). The ellipse shows how lines can develop called the Lines of Non-Extension (LoNE). There is no extensional strain along these lines, which is shown graphically in the ellipse, but also analytically in Mohr’s circle. LoNEs only develop when the two principal strains have opposite signs, which means the material is undergoing tension in one direction and compression in an orthogonal direction.

Figure 3-4: The strain ellipse is shown in three different cases. An original circle of material is deformed in case 1 with compression and tension, case 2 with tension in all directions and case 3 with compression in all directions. Note that the directions of non-extension only exist in case 1. [9]
rections as specified by Iberall. The maximum shear direction is always 45° from the principal strain, which is shown visually by Mohr’s circle. Figure 3-5 shows the finite strain ellipse and Mohr’s circle where \( \lambda_1 \) and \( \lambda_2 \) are the principal stretches and \( \lambda \) is stretch at a point on the ellipse. The direction of non-extension is denoted as \( \phi \). In the diagram \( \lambda = 1 \), which means it has no extension.

Using the equation of an ellipse the stretch, \( \lambda \), can be calculated at any point along the ellipse [42]

\[
\frac{x}{\lambda_1} \cos^2 \phi + \frac{y}{\lambda_2} \sin^2 \phi = 1
\]

\[
\lambda = \lambda_1 \cos^2 \phi + \lambda_2 \sin^2 \phi
\]  

(3.9)

To find the direction of non-extension set \( \lambda = 1 \) and solve for \( \phi \) using the trigonometric identity \( \cos^2(\phi) + \sin^2(\phi) = 1 \).

\[
1 = \lambda_1 \cos^2 \phi + \lambda_2 \sin^2 \phi
\]

\[
\cos^2 \phi + \sin^2 \phi = 1
\]

\[
\sin^2 \phi = \frac{1 - \lambda_1}{\lambda_1 - \lambda_2}
\]

\[
\cos^2 \phi = \frac{1 - \lambda_2}{\lambda_1 - \lambda_2}
\]

\[
\tan^2 \phi = \frac{\sin^2 \phi}{\cos^2 \phi}
\]

\[
\tan \phi = \sqrt{\frac{-(\lambda_1 - 1)}{\lambda_2 - 1}}
\]  

(3.10)

The principal stretches can be written as strain using the relations \( \lambda_1 = e_1 + 1 \) and \( \lambda_2 = e_2 + 1 \), which results in Equation 3.8

\[
\tan \phi = \sqrt{\frac{-e_1}{e_2}}
\]  

(3.11)

Note that the strains are the infinitesimal strains, which is the assumption that finite strain ellipse is small enough to have a homogeneous deformation.
Equation 3.8 can also be derived using Mohr’s circle. Referring to Figure 3-5, $R$ is the radius of Mohr’s circle and $w$ is the distance to the center of Mohr’s circle.

\[
\cos 2\phi = \frac{w}{R} \\
R = \frac{e_1 - e_2}{2} \\
w = e_2 + R \\
(3.12)
\]

\[
\cos 2\phi = \frac{e_1 + e_2}{e_1 - e_2}
\]

Using the trigonometric identities $\cos 2\phi = 2\cos^2\phi - 1$ and $\cos 2\phi = -2\sin^2\phi + 1$ we find

\[
\sin^2\phi = -\frac{1}{2} \left( \frac{e_1 + e_2}{e_1 - e_2} - 1 \right) \\
\cos^2\phi = \frac{1}{2} \left( \frac{e_1 + e_2}{e_1 - e_2} + 1 \right) \\
(3.13)
\]

then using $\tan^2\phi = \sin^2\phi/\cos^2\phi$ we arrive back to Equation 3.8

\[
\tan\phi = \sqrt{\frac{-e_1}{e_2}} \\
(3.14)
\]
3.3 Computing the Lines of Non-Extension

Iberall was the first to produce depictions of LoNE on the human body. His method was qualitative, but there has been research to calculate LoNE analytically \cite{9,18,31,60,61}. Up until now there has been one type of methodology to calculate LoNE, which I refer to as connection methods. These will be explained in greater detail in addition to a new method developed based on streamlines in this thesis.

3.3.1 Connection Methods

Connection methods are based on discreet data and connect the directions of non-extension together. The first method was developed by Wolfrum in 2006 \cite{61} as an extension of Bethke’s thesis. She examined the nearest neighbors of the non-extension directions and connected together the directions with a line. Since many possibilities exist, the line with the shortest distance was chosen to connect the lines together. Wolfrum’s method is illustrated in Figure 3-6.

This method was improved by replacing the line with a cubic spine that would smoothly connect the directions of non-extension together, however this methodology has not been published. Domingues improved this methodology by considering the angle between the directions of non-extension and choosing only to connect the lines together if the angle was within a certain threshold \cite{18}. To enhance the resolution of the calculation the triangular mesh was subdivided into smaller triangles.

Connection methods have two problems: 1) the result will always connect the nodes of the data mesh together which can be problematic if the resolution is limited and 2) the result will not be able to equal the analytic solution if only the nearest neighbors are considered. With resolution limited to a couple square centimeters it was difficult to get smooth results for LoNE that accurately depicted their contours. These problems are illustrated in Figure 3-7 when considering a homogeneous deformation that has an analytical solution for LoNE. Improvements could be made to the connection algorithms and considering the k-nearest neighbors, but instead I attempted to solve both problems simultaneously by using a streamline approach.
Figure 3-6: Directions from point A to B are examined and possible lines are drawn (left). After the line with the shortest distance is determined they are connected together (right) [61].

Ultimately this represents the transition from an algorithm based on discreet calculations to the assumption that the material can be assumed to be continuous and therefore integrated.

3.3.2 The Streamline Approach

A LoNE is a contour along the surface of material that remains tangential to the non-extension direction. If the LoNE directions are treated as a vector field with constant magnitude, the numerical integration of this vector field produces streamlines tangential to the vector field.

One mathematical complexity and limitation that continually arises in the context of LoNE mapping is that we only consider surface deformation of the skin. Skin has a thickness, but what we can measure is only the surface. Surface deformation presents the challenge that strictly 2D or 3D methods cannot be used for analysis. To overcome this difficulty a local coordinate system must be continually used that is normal to the surface. This complexity will continually come up in the mathematics.

Figure 3-8 illustrates the streamline approach. The directions of non-extension can be considered an un-directed vector field with two sets of vectors, the first and second directions of non-extension, which are shown in red and blue. In order to calculate the streamline a seed point must be selected. Each vector field is numerically integrated
Consider a material that undergoes a homogeneous deformation, meaning the strain field is the same everywhere. Because the deformation is homogeneous, the LoNE direction should be the same everywhere: locally and globally. Using a mesh connection algorithm that only considers the nearest neighbors will result in the a solution similar to the left figure. However the actual solution is the right figure. The LoNE field near the actual data point is correct, but globally different than the analytical solution.

from the seed point. The vector field is interpolated at each integration step, which allows the streamline to exist within each mesh element.

There are three choices that need to be made when calculating LoNEs as streamlines:

1. vector field interpolation method
2. numerical integration technique
3. seed points used in the integration.

Each one of these choices will be discussed in detail. In summary I chose a bilinear interpolation method. In the future, a more advanced method could be used such as b-splines. For numerical integration, I chose Euler’s method, the simplest numerical integration technique for ordinary differential equations. In the future a more accurate method, such as the Runge-Kutta method, could be used. To select seed points, I created an interactive computer tool to try different selections quickly.
Figure 3-8: An illustration of LoNEs as streamlines. The red and blue vectors are the directions of non-extension. By numerically integrating this vector field with seed points, LoNEs can be calculated.

**Vector Field Interpolation**

The streamline approach used here requires interpolation of the vector field at each step to determine the vector field at the integration point. The vector field was bilinearly interpolated using the k-nearest neighbors. Specifically, nine nearest neighbors were used. The k-nearest neighbors, S, are transformed to the local tangential coordinate system, $S'$ using Equation 3.15.

\begin{align*}
S' &= R^{-1}S \\
S' &= S' - \langle S' \rangle
\end{align*}

(3.15)

Once the k-nearest neighbors are in the local coordinate frame they are used to interpolate the components of the vector field. I chose a bilinear interpolation the components of the vector field, $u$. This process is completed using a least-squares approach, which is shown by Equation 3.16, where $\bar{u}(x, y)$ is the interpolated vector.
field.

\[
\mathbf{u}(x, y) = a + bS'_x + cS'_y + dS'_xS'_y
\]

\[
\mathbf{u}(x, y) = \begin{bmatrix}
1 & S'_{x1} & S'_{y1} & S'_{x1}S'_{y1} \\
\vdots & \vdots & \vdots & \vdots \\
1 & S'_{xk} & S'_{yk} & S'_{xk}S'_{yk}
\end{bmatrix}
\begin{bmatrix}
a \\
b \\
c \\
d
\end{bmatrix}
\]

\[
\mathbf{u}(x, y) = \mathbf{A}\bar{a}
\]

\[
\bar{a} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{u}(x, y)
\]

\[
\bar{u}(x, y) = \bar{a} + \bar{b}x + \bar{c}y + \bar{d}xy
\]

**Numerical Integration**

This interpolated vector field is used to calculate streamlines. In the streamline calculation the current position plus the velocity at that point multiplied by a time step, \(dt\), is the new position. Because the vector field is not technically a velocity field the time step used in the integration is not technically a time step, but can be considered a spatial parameter. This is also allowable because the vector field has constant magnitude everywhere. As long as the spatial step is smaller than the mesh size, an accurate interpolation should be achieved.

One additional complexity is that our vector field lies along a surface and is neither 2D or completely 3D. In order to solve this problem the integration must be carried out using a local 2D coordinate system and continually transforming the coordinates to 3D. This process is carried out in Equation 3.17.

\[
\mathbf{X}'_i = \mathbf{R}^{-1}\mathbf{X}_i
\]

\[
\mathbf{X}'_{i+1} = \mathbf{X}'_i + \bar{\mathbf{u}}(\mathbf{X}'_i)dt
\]

\[
\mathbf{X}_{i+1} = \mathbf{R}\mathbf{X}'_{i+1}
\]
Seed Point Selection

One downside of streamline vector field visualization is that the calculation requires selecting seed points. There is a large body of work on selecting seed points to produce equally spaced streamlines [33]. To avoid this complexity a seed point selecting tool was developed in MATLAB, which is discussed in detail in Section 3.3.3. The tool augments the ability of the MATLAB data cursor in order to select and then subsequently visualize each LoNE. Its interactivity allows the user to quickly add new seed points or remove seed points.

3.3.3 LoNE Discussion

In this thesis, the concept of streamlines was applied to calculating LoNE. It is a unique decision considering streamlines are not typically applied to solid mechanics, but it is a useful technique. If you consider LoNEs as streamlines, there are various techniques to visualize LoNE. Numerical integration techniques applied to seed points have the benefit of producing numerical space curves defined by Cartesian coordinates. Using this methodology the LoNEs can be exported to computer aided design (CAD) software. In the future, other methods should be used to visualize LoNEs. One promising method is surface Line Integral Convolution (surface LIC) [8]. This technique is more aligned with the field of computer graphics and is implemented in Paraview, a scientific data visualization suite. Surface LIC produces rasterized textures on the surface, by convolving a noisy image with a vector field. The technique has the benefit of visualizing the entire vector field instead of only the streamlines that connect to seed points. Seed point visualization may miss interesting features of the deformation. An example of surface LIC is shown in Figure 3-9.

In summary, the concept of the Lines of Non-Extension has various misconceptions. LoNE describes the deformation field of a material. LoNE should be thought of as contours not specific to human skin, but rather a function of deformation. This chapter derived the equations for the directions of non-extension from the finite strain ellipse and Mohr’s circle. These directions were treated as a vector field and inte-
Figure 3-9: An example of surface Line Integral Convolution. This technique produces rasterized textures on surfaces to visualize streamlines of flow fields. Source: [http://www.paraview.org/Wiki/ParaView/Line_Integral_Convolution](http://www.paraview.org/Wiki/ParaView/Line_Integral_Convolution)

grated using a streamline approach to produce quantitative lines of non-extension. These lines actually can extend slightly throughout a progressive deformation and are not strictly of “non-extension”.
Chapter 4

Methods

This chapter describes the experimental methodology used to measure human skin deformation on multiple subjects using digital image correlation (DIC). The deformation and strain of skin was measured at the human elbow joint, which has not been previously studied in the context of MCP space suit design. The upper body is important for everyday functional tasks and the elbow is a great joint to start at considering its similarities to the knee. Initial tests were performed on a small section of the elbow using a two-camera DIC system. The methodology and experiment was expanded to measure nearly half of the surface area of the elbow using a four-camera DIC system and the support of a mechanical rig to reduce experimental setup variability between subjects.

4.1 Experimental Setup

The experimental setup consisted of a multiple view camera system that simultaneously imaged the area of interest, a mechanical rig to align subjects with the camera system and measure elbow joint angle, and a novel speckle patterning technique for DIC.
4.1.1 DIC Camera System

Four cameras (Basler acA2500-14gm, GigE, monochromatic, 5 megapixel) were placed about the elbow joint in an arc configuration such that nearly 180° of the joint was viewable. Figure 4-1 shows the camera arrangement around the elbow. The GigE protocol was suggested to ensure reliable image capture and synchronization. USB 3.0 network cameras were still new and potentially unreliable at the time of purchase. An Edmond Optics 16mm focal length lens with low-distortion was used to provide a large field of view (FOV) of the joint. The simple field of view equation, $FOV = \frac{(sensor size)(distance to object)}{(focal length)}$, was used to initially size the system [47]. F-number 8 ($f/8$), which is the focal length divided by entrance pupil diameter, was used for image capture. This setting was found to provide an acceptable depth of field and brightness given the lighting conditions. Two 8-inch LED lights produce by Metaphase Technologies were used to illuminate the subject. The camera and lens are shown in Figure 4-2.

To perform DIC the cameras must be synchronized. The cameras were synchronized using hardware triggering. The trigger lines were wired in parallel from all cameras and a 5 Volt square wave was transmitted to the trigger input of the cameras via a USB data acquisition device with analog output (National Instruments USB-6001) to signal image capture. All image acquisition was performed in MATLAB (Mathworks Inc., Natick, Massachusetts) using the Image Acquisition Toolbox.

Prior to data collection, the camera system was calibrated using a black and white dot pattern of a known size, which was used to determine the intrinsic properties of the cameras and extrinsic properties of the stereoscopic geometry [20].

4.1.2 Elbow Rig

A mechanical rig was designed to assure consistency of the elbow positioning for all subjects. The elbow rig is shown in Figure 4-1 and specifically in Figure 4-3. The rig consists of two metal supports that can pivot. A protractor is used to measure the rig joint angle that is approximately the subject’s elbow joint angle, $\theta$. The pivot can
Figure 4-1: Four cameras and one light were attached to a tripod in an arc configuration to view the elbow joint. The cameras were focused at the elbow joint, the area of interest (AOI). The rig was attached to the wall so that the elbow joint of each subject remained in the camera’s AOI. The elbow joint angle is denoted as $\theta$ and could be fixed and measured by the rig using a protractor.

Figure 4-2: Cameras: Basler acA2500-14gm, GigE, monochromatic, 5 megapixel (left). Lenses: Edmund Optics 16mm, 100-500mm primary working distance, high resolution fixed focal length lens (right). Source: [www.baslerweb.com](http://www.baslerweb.com) and [www.edmondoptics.com](http://www.edmondoptics.com)
be locked so the subject can use the rig for positioning and not support the weight of the rig.

4.1.3 Speckle Patterning

To perform 3D-DIC, a unique surface texture is required that is sufficiently random [49]. A speckle pattern was applied to the skin to create a unique texture. White Crayola Tempera was painted on with a brush. After the white paint dried, black Crayola Tempera paint was applied using a 3D printed speckle stamp. This paint also needed to dry to avoid light reflections. These paints were used because they are non-toxic and easily washable. An example of the applied texture on skin and the 3D printed stamp is shown in Figure 4-4. This patterning was the result of various attempts to use other speckling techniques. Earlier techniques are shown in Figure 4-5 and include pen, eye-liner, spray paint, and temporary tattoos. These had various degrees of being identifiable, washable and easily applicable, but the speckle stamp was found to be optimal. Temporary tattoos were promising, but their material altered the deformation of human skin.

4.2 Experimental Procedure

Skin deformation and strain at the elbow joint of the human body was measured for six subjects (n=6, age: \( \mu = 23.2 \) years, \( \sigma = 2.8 \) years) using 3D-DIC. This experimental procedure was approved by the MIT Committee on the Use of Human Subjects (COUHES). The subjects were male and female, had various anthropometrics, and varying skin tones. The anthropometrics are listed in Table 4.1. The forearm length was measured from the lateral epicondyle to the styloid process of ulna, the upper-arm length was measured from the acromion to the lateral epicondyle, and the bicep and forearm circumference was measured at the largest circumference along the limb. Additional anthropometrics were recorded for each subject and are reported in Table A.1 of Section A.1.

The cameras remained fixed throughout the entire data collection period so only
Figure 4-3: Elbow mechanical rig constructed out of t-slotted framing. Center pivot allows full elbow range of motion. The upper arm rests on the bottom cylinder and the top cylinder is used for hand placement. The current configuration is for the right arm, but the rig can be reconfigured for the left arm. The rig mounts to the wall allowing repeatable placement of subjects.

Figure 4-4: Speckle pattern applied to the skin (left). The base coat is a white Crayola Tempera paint applied with a brush and the top is a black Crayola Tempera paint applied with a speckle stamp. The 3D printed speckle stamp was made on a Makerbot Replicator 2X out of ABS plastic. (right)

Table 4.1: Subject Anthropometrics (cm)

<table>
<thead>
<tr>
<th>Subject</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm length</td>
<td>26.5</td>
<td>29</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Upperarm length</td>
<td>34</td>
<td>33</td>
<td>28.5</td>
<td>32</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>Bicep circumference (relaxed)</td>
<td>31</td>
<td>29</td>
<td>22.5</td>
<td>29</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Bicep circumference (flexed)</td>
<td>34</td>
<td>32</td>
<td>24</td>
<td>30.4</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>Forearm circumference</td>
<td>27</td>
<td>25.5</td>
<td>19.5</td>
<td>26.5</td>
<td>27</td>
<td>26</td>
</tr>
</tbody>
</table>
one calibrations was necessary and all data would be collected in the same coordinate system.

Skin deformation was recorded for the lateral side of the right elbow joint. Each subject was positioned at increments of 15° joint angles using the mechanical rig starting at 0° elbow flexion to their maximum elbow flexion angle, which was typically 135°. All subjects were instructed to keep their palms facing upward throughout elbow flexion so that each subject’s musculature would be similar. Images were captured as a static pose at each joint angle.

The experimental procedure was as follows:

1. Subject reads and signs experiment consent forms
2. Experimenter explains the experimental procedure to the subject
3. Experimenter measures anthropometrics of the subject
4. Speckle pattern is applied to the skin in the area of interest
5. Subject is positioned in elbow rig
6. Images are captured at every 15° of elbow flexion
7. Experiment ends and subject may rinse off speckle pattern in sink

The COUHES experiment consent forms and experimental checklists are located in Section A.2 for reference.
4.3 Methods Limitations

The development of the experimental setup and method was the result of an iterative design and testing. Often, experimental methods that do not work are not reported, but for completeness I will mention these here. At first two webcams were used to collect images. The cameras could be calibrated, but produced results with unreasonable measurement errors. These errors mainly came from synchronization issues. In order to fix these problems cameras with hardware triggering were used. Machine vision cameras were used that did not have auto-focus, auto-cleaning, that may interfere with the calibration. Various speckle methods were tried. The speckle stamp proved to be the fastest, easiest, and most reliable method. It is still is tedious and requires practice. The camera system started out with two cameras. Simple tests were completed on the elbow without a mechanical rig. After the method was sound, two additional cameras were purchased. Handling the data from multiple cameras required special data processing techniques to be developed involving the calibration procedure. With four cameras only half of the surface of the elbow can be captured. In the future the camera system will be expanded to 8 cameras to collect the entire elbow joint.
Chapter 5

Data Analysis

The data analysis process consists of optical computer vision techniques, mechanics, mesh stitching and 3D visualization. This process uses a combination of commercial software and custom software for data acquisition, image processing, and visualization. The data analysis consists of four major steps that will each be described in the proceeding sections:

1. Calculate strain using 3D-DIC
2. Stitch datasets together from multiple stereoscopic camera pairs
3. Calculate LoNE
4. Analyze results of multiple subjects.

Digital image correlation calculates the full strain field of the surface of the object. Ultimately this strain field can be used to calculate the LoNEs as originally described and shown by Arthur Iberall [26]. This section describes the data analysis process after obtaining strain data through 3D-DIC to LoNE calculations in detail. Figure 5-1 shows an overview of the data analysis process.

5.1 3D-DIC

The images were initially acquired using the MATLAB (Mathworks Inc., Natick, Massachusetts) image acquisition toolbox. The images were processed using VIC-3D,
5.1.1 DIC Explanation

Even though a commercial code was used to perform 3D-DIC, this section overviews a basic explanation of the digital image correlation method. For a more complete explanation refer to textbooks by Schreier et al. [49] and Hartley et al. [20]. At first glance it appears that 3D-DIC is actually tracking the individual speckles. This seems like a logical step from infrared motion capture, but it is not the case. DIC actually performs correspondence between images by finding matching image subsets. The speckle pattern provides a unique texture and dataset to ensure subsets are matched correctly. Deformation and lighting conditions need to be accounted for in the matching process. Each subset corresponds to a single data point in cartesian space. As these subsets are followed throughout the deformation, a strain calculation can be performed on the point cloud by determining the deformation gradient.

Figure 5-3 shows an overview of the 3D-DIC method. In the reference frame the image is broken up into subsets. A stereocorrespondence, indicated by arrow “a”, is performed to triangulate each subset to determine the 3D location of the subset on
the actual body. Next, a deformation correspondence, indicated by arrow “b”, is performed between the reference frame and the deformed frame. Once a correspondence is made between all the frames a strain calculation can be performed to determine the deformation gradient of all corresponding points.

5.2 Dataset Stitching

In VIC-3D, the data processing process can only be performed with stereoscopic camera pairs, therefore this process is repeated twice for a four camera system (Camera 1-2 and Camera 3-4). The data was exported to MATLAB to be further processes.

First the data from multiple stereoscopic camera pairs must be combined into one data set. The data sets need to overlap. It is easiest to combine the camera pairs when the data is in the same coordinate system. This is achieved by setting the global coordinate system of each stereoscopic camera pair to a coordinate system defined by the calibration board seen in the first frame of all cameras. This was carried out in camera calibration procedure of VIC-3D. Once the data is in MATLAB, the two datasets for each stereoscopic pair are converted from a curvilinear grid data type into a triangular mesh (vertices and triangular faces). The two triangular meshes are stitched together at their overlap using an algorithm inspired by Wuttke [63].

Because there is overlapping data there is three possible options to combine the
Figure 5-3: 3D-DIC stereo and deformation correspondence. The correspondence of subsets for the stereo pair (arrow “a”) is performed in order to determine the 3D location of the subset on the object by triangulation. Then a deformation correspondence (arrow “b”) is performed between the reference frame and the deformed frame to track the motion of the subset. When every subset has been triangulated and tracked a strain calculation can be performed on the point cloud.

data sets: 1) keep all of the data and merge the data sets by re-meshing the data at the overlap, 2) average the overlapping data, or 3) only keep data that meets a certain criteria. Option 1 will cause the surface to be rough at the overlap. Option 2 may introduce uncertainty in the data by averaging quantities that do no exactly overlap. Option 3, although discards data, keeps the surface smooth and does not introduce uncertainty. Option 3 was selected for these reasons. Measurement “quality” was chosen to be the criteria for discarding data at the overlap. “Quality”, $q$, was defined as the inverse of the standard deviation of the matching error, $q = \frac{1}{\sigma}$. The matching error gives an estimate of how accurately subsets were matched. As $q$ grows the matching error decreases. Typically, near the edges of the data sets there is lower quality. Because the quality decreases at the edge of the data set, the magnitude of quality from the data sets will intersect. Data with the higher quality is kept. This process is graphically shown for a 1D data set in Figure 5-4. The data from Camera Pair 1-2 eventually has less quality than Camera Pair 3-4 and the data from Camera Pair 3-4 eventually has less quality than Camera Pair 1-2. At this intersection point, the data that is lower in quality is discarded and the two data sets are stitched
together. The actual data has two surfaces intersecting, which is shown in Figure 5-5. The quality intersection is used to cut the two data sets. The two data sets are then stitched together.

5.3 The LoNE Calculator Version 4

The Lines of Non-Extension (LoNE) Calculator has been in development at the MIT Man-Vehicle Lab (MVL) since 2005. The term “calculator” refers to a general body and a collection of source codes rather than a specific source code. Moving forward, with the movement of open source code and the widespread usage of software version control, the term “calculator” will hopefully refer to a specific source code with various branches and contributors.

For this thesis, a new LoNE Calculator was evolved from previous work to use data from digital image correlation (DIC) and implement the streamline approach. Based off of the previous work and additions to the LoNE Calculator, this code is called “LoNE Calculator Version 4”. All LoNE code has been developed in MATLAB. Initial code was developed by Bethke [9] and Wolfrum [61] to calculate strain from laser scan data (Version 1). For reference, Version 1 is shown in Figure 5-6. Domingues and Marreiros along with others wrote a code to calculate strain using motion capture data [17,31] (Version 2). Wessendorf updated Bethke’s code to calculate strain from dynamic motions using infrared motion capture data [60] (Version 3). This section will discuss how Version 4 works and the ideology behind the software’s structure.

5.3.1 Code Structure

At the core of the design of the LoNE code is the debate between the utility of a command line interface (CLI) and the graphical user interface (GUI). A simple web search can provide various opinions on the disadvantages and advantages of each. Previous LoNE codes were based on a GUI. A collection of various functions would be called from the GUI’s main implementation script. GUI’s are useful to visualize the strain data, but a significant portion of the LoNE code went into maintaining
Figure 5-4: 1D data stitching using quality example. This notional plot shows how the data from each camera pair overlaps and decreases in quality near the edge. All data in lower quality than the intersection point is discarded. The remaining data is stitched together to form the merged data set.

Figure 5-5: Quality data from two camera pair data sets. The XY axis are the local planar coordinates of the overlapping data. The quality is in the z-axis. The quality intersects in magnitude from the two data sets. This intersection is used to cut the data. The data is than stitched back together into one data set along this cut.
the GUI overhead. It was also difficult to automate repetitive actions. In Version 4,
the core LoNE code was changed to a CLI, where repetitive actions could easily be
automated by scripts. The data visualizations are implemented by GUIs where user
interaction was necessary, such as the Interactive LoNE Tool.

In order to achieve a CLI style code, Version 4 leverages object-oriented program-
ning, which is enabled by MATLAB’s ability to define and implement classes. There
are two major classes in Version 4:

- Data
- DataArray.

Each implementation of the Data class corresponds to each state of deformation.
For example, the elbow positioned at 0° flexion would correspond to Data object and
the elbow positioned at 15° would correspond to another Data object. The Data class
has methods that allow the data to be imported, analyzed, and visualized.

Listing 5.1 shows how one could use the MATLAB CLI to easily visualize principal
strain data, assuming the Data object, data, exists. Data has the method plot which
has a string input that specifies what data is plotted. The period allows a method
of the object to be called so that data.plot('ep1') actually calls the method plot
as defined by the Data class. Note: >> specifies the command being entered into the
MATLAB command line. For example, running the commands in Listing 5.1 would
produce the plot shown in Figure 5-7.
Listing 5.1: Command line example for plotting data

```matlab
>> figure
>> data.plot('epl');
>> title('First-Principal-Strain');
```

The DataArray class consists of an array of Data objects. An implementation of a DataArray class allows entire motions to be stored for each test trial, analyzed, and visualized. For instance, a DataArray object can have a method to create a movie for elbow flexion by calling the plotting functionality of each Data object stored.

A simple code example is shown in Listing 5.2 to illustrate how the Data class and DataArray class work together. First the strain data from VIC-3D must be imported. The VIC-3D data is saved into a matlab structure data file (.mat) and this file is parsed into Matlab by `getVICData()`. This data is meshed by a custom triangulation method, `triangulateVIC()`. Data objects are initialized by the VIC-3D data and then used to initialize the DataArray object.

Listing 5.2: Using Data and DataArray objects with VIC-3D data

```matlab
% loop over filenames
for i = 1:length(filenames)
    % get data from VIC-3D .mat files
    data = getVICData(filenames{i});
    % mesh data from VIC-3D
    [faces, points, data] = triangulateVIC(data);
    % initialize Data object with VIC-3D data and store ...
    object in array
    data_array(i) = Data(data, faces);
end
% Create instance of DataArray
d = DataArray(data_array);
```

The Data and DataArray objects are usually called from one main script although they can be directly operated on and manipulated by the CLI.
5.3.2 Numerical LoNE Calculation

This section describes how Equation 3.17 is numerically implemented in the LoNE Calculator Version 4. The code is shown in Listing 5.3. It is not much different than the usual implementation of Euler’s method, \( \bar{x}_{i+1} = \bar{x}_i + \bar{v}(\bar{x}_i)dt \), except that the integration is always in the local coordinate system. This is because the streamlines need to remain on the surface. The coordinates are transformed to the local frame, the velocity field is determined at the current position by interpolation, the position is projected into the future using the velocity, and the coordinates are transformed back to the global frame.
Listing 5.3: Numerical Integration of LoNE

```plaintext
% initialize integration
k = 1; % integration step
X(k) = X0; % global X coordinate seed point
Y(k) = Y0; % global Y coordinate seed point
Z(k) = Z0; % global Z coordinate seed point
% numerically integrate until user defined limit
while k < iteration_limit
    % Transform X to x: global to local coordinate system by ...
    % rotation matrix R and translation T
    x_vec = inv(R)*([X(k) Y(k) Z(k)])' - T;
    % store x_vec
    x = x_vec(1);
    y = x_vec(2);
    z = x_vec(3);
    % get velocity bilinear interpolation constants
    [b_u, b_v] = getBilinearInterpolationConstants(X(k),Y(k),Z(k));
    % Interpolate velocity field at current position
    % b: bilinear interpolation constants b
    u = b_u(1) + b_u(2)*x + b_u(3)*y + b_u(4)*x*y;
    v = b_v(1) + b_v(2)*x + b_v(3)*y + b_v(4)*x*y;
    % Forward Euler Integration in local coordinates
    x_new = x + u*dt;
    y_new = y + v*dt;
    z_new = 0; % set the local z to 0
    % Transform x to X: local to global coordinate system by ...
    % rotation matrix R and translation T
    X_vec = R*[x_new y_new z_new]' + T;
    % store the global coordinates of the trajectory
    X(k+1) = X_vec(1);
    Y(k+1) = X_vec(2);
    Z(k+1) = X_vec(3);
    % increment k
    k = k + 1;
end
```
5.3.3 The Interactive LoNE Tool

The Interactive LoNE Tool (ILT) is built on top of the LoNE Calculator Version 4. The ILT is a seed point selection tool that can be used to determine and preview LoNE geometry. Seed points are selected as starting points for the LoNEs and are used to integrate the directions of non-extension vector field.

The ILT can be invoked from the MATLAB command line or by scripting. An example is shown in Listing 5.4. A Data object, called data, has already been created and saved locally as data.mat. The ILT is invoked by calling interactivePlotStream(). This code snippet will produce the ILT GUI shown in Figure 5-8. The ILT augments MATLAB data cursor tool. The data cursor is used to select points on the surface to be used as seed points. Once the points are selected the tool will display the LoNEs, which is shown as the pink and light blue lines in Figure 5-8. These streamlines can be confirmed or erased until an appropriate set of lines are displayed. The tool will then save the streamlines to be quickly visualized later.

Listing 5.4: Numerical Integration of LoNE

```
1   >> load('data.mat');
2   % run Interactive LoNE Tool with lone option
3   >> data.interactivePlotStream('lone');
```

5.4 Data Flattening and Normalization

Visualizing three-dimensional data on a two-dimensional page is a continual challenge. It is also difficult to compare three-dimensional data between subjects that have varying anthropometry. In order to overcome both of these challenges a method was developed for flattening elbow data and then normalizing the data by anthropometry.

The flattening and normalization was achieved by placing the data sets in a cylindrical coordinate system where the cylindrical axis runs along the arm. The cylindrical axis is split into two sections: the upperarm and the forearm, which are defined by the distance from the elbow joint. The upperarm was normalized by the overall
Figure 5-8: Interactive LoNE tool for seed point selection that augments the MATLAB data cursor.
upperarm length and indicated by positive y-value. The forearm was normalized by the overall forearm length and indicated by a negative y-value. The circumference was used to normalize the x-axis of the data. The circumference was calculated by the arc-length of the data set along the circumferential direction of the cylindrical coordinate system. The circumference was then normalized by the elbow circumference of each subject. This simplifies the data comparison across subjects because the three dimensional geometric variation is removed.
Chapter 6

Results

The results section presents skin deformation data for the elbow joint. The preliminary results show skin deformation using a two camera DIC system. The lateral results of the elbow are shown for six subjects. In-depth results are shown for Subject A using a four camera DIC system, which shows nearly half of the lateral surface area of the elbow joint. Results from subjects A-F are shown. Finally, data was normalized to enable numerical comparisons between subjects. This normalization also allowed the data to be combined to show the average subject. Note that all strain data is Green-Lagrangian strain and shown in the undeformed reference frame unless otherwise specified.

6.1 Preliminary Results

Two stereoscopic cameras were used to determine if DIC was a feasible technology for measuring skin deformation. To test the concept, a section of the lateral side of the elbow joint was speckled on Subject D. Images were acquired quasi-statically such that the subject would pose at each position. Figure 6-1 shows the results of the deformation analysis throughout four deformation states. The commercial DIC software calculates the Green-Lagrangian strain tensor in a local coordinate system. The principal strain magnitudes, $E_1$ and $E_2$, are labeled and displayed in two separate rows of Figure 6-1. $E_1$ reaches 0.5 near the edge of the data set and
$E_2$ varies from -0.4 to 0.4. Both strain values decrease towards zero as moving away from the joint. The posterior side of the elbow experiences tension in both principal directions. The anterior side of the elbow experience compression in the longitudinal direction but tension in the circumferential direction. The direction of the principal strain components are also shown. The red vector represents the direction of $E_1$ and the blue vector represents the direction of $E_2$. Note that the vectors are undirected and are shown with unit magnitude. LoNE is also shown. The streamline of the first direction of non-extension is shown in red and the streamline of the second direction of non-extension is shown in blue. The differentiation in color for LoNE is only significant to make the figure intelligible. The light-blue area indicates where there is the lack of non-extension direction. This means that the skin is undergoing tension or compression in both principal strain directions. A pink star is used to indicate the where the elbow is located in the 2D raw image with association to the 3D surface.

### 6.2 Lateral Results

The data for Subject A is shown in Figure 6.2. The elbow joint angles are 0, 30, 60, 90° increasing from left to right. The data analysis is shown incrementally from top to bottom. The first row shows the the raw images taken from one of the four synchronous cameras. The second row shows the magnitude of the second principal Green-Lagrange strain. The surface is always represented in the undeformed configuration. The data shows that near the tip of the elbow the Green strain reaches 0.3. The third row shows the principal directions of the strain. The red is always used for the first principal strain direction and the blue is for the second principal strain directions. These directions are orthogonal. The fourth row shows the LoNEs that were calculated for the direction of non-extension. There are two LoNE directions which are shown by the red and blue lines. The light blue areas of the surface denote regions that do not have LoNE directions, which is when $E_1$ and $E_2$ have the same sign.

Principal directions can also be visualized as lines using the same methodology.
Figure 6-1: Five rows of data are shown that follows the data processing sequence. Each column indicates a different deformation state. First row: raw monochromatic images acquired from the left stereo image. Second row: first principal Green-Lagrangian strain magnitude, E1. Third row: second principal Green-Lagrangian strain magnitude, E2. Fourth row: directions of principal strain where red corresponds to E1 and blue corresponds to E2. Fifth row: LoNE streamlines obtained by integrating the directions of non-extension (not shown). The red streamlines correspond to the first direction of non-extension and the blue streamlines correspond to the second direction of non-extension.
Figure 6-2: Strain results of Subject A. The elbow joint angle increases from left to right in 30° increments from 0° to 90°. The data processing is shown incrementally from top to bottom. Row 1: the raw images from one of the four cameras, row 2: the magnitude of the second principal Green strain, row 3: the principal strain directions as vectors (red corresponds to the first principal strain and blue corresponds to the second principal strain), and row 4: the first and second LoNEs shown respectively in red and blue. The pink arrows are used to indicate how the data corresponds to the initial images.
that was applied to the directions of non-extension. These lines are referred to as
the lines of principal strain. Figure 6-3 shows the LoNEs and the lines of principal
strain projected onto the deformed configuration at 90° elbow flexion. The lines were
calculated using the strain field at 90° elbow flexion. It should be noted that the lines
of principal strain are calculated using a uniform strain field where the magnitude of
each principal direction is unity. This is to visualize the general directionality of the
field. In traditional fluids the magnitude of each vector would have to be taken into
account for the streamline calculation.

Figure 6-4 shows an enlarged data set for Subject A at 90° elbow flexion. The
original image is shown for reference as well as the image at the current state of
deformation. Directional strain quantities are shown as well as their streamline coun-
terparts.

The location of the data stitching is visible in Figure 6-4 by the discontinuity in
strain magnitude in the upper left corner. $E_1$ and $E_2$ near the olecranon approach
0.5 and 0.3 respectively. $E_2$ approaches a minimum of -0.4 within the cubital fossa.
LoNE is shown along with areas that do not have non-extension directions. This
occurs when $E_1$ multiplied by $E_2$ is greater than 0 or when $E_1$ and $E_2$ have the same
sign and the skin is undergoing compression or tension in both principal directions.

6.3 Subjects A-F

The strain field for subjects A through F was measured. The range of principal strain
at 90° elbow flexion is reported in Table 6.3 which shows the large range of strain
experienced by human skin.

The data for each subject during one trial at 90° elbow flexion is shown in Figure

<table>
<thead>
<tr>
<th>Subject</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_i$ (min)</td>
<td>-0.41</td>
<td>-0.43</td>
<td>-0.34</td>
<td>-0.44</td>
<td>-0.42</td>
<td>-0.49</td>
</tr>
<tr>
<td>$E_i$ (max)</td>
<td>0.46</td>
<td>0.36</td>
<td>0.49</td>
<td>0.60</td>
<td>0.42</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 6.1: Range of Principal Strain
Figure 6-3: LoNEs (left) and lines of principal strain (right) are shown in the deformed configuration at 90° elbow flexion. The red and blue represent the first and second directions of non-extension for the LoNEs and first and second lines of principal strain.

6-5. The data, although 3D, is being viewed from a side angle perspective to visualize most of the data simultaneously. Data for a single subject is shown in each row. From the raw image snapshots, the varying anthropometrics can be seen. Each subject experiences similar principal strain magnitudes. Interestingly the directionality of the strain appears to be different for subjects E-F from subjects A-D. This is reflected in the Lines of Principal Strain (LoPS) column as well as the LoNE column. Instead of the strain field being smooth it appears to bend down towards the back of the elbow. This subject snapshot shows that although the strain fields are qualitatively similar in magnitude there are visible differences in the directionality of the strain field.

The LoNE maps for six subjects are shown in Figure 6-6 in a 3D perspective view. LoNE was calculated at 90° elbow joint flexion for each subject using similar locations for the seed points. The LoNEs are shown in the undeformed configuration. The data for is not scaled between subjects so the results presented are in their original coordinate system with a translation applied to visualize each subject separately.

6.4 Data Normalization

The strain data at 90° elbow flexion was flattened to two-dimensions and normalized by anthropometry. This flattening and normalization procedure is detailed in Section
Figure 6-4: Detailed strain measurements of Subject A. The raw images are shown for the reference configuration at 0° elbow flexion and the current deformation state of 90°. Principal strain, $E_1$ (a), and $E_2$ (b) are shown along with their direction (c). The principal directions were used to compute lines of principal strain (d). The non-extension directions are also shown (e) with the corresponding LoNEs (f). Note that there is not always non-extension directions which is shown in light blue. The pink arrows are used to indicate how the data corresponds to the initial images.
5.4 The principal strain magnitudes are shown in Figure 6-7 and the LoNEs are shown in Figure 6-8. The data covers approximately 40% of the forearm and upperarm. The data also covers approximately 40% of the circumference of the elbow. An interesting note is that Subject C appears to have a longer arm, but in fact that particular subject had a smaller arm where more data could be collected with respect to the length of the forearm and upperarm.

The data can be compared between subjects on a point by point basis after normalization. The principal strain from six subjects was averaged at each point in the data set for 90° elbow flexion. The average strain values represent the “mean” subject. If data was not present for anyone of the six subjects the data for the “mean” subject was left blank. Figure 6-9 shows the average principal strain magnitudes. The strain field is continuous, but there are various holes, especially near the lateral epicondyle. These holes are from the sharp curvature at the brachioradialis muscle that makes the region difficult to image from the camera’s point of view.

The standard deviation of the aggregate subject data was also computed for each principal magnitude in Figure 6-10. The interesting trends to notice is that the standard deviation of the data reduces when moving away from the elbow joint. The most variation is at the back of the elbow, the edges in general, and where the data is stitched together. The variation at the stitching edge is most likely a manifestation of the data being more variable at the edge when DIC has high reprojection errors from the extreme viewing angle.

There are limitation of the normalization techniques used here. It is assumed that elbow can be approximated by a cylindrical coordinate system. It assumes that the normalized arm length allows data to be compared between subjects, which means arms have linear geometric scaling between subjects, which is not necessarily the case. Similar limitations arise from normalization in the circumferential direction. There is also significant difficulty to compute average directional strain information such as LoNE. This is because LoNE implicitly depends on the local coordinate system of each subject. In order to compute an average LoNE map an average local coordinate system would have to be calculated. At this point, significant work has
to be completed to check these concerns. If these assumptions are reasonable then it would be feasible to perform statistical tests on regions of the data to determine if subjects are statistically different in various regions. As of now six subjects is a small sample size to conclude generalizable results. This methodology can be used to assess more subjects in the future.

6.5 Results Discussion

6.5.1 Subject Variability

Human subject testing immediately provokes the question of within and between subjects variability, especially when working with biological data such as skin deformation. This thesis was a development of skin deformation measurement technology. As of now six subjects is a small sample size to conclude generalizable results about the elbow joint. However this methodology can be used to assess this question in the future. Some of the major variables to be considered in future studies are:

- Anthropometrics
- Subject age
- Skin tone
- Use of topical skin care products
- Skin damage such as scars, cuts, and burns
- Environmental conditions such as humidity and temperature.

These variables could affect the strain measurement results. To add to the complexity, many of these variables vary over time within subjects. Even exercise could cause muscles to change size and affect skin deformation. By examining the directionality of LoPS and LoNE with subjects E-F compared to subjects A-D it is certain that the cause of strain direction variability needs to be studied in further detail by controlling some of the major variables. Depending on the scientific hypotheses different variables should be controlled in future experiments.
Experimental test conditions can also affect results. Early tests showed that wrist pronation and supination can alter skin deformation at the elbow joint. This means that should positioning could also influence results near the elbow joint. More generally, joint position influences skin deformation at other joints. This thesis did not assess variability of repeated measurements, but should be an early future experiment.

Between subjects results comparisons are more difficult because strain data is dependent on the geometry of the human subject. Every subject has varying anthropometrics, which makes it difficult to directly compare data sets based on cartesian location. The elbow is fairly simple one-degree of freedom joint that is roughly cylindrical. This made it possible to normalize the data by limb length and circumference of each subject as described by Section 6.4. A generalizable process needs to be developed for surface normalization at any location on the body if subject data is to be directly compared. Another method of comparing subject deformation can be manually segmenting the body into sections and comparing gross strain values such as maximum or minimum principal strain, average strain, or direction of principal strain. This is a necessary first step to assess scientific hypotheses with statistical tests.

6.5.2 Measurement Quality

Making measurements on a dynamic surface of the human body using stationary cameras is difficult. If a large number of cameras is not available, significant effort goes into determining camera placement to best image the regions of interest on the human body. The elbow is a simple one-degree of freedom joint, which allows optimum camera placement easily determinable. With this in mind, it is still difficult to capture the entire surface of the elbow. Figure 6-6 shows data drop outs near the brachioradialis muscle because that section for some subjects has a sharp initial curvature not visible by the cameras. One solution could be to simply add more cameras, but given typical budget constraints initial work should be pursued to simulate the location of the cameras given a specific movement. This could be used to determine optimum camera placement to minimize data drop out.
Another topic for discussion is data stitching. This thesis used a brute force approach of determining the data overlap, removing data with less quality, and adding mesh faces to stitch the data together. This resulted in visible stitching artifacts, shown when looking closely at Subject A and B along the longitudinal direction in Figure 6-7. These discontinuations in the strain field can result in discontinuations or jumps in the LoNE streamline calculation. To improve the stitching algorithm, the data from both camera sets should be incorporated together by averaging or smoothing to remove discontinuations.

### 6.5.3 Assessing Error

The measurement error was assessed for DIC on skin deformation. Before determining the error of the system it is important to understand how much error is tolerable. It is currently unknown how much strain error is tolerable to maximize mobility and minimize energy expenditure, however an upper bound for strain error can be estimated by considering tolerable pressure variation based on physiology. The tolerable strain error based on pressure error was calculated to be 0.001 or approximately 5% of the total strain required to produce 29.7 kPa of pressure at a fifth percentile male bicep. A detailed explanation of this calculation is in Appendix.

Given this upper bound for strain error, an analysis on DIC was performed to estimate the strain error of the measurement system. The general method of error analysis is to image an object of a known deformation field and compare the empirical strain values from DIC to the analytical strain field of the object on a point by point basis. First, the error was determined for a homogeneous 2D deformation. A speckle image was analytically deformed in an image editing program to stretch in two orthogonal directions. The results are shown in Figure 6-11. Second, the error was determined for a non-linear out of plane deformation. The undeformed object was 3D printed with a speckle pattern on a Makerbot Replicator 2X out of ABS plastic. The undeformed object was deformed analytically in MATLAB and then 3D printed. The results are shown in Figure 6-12. The strain error is reported in Table 6.5.3. The 2D analysis shows that the DIC system is below the tolerable strain error.
However, the strain errors grow substantially for the 3D analysis. This is most likely from using a strain field with small principal strain magnitudes on an object with manufacturing imperfections. These strain magnitudes are, although visible in the deformation object, below the manufacturing tolerance of the 3D printer. Further studies should assess strain error in 2D non-linear deformations as well as explore methods to produce accurate analytically deformed 3D objects.

Table 6.2: Strain error results. Root mean square error (RMSE) and mean percent error (MPE) are reported between the analytical deformation and the empirical strain measurements.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Strain</th>
<th>RMSE</th>
<th>MPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D Analysis</td>
<td>$E_1$</td>
<td>0.0001</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>0.0001</td>
<td>2%</td>
</tr>
<tr>
<td>3D Analysis</td>
<td>$E_{11}$</td>
<td>0.003</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>$E_{22}$</td>
<td>0.005</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>$E_{12}$</td>
<td>0.004</td>
<td>89%</td>
</tr>
</tbody>
</table>
Figure 6-5: Strain fields of subjects A-F at 90° elbow flexion. The principal strain magnitudes, $E_1$ and $E_2$ are shown along with Lines of Principal Strain (LoPS) and Lines of Non-Extension (LoNE). A horizontal scale is shown for metric distance comparisons. Raw image snapshots are also shown for each subject. The pink arrows are used to indicate how the data corresponds to the initial images.
Figure 6-6: LoNEs for multiple subjects are shown for when the elbow is at 90°. The results are shown on the undeformed configuration. The seed points used for each subject were similar locations. There are two LoNE directions which are shown by the red and blue lines. The light blue areas of the surface denote regions that do not have LoNE directions. The pink arrows are used to indicate how the data corresponds to the initial images.
Figure 6-7: Normalized and flattened elbow principal strain magnitudes at 90° flexion. The y-axis is the distance from the elbow joint normalized by the upperarm and forearm length of each subject. The x-axis represents the circumference of the data normalized by the overall elbow circumference of each subject.
Figure 6-8: Normalized and flattened elbow LoNE at 90° flexion. The y-axis is the distance from the elbow joint normalized by the upperarm and forearm length of each subject. The x-axis represents the circumference of the data normalized by the overall elbow circumference of each subject.
Figure 6-9: The “Mean” Subject. The principal strain magnitudes from each of the six subjects was averaged on a point by point basis in the normalized and flattened coordinate system.
Figure 6-10: The variability of the “Mean” Subject. The sample standard deviation of the principal strain magnitudes from each of the six subjects was computed on a point by point basis in the normalized and flattened coordinate system.

Figure 6-11: A flat image was analytically stretched homogeneously in two directions. The original images of the object are shown. The analytical $E_{11}$, which is homogeneous across the object, is plotted next to the empirical results from 3D DIC.
Figure 6-12: A flat plate with thickness was analytically buckled and created using a 3D printer. Sketches of the deformation are shown along with the original images of the object. The analytical $E_{11}$ is plotted next to the empirical results from 3D DIC.
Chapter 7

Discussion

This chapter discusses this thesis’ contribution to the literature, limitations of the study presented, a discussion of ideas to use this data to make MCP suits, and future work.

The primary goal of this thesis was to develop a methodology to quantify strain and deformation of human skin to inform how to make a mechanical counter pressure space suit that maximize mobility and minimizes energy expenditure. This goal was driven by three research objectives: measure strain at a spatial resolution less than 1 cm\(^2\), develop a rigorous method to compute the Lines of Non-Extension, and examine the variation of skin strain and LoNE on multiple subjects.

7.1 Contributions

7.1.1 Research Objective 1

Research Objective 1 was to measure human skin strain at a spatial resolution less than 1 cm\(^2\). Using 3D DIC the spatial resolution of strain measurements was on the order of 1 mm\(^2\). This is shown in Figure 7-1 by examining the size of the mesh elements in the data from Section 6.1. The mean and standard deviation of the mesh area faces is reported in Table 7.1.1. The millimeter scale mesh size is achieved by how DIC computes the displacements. The original image is broken down into small
subsets of pixels. Subsets actually overlap, which creates increased resolution beyond simply dividing the image by subset size.

Although 3D DIC can achieve a mesh size smaller than 1 cm² it requires targeted camera placement to ensure the cameras are close enough to the subject to image the skin, but far enough away to capture the movement through the entire range of motion. This becomes a challenging problem if you want to simultaneously image the entire human body. Using many cameras can solve this problem, but requires significant data processing and increases the cost of the system. However, 3D DIC will continue to become cheaper an easier to perform with decreasing costs of imaging systems and the development of open source software tools.

7.1.2 Research Objective 2

The second research objective was to determine a mathematically rigorous method to compute LoNE throughout a progressive deformation. This was achieved using a streamline approach as described by Section 3.3.2. This method is a continuous approach that is not as affected by data resolution, mesh type, or mesh connectivity as much as connection methods. To showcase this computational ability, Figure 7-2 shows the LoNEs in black with the finite strain ellipse method projected onto the data set to highlight how Iberall’s qualitative method can now be achieve quantitatively. Through this rigorous assessment of LoNE it was determined that the LoNE map is not exactly the same for each state of deformation although it is similar. This has been shown by this thesis for a one degree of freedom isolated joint movement, but needs to be explored further for functional tasks. This is important because it is a critical assumption of LoNE that lines exist on the body that do not extend during

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>μ</td>
<td>0.48 mm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ</td>
<td>0.05 mm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-faces</td>
<td></td>
<td>20138</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1: Mesh Area Info
Figure 7-1: The mesh area of the preliminary results shown in Section 6.1 was examined to show that 3D DIC was computing the strain with a mesh resolution less than 1 mm².

motion. The LoNE concept should be altered to state specifically that lines exist on the body that minimize extension and compression during specific motions, but these lines may not necessarily have no extension or compression throughout the entire range of motion.

7.1.3 Research Objective 3

The third research objective was to examine the variation of skin deformation, strain, and LoNE between multiple subjects. This was examined in Section 6.4 by normalizing elbow data for multiple subjects. Some subjects appear to have similar strain maps, especially with regards to principal strain magnitude, but the directionality of the deformation can vary more greatly. This can be from uncontrolled variables in this data set, which are discussed in Section 6.5.1. LoNE mapping can also be variable because of the streamline approach. The streamline ending location becomes more variable the further the vector field is integrated away from the seed point. Although the data was averaged across multiple subjects, a formal statistical analysis was not performed. Given the focus of this thesis on the development of the measurement technique future work should examine scientific hypothesis of subject variability validated by inferential statistics.
7.1.4 Hypotheses

Digital image correlation can be used to measure skin deformation at a resolution higher than motion capture systems that were previously used. Using this higher resolution data this thesis developed a rigorous method to compute LoNE based on streamlines. From a broad perspective this confirms Hypothesis 1 from Section 1.3.1 of this thesis. With regards to Hypothesis 2 from Section 1.3.2 it was qualitatively shown that LoNE has a similar pattern between various subjects, but still is inherently variable. This is especially true from Subject E-F, which displayed principal strain directions inverted to Subjects A-D. This thesis did not go as far as quantifying the variability between subjects. It may still be possible to do so, but further work needs to be developed to normalize subject data in a way that is numerically comparable.

7.2 Making MCP Suits from Strain Fields

One of the primary focuses of this thesis was to determine how to make a MCP space suit that maximizes mobility and minimizes human energy expenditure. By measuring human skin deformation there is still not a one-to-one correlation of how this data should be used to make an MCP suit. Making a suit is an engineering
challenge, but has a significant design component. In order to make a tight fitting suit that is intimately interacting with the surface of the human body with large pressures, the suit should be synonymous with a second skin. The second skin should be similar to human skin that it will have a pre-tension that applies pressure and it should move with the body to not effect human motion. The designer and engineer can be informed by skin deformation visualizations. One example of how skin strain and LoNE mapping can be used to make an MCP suit is shown in Figure 7-3. Various materials could be used to match the magnitude of deformation of human skin. Areas with larger deformations should have materials that are less stiff to not adversely affect mobility. The directionality of the strain field could be used to align and orient fabrics or material properties. The LoNE map could be used to determine how the fabric should be fused or sewn together.

Mobility and energy expenditure are often the main variables discussed for space suits. These metrics can be fairly quantified. Few studies have actually quantified the amount of increased mobility and decreased energy expenditure when using MCP suits, the most recent being from Ruckman et al. [48]. Energy expenditure is difficult to quantify without a fully functioning engineering prototype and vacuum chamber testing. This type of full-scale testing has not been conducted since Annis and Webb in 1971. As a first step, mobility testing should be conducted at component level. Although MCP donning and doffing methods are being developed [21–24], initial tests on garments that require donning and doffing assistance from experimenters should be examined for mobility. Although mobility should be improved without gas pressurization, the selection of an overly stiff material for MCP, could also cause MCP suits to be highly immobile. Based off of the elbow data presented in this thesis a reasonable next step would be to conduct component level testing of the elbow joint, which can then be applied to knees.

Although subjective metrics such as “comfort” and “fit” are not often highly considered in engineering applications, any space suit needs to emphasize these metrics. This is especially true for an MCP suit that interacts closely with the skin. Subjective comfort can determine whether or not an astronaut will wear garments. A
Figure 7-3: A conceptual sketch of second skin garment concept is shown for the elbow. Different colors highlight varying material properties. The principal strain directions can determine fabric alignment. The fabric is joined at the LoNE to reduce deformation along seams.

typical example of this is the Russian Pingvin “Penguin” suit. This suit was designed to provide increased body loading during long duration space flight, but is deemed uncomfortable by various astronauts and cosmonauts. Matching the deformation of the suit with the deformation of the human body should reduce friction and increase comfort to provide a garment that is wearable for extended periods of time.

7.3 Challenges and Limitations

There are various limitations of this research. The first limitation is the small subject size. Now that this methodology has been developed this thesis can provide pilot data to influence the development of a larger human subject experiment. With a small number of subjects, it has been shown that the directions of principal strain can vary in visually obvious ways. This thesis only looked at the isolated joint movement of the elbow, but this is an extremely limited subset of motions. Isolated joint motions can validate component level testing, but functional tasks are more relevant to space suit operations. A significant challenge moving forward is how to position cameras and lighting for a wide range of functional tasks. A motion capture room configuration where many cameras are mounted around the perimeter of the ceiling could be reasonable. Another significant challenge will be determining the best method
to process data from many cameras. This has been researched for reconstruction of static scenes. One example, is simultaneous localization and mapping (SLAM) used by autonomous vehicles to map out the environment, but is not as well determined for an environment that is dynamically stretching and deforming. Strain is typically mapped to the initial reference configuration, but there is human joint motions that cause new information to appear throughout a deformation. For example your underarm will be exposed after shoulder flexion. This leads to a more general problem of the inability to track deformation after the surface disappears from the line of sight of the camera. As the elbow flexes passed $90^\circ$ the skin starts to buckle and fold. At this point the strain can no longer be measured using DIC. Wearable sensors maybe the only solution to measure deformation within buckles and folds.

This thesis examined the error of strain measurements in 2D and 3D. However the 3D strain error technique showed large errors. An additional limitation of this study is how variable the strain error is in 3D configurations. Fundamentally, optical DIC can only measure in-plane surface deformation because it can only see the surface of the object. It may be feasible to measure out-of-plane skin deformation given the development of volumetric DIC used on computed tomography (CT) and magnetic resonance imaging (MRI) [49, 209].

Another limitation is that DIC only measures strain and deformation. To understand the mechanics of skin deformation there needs to be a non-intrusive method to measure stress along the surface of the skin. If stress can be measured, the anisotropy of skin can be determined. Pressure production in MCP space suits corresponds to the required stress traction on the surface of the skin. Without understanding the anisotropy of skin, it is difficult to understand how the skin will deform with the applied pressure.

7.4 Direction for Future Research

Developing MCP space suits from skin strain mapping has various future directions. This thesis has build upon various techniques developed to quantitatively determine
LoNE. Given the streamline approach there is now a quantitative method to map LoNE as well as various other deformation quantities. There are four future research topics that need further consideration to develop MCP suits with regards to mobility and minimum energy expenditure:

- Assessment of within and between subject skin strain variability for functional tasks
- Determination of tolerable MCP pressure variations
- MCP textile patterning and material construction
- Quantitative mobility and energy expenditure assessments of MCP garment components and garment assemblies.

With regards to assessing skin strain variability, this thesis should be considered initial methodology and pilot data collection for a designed human subjects experiment to assess skin strain variability. This thesis points out various variables that affect skin deformation. If MCP space suits require skin deformation data, it will become unreasonable to measure every individual subject. An analysis of variability should aid the development of a model to predict skin deformation fields. This will most likely be grounded on solid mechanics simulation, particularly the finite element method.

In addition to the variability of human skin strain within and between subjects, it is essential to understand the tolerable variation in mechanical counter pressure produced on the skin. Pressure production for MCP suits is caused by a stress around a radius of curvature. This stress corresponds to a particular strain depending on the properties of material used. Human movement will inevitably cause additional deformation of the material, which will affect the applied pressure. Understanding the tolerable pressure variation will allow better suit design. Effects of pressure variations have been previously reported [44, 53, 55], but it is still not clear how much MCP can vary across the garment and at different locations on the body.

MCP textile patterning is one of the largest design questions. It is difficult to create textile patterns from three-dimensional data. It is conceivable that and un-
derstanding of tolerable pressure variation and the human skin strain field can be translated into these patterns, but significant research should be pursued to understand this problem.

Given that future MCP garments will be developed there needs to be methodology to quantitatively compare mobility between garments. There are few mobility tests of MCP space suits to date. In order to prove mobility improvements these tests need to be conducted such that they can be compared to gas-pressurized space suits.

7.5 Final Conclusions

Historically, all human spaceflight programs that required EVA have used gas-pressurized space suits. In order to improve mobility various joint design techniques have been developed, but these techniques either alter natural human mobility or still cause fatigue and exhaustion. For these reasons the current space suits are problematic for planetary exploration [27]. An alternative concept for space suit design is MCP, which could reduce fatigue and improve mobility. This thesis extends the research in MCP space suits by providing a fundamental method to quantify human skin deformation and strain at joints. It provides a novel application of streamlines to calculate the Lines of Non-Extension as well as a rigorous assessment of LoNE. This thesis provides data for the human elbow joint for multiple subjects. These results show the viability of the methods developed throughout this thesis. This data and method can be used to create second-skin garments. This data and techniques can be used, not only for MCP suits, but also to develop and improve any garment, wearable device, or wearable sensor that intimately interacts with the surface of the human body.

If you want to live, explore, and run on Mars, space suits need to become as natural and as enabling as clothing here on Earth.
Appendix A

Experiment Procedures

A.1 Anthropometrics

All recorded anthropometrics for experimental testing are shown in Table A.1 in centimeters. These anthropometrics were recorded using the Experimental Checklists. Refer to the checklist for a diagram of anthropometric locations.

<table>
<thead>
<tr>
<th>Subject</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm length</td>
<td>26.5</td>
<td>29</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Upperarm length</td>
<td>34</td>
<td>33</td>
<td>28.5</td>
<td>32</td>
<td>29</td>
<td>33</td>
</tr>
<tr>
<td>Bicep circumference (relaxed)</td>
<td>31</td>
<td>29</td>
<td>22.5</td>
<td>29</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Bicep circumference (flexed)</td>
<td>34</td>
<td>32</td>
<td>24</td>
<td>30.4</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>Forearm circumference</td>
<td>27</td>
<td>25.5</td>
<td>19.5</td>
<td>26.5</td>
<td>27</td>
<td>26</td>
</tr>
<tr>
<td>Wrist circumference</td>
<td>17.5</td>
<td>16</td>
<td>14</td>
<td>17</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>3/4 Forearm</td>
<td>21.5</td>
<td>17.5</td>
<td>14</td>
<td>19</td>
<td>17</td>
<td>18.5</td>
</tr>
<tr>
<td>1/2 Forearm</td>
<td>24</td>
<td>24</td>
<td>17</td>
<td>23</td>
<td>20.5</td>
<td>22</td>
</tr>
<tr>
<td>1/4 Forearm</td>
<td>28.5</td>
<td>27</td>
<td>20</td>
<td>26</td>
<td>23</td>
<td>25.5</td>
</tr>
<tr>
<td>Elbow Circumference</td>
<td>27</td>
<td>26</td>
<td>22</td>
<td>27.5</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>3/4 Upperarm</td>
<td>31</td>
<td>28</td>
<td>21</td>
<td>26.5</td>
<td>25.5</td>
<td>26.5</td>
</tr>
<tr>
<td>1/2 Upperarm</td>
<td>31</td>
<td>30</td>
<td>22.5</td>
<td>30</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>1/4 Upperarm</td>
<td>36.5</td>
<td>39.5</td>
<td>26</td>
<td>33</td>
<td>37</td>
<td>32.5</td>
</tr>
</tbody>
</table>
A.2 Human Subject Test Forms

These experimental checklists were used to collect data from each subject during skin strain measurement tests. The forms ensured all anthropometric data was taken and all experimental procedures were followed for each subject.
Measuring Human Skin Deformation and Strain
MIT Man Vehicle Lab
COUHES Protocol #1404006347
Prof. Dava Newman (dnewman@mit.edu)
Edward Obropta (eobropta@mit.edu)

Experiment Checklist

Date: __________

Test ID: __________

Subject ID: __________

___ Subject Consent Form
___ Measure Subject Anthropometrics
___ Mark ½ Forearm and ½ Upper Arm
___ Put on Arm Band
___ Paint Subject
___ Adjust Rig
___ Check Camera Field of View
___ Check Camera Calibration
   Calibration Directory: /2014-xx SUBJECT-xx_trial-xx/calibration-
___ Wait for paint to dry
___ Remind subject of wrist position on rig
___ Acquire Images
   Joint: 0 __ 15 __ 30 __ 45 __ 60 __ 75 __ 90 __ 105 __ 120 __ 135 __
___ Copy Images to Data Drive
___ Backup images to mvl-server
Measuring Human Skin Deformation and Strain  
MIT Man Vehicle Lab  
COUHES Protocol #1404006347

Investigator: Prof. Dava Newman (dnewman@mit.edu)  
Co-Investigator: Edward Obropta (eobropta@mit.edu)

**Subject ID:** ____________________  
**Last Name:** ____________________  
**First Name:** ____________________  
**Email:** ____________________  
**Date:** ____________________  
**Age:** ____________________

**Anthropometrics**  
Units in centimeters

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forearm Length</td>
<td></td>
</tr>
<tr>
<td>Upperarm Length</td>
<td></td>
</tr>
<tr>
<td>Wrist Circ (967)</td>
<td></td>
</tr>
<tr>
<td>Bicep relaxed (113)</td>
<td></td>
</tr>
<tr>
<td>Bicep flexed (111)</td>
<td></td>
</tr>
<tr>
<td>Forearm (369)</td>
<td></td>
</tr>
<tr>
<td>¾ Forearm Circ (1)</td>
<td></td>
</tr>
<tr>
<td>½ Forearm Circ (2)</td>
<td></td>
</tr>
<tr>
<td>¼ Forearm Circ (3)</td>
<td></td>
</tr>
<tr>
<td>Elbow Circ (4)</td>
<td></td>
</tr>
<tr>
<td>¾ Upperarm Circ (5)</td>
<td></td>
</tr>
<tr>
<td>½ Upperarm Circ (6)</td>
<td></td>
</tr>
<tr>
<td>¼ Upperarm Circ (7)</td>
<td></td>
</tr>
<tr>
<td>0 Upperarm Circ (8)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Strain Error

B.1 Determining Tolerable Strain Error

Starting from the thin-walled pressure vessel assumption where $P$ is the mechanical counter pressure, $\sigma_h$ is the hoop stress in the fabric, $t$ is the fabric thickness, and $R$ is the limb radius:

$$P = \frac{\sigma_h t}{R}.$$  \hfill (B.1)

Assuming that the fabric is perfectly linearly elastic with Young’s Modulus, $E$, and hoop strain, $\epsilon_h$, the stress-strain relationship is

$$\sigma_h = E \epsilon_h.$$  \hfill (B.2)

By combining these equations the fabric strain can be related to the counter pressure as,

$$\epsilon_h = \frac{PR}{Et}.$$  \hfill (B.3)

Assuming there is an error in the strain measurement $\epsilon_{error}$ that produces a pres-
sure error $P_{\text{error}}$ the equation becomes

$$\epsilon_h + \epsilon_{\text{error}} = \frac{(P + P_{\text{error}})}{Et}. \quad (B.4)$$

If it is assumed that the system is designed properly only the error needs to be considered:

$$\epsilon_{\text{error}} = \frac{P_{\text{error}}R}{Et}. \quad (B.5)$$

Assuming $t = 5$ mm from previously determined mobility requirements, $E = 10$ MPa from recent fabric tests, $P_{\text{error}} = \pm 1.6$ kPa from a previous study [11], and $R = 4.34$ cm, which is based on a 5% male relaxed bicep circumference of 27.3 cm, the strain error becomes $\epsilon_{\text{error}} = \pm 0.001$. This is 5% of the originally required strain.

It is not an exact correlation between skin deformation and how the material should deform so it is not clear how much error can be tolerated when measuring skin deformation. Given the calculation of $\epsilon_{\text{error}} = \pm 0.001$ it is reasonable to assume that our skin deformation measurements must be at least within $\pm 5\%$.

### B.2 The effect of strain error on LoNE

Ultimately, the error in the strain measurement will affect the principal strain direction, direction of non-extension and LoNE. The error can be visualized using Mohr’s circle in Figure [B-2]. Mohr’s circle can be considered a circle with finite thickness where the thickness of the circle represents the uncertainty in the measurement. Analytically the error can be calculated by using the following equation for non-extension and principal strain directions, where $\phi$ is the non-extension angle, $\theta_p$ is the angle of the principal direction from the local coordinate system, $E_i$ is the principal strain magnitudes, and $E_{ij}$ is the strain tensor:

$$\phi + \theta_p = \tan^{-1}\sqrt{-\frac{E_1}{E_2}} + \frac{1}{2}\tan^{-1}\left(\frac{2E_{12}}{E_{11} - E_{22}}\right). \quad (B.6)$$

For example, if we assume $E_{11} = 0.5$, $E_{22} = 0.5$, and $E_{12} = 0.3$ each have an error
of ±20% then the maximum error is $\phi = \pm 13\%$, which corresponds to $\phi = \pm 7^\circ$. An error in strain results in a lower error in LoNE by percentage, which is advantageous. When calculating LoNE based on a streamline approach the error grows as the LoNE grows from it’s initial seed point, which should be taken into consideration for future error analysis.

Figure B-1: MCP pressure production.

\[ P = \sigma_h \frac{t}{R} \]

Figure B-2: Mohr’s Circle with finite thickness to represent uncertainty in strain measurements and its relation to non-extension directions and LoNE.
Appendix C

Software

This appendix contains software to display strain data, analyze principal strain directions, and compute the directions of non-extension. Computation of LoNE is contained the Data Analysis section.

C.1 Data Class

The Data class holds the strain data for one frame of deformation. The class has various methods to display results and analyze the strain data.

Listing C.1: The Data class

1 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
2 % Data Class - LoNE Calculator v 4
3 % ------------------------------------------------------------- %
4 % Eddie Obropta - MIT Man-Vehicle Lab
5 % Professor Dava Newman
6 % (C) 2014
7 % ------------------------------------------------------------- %
8 % Summary: Data contains data for one state of deformation.
9 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
classdef Data < handle
% The Data class holds strain data for one deformation state
% Data holds functions to be executed for plotting or analysis

    properties
% data from DIC inputs
    x y z % reference points (mm) [n x 1]
xp yp zp % deformed points (mm) [n x 1]
masks %
u1 u2 u3 % deformation vector (mm) [n x 1]
e11 e12 e22 % strain tensor components for each point [n ...
x 1]
ep1 ep2 ep3 % principal strain for each point [n x 1]
sigma % std deviation correlation match (pixel) [n x 1]
sigma_x sigma_y sigma_z
x_image y_image % image coordinates (pixel) [n x 1]
u_image v_image % image displacement (pixel) [n x 1]
e13 e23 e33 % 3d strain components for each point [n x 1]

% triangulation data
    faces % [n_cell x 3] matrix
    TR % triangulation class

% face data for specific cells or mesh elements
    ep1_face ep2_face ep3_face % [n_cell x 1]
e11_face e12_face e13_face % [n_cell x 1]
e22_face e23_face e33_face % [n_cell x 1]

% seed point for streamlines
    seed % [n_seeds x 3] matrix [x y z]

% lone stream data
    lones1x lones1y lones1z % [n x 1]
lones1_idx % cell array - each cell is lone idxs
lones2x lones2y lones2z % [n x 1]
lones2_idx % cell array - each cell is lone idxs

120
% deformed data
lones1xp lones1yp lones1zp % [n x 1]
lones2xp lones2yp lones2zp % [n x 1]

% principal stream data - new data structure
prins1x prins1y prins1z % [n x 1]
prins1_idx % cell array - each cell is lone idxs
prins2x prins2y prins2z % [n x 1]
prins2_idx % cell array - each cell is lone idxs
% deformed data
prins1xp prins1yp prins1zp % [n x 1]
prins2xp prins2yp prins2zp % [n x 1]

% point incenters
P % [n_cell x 3] matrix [x y z]
% local coordinate vectors
t1 t2 t3 % [n x 3]
% principal directions
ep1_vec ep2_vec % [n x 3]
el1_vec el2_vec % [n x 3]

OPTIONS % structure, example: OPTIONS.some_option = true
end % properties

methods

%% Constructor
function d = Data(data,faces)
    % constructor using DIC data
    % constructor data and faces
    if nargin == 2
        d.x = data.x;
        d.y = data.y;
        d.z = data.z;
        d.xp = data.xp;
        d.yp = data.yp;
        d.zp = data.zp;
d.mask = data.mask;
d.u1 = data.u1;
d.u2 = data.u2;
d.u3 = data.u3;
d.e11 = data.e11;
d.e12 = data.e12;
d.e22 = data.e22;
d.ep1 = data.ep1;
d.ep2 = data.ep2;
d.sigma = data.sigma;
d.x_image = data.x_image;
d.y_image = data.y_image;
d.u_image = data.u_image;
d.v_image = data.v_image;
d.faces = faces;
end
end

%% ANALYSIS
% Store data in triangulated format
function triangulate(obj)
    obj.TR = triangulation(obj.faces, obj.x, obj.y, obj.z);
end

% Mean and std of area of triangular faces
function [avg, dev] = meshSizeInfo(obj)
    area = [];
    % loop over faces
    for i=1:size(obj.faces,1)
        % store vertices as points
        P1 = [obj.x(obj.faces(i,1)) obj.y(obj.faces(i,1)) ...
               obj.z(obj.faces(i,1))];
        P2 = [obj.x(obj.faces(i,2)) obj.y(obj.faces(i,2)) ...
               obj.z(obj.faces(i,2))];
        P3 = [obj.x(obj.faces(i,3)) obj.y(obj.faces(i,3)) ...
               obj.z(obj.faces(i,3))];
% calculate area and store
area(i) = 1/2 * norm(cross(P2-P1, P3-P1));
end
% average and standard deviation
avg = mean(area);
dev = std(area);
end

% Calculates mean strain data of face from averaging ...
vertices.
function pointToFaceData(obj)
for i = 1:size(obj.faces, 1)
    obj.e11_face(i) = mean([obj.e11(obj.faces(i, 1)) ...
                             obj.e11(obj.faces(i, 2)) obj.e11(obj.faces(i, 3))]);
    obj.e12_face(i) = mean([obj.e12(obj.faces(i, 1)) ...
                             obj.e12(obj.faces(i, 2)) obj.e12(obj.faces(i, 3))]);
    obj.e22_face(i) = mean([obj.e22(obj.faces(i, 1)) ...
                             obj.e22(obj.faces(i, 2)) obj.e22(obj.faces(i, 3))]);
    obj.ep1_face(i) = mean([obj.ep1(obj.faces(i, 1)) ...
                             obj.ep1(obj.faces(i, 2)) obj.ep1(obj.faces(i, 3))]);
    obj.ep2_face(i) = mean([obj.ep2(obj.faces(i, 1)) ...
                             obj.ep2(obj.faces(i, 2)) obj.ep2(obj.faces(i, 3))]);
    try
        obj.e13_face(i) = ... mean([obj.e13(obj.faces(i, 1)) ...
                                     obj.e13(obj.faces(i, 2)) ... obj.e13(obj.faces(i, 3))]);
        obj.e23_face(i) = ... mean([obj.e23(obj.faces(i, 1)) ...
                                     obj.e23(obj.faces(i, 2)) ... obj.e23(obj.faces(i, 3))]);
        obj.e33_face(i) = ... mean([obj.e33(obj.faces(i, 1)) ...
                                     obj.e33(obj.faces(i, 2)) ... obj.e33(obj.faces(i, 3))]);
    catch

123
disp('STATUS: Attempted to save e13,e23,e33 ...
    but no data was available');
end
end

function faceToPointData(obj)
    %TR = triangulation(obj.faces,[obj.x obj.y obj.z]);
    for i = 1:length(obj.x)
        ti = vertexAttachments(obj.TR,i);
        obj.e11(i) = mean(obj.e11_face(ti{1}));
        obj.e12(i) = mean(obj.e12_face(ti{1}));
        obj.e22(i) = mean(obj.e22_face(ti{1}));
        obj.ep1(i) = mean(obj.ep1_face(ti{1}));
        obj.ep2(i) = mean(obj.ep2_face(ti{1}));
        try
            obj.e13(i,1) = mean(obj.e13_face(ti{1}));
            obj.e23(i,1) = mean(obj.e23_face(ti{1}));
            obj.e33(i,1) = mean(obj.e33_face(ti{1}));
            obj.ep3(i,1) = mean(obj.ep3_face(ti{1}));
        catch
            disp('STATUS: Attempted to save e13,e23,e33 ...
                but no data was available');
        end
    end % end function

function localCoordinates(obj)
    obj.P = incenter(obj.TR);
    obj.t3 = faceNormal(obj.TR);
    % calculate x direction vector that points in the ...
    global x
    % direction
obj.t1 = [-obj.t3(:,3) zeros(size(obj.t3,1),1) ...
    obj.t3(:,1)];

mag1 = ...
    sqrt(obj.t1(:,1).^2+obj.t1(:,2).^2+obj.t1(:,3).^2);

% normalize to unity
obj.t1 = obj.t1 ./ [mag1 mag1 mag1];

% y direction is cross product of z and x directions
obj.t2 = cross(obj.t3, obj.t1);

mag2 = ...
    sqrt(obj.t2(:,1).^2+obj.t2(:,2).^2+obj.t2(:,3).^2);

% normalize to unity
obj.t2 = obj.t2 ./ [mag2 mag2 mag2];

end % end function

% Calculate Principal Strain and Directions
function principalDirections(obj)
    data = calcPrincipalDirections(obj);
    data.t1 = obj.t1;
    data.t2 = obj.t2;
    data.t3 = obj.t3;
    data = convertDirectionsTo3D(data);

    % store principal direction vectors - eigenvectors
    obj.ep1_vec = [data.e1p_xu_3D' data.e1p_yu_3D' ...
                   data.e1p_zu_3D'];

    obj.ep2_vec = [data.e2p_xu_3D' data.e2p_yu_3D' ...
                   data.e2p_zu_3D'];

    obj.el1_vec = [data.en1_xu_3D' data.en1_yu_3D' ...
                   data.en1_zu_3D'];

    obj.el2_vec = [data.en2_xu_3D' data.en2_yu_3D' ...
                   data.en2_zu_3D'];

    % store principal strain magnitude - eigenvalues
    obj.ep1_face = data.e1p_eig;
    obj.ep2_face = data.e2p_eig;
    obj.faceToPointData();

end % end function
function globalStrain(obj)
    for i = 1:size(obj.faces,1)
        % tangential coordinate system
        dirt = [obj.t1(i,:); obj.t2(i,:); obj.t3(i,:)];
        dirp = eye(3);
        % assemble rotation matrix
        for k = 1:3
            for l=1:3
                A(k,l) = dot(dirp(k,:),dirt(l,:));
            end
        end
        E = [obj.e11_face(i) obj.e12_face(i) 0; obj.e12_face(i) obj.e22_face(i) 0; 0 0 0];
        % rotate strain tensor
        E_rot = A*E*A';
        % store strain
        obj.e11_face(i) = E_rot(1,1);
        obj.e12_face(i) = E_rot(1,2);
        obj.e22_face(i) = E_rot(2,2);
        obj.e13_face(i,1) = E_rot(1,3);
        obj.e23_face(i,1) = E_rot(2,3);
        obj.e33_face(i,1) = E_rot(3,3);
    end
    % convert face data to point
    obj.faceToPointData();
end
end

function localStrain(obj)

end

function globalStrain(obj)
    for i = 1:size(obj.faces,1)
        % tangential coordinate system
        dirt = [obj.t1(i,:); obj.t2(i,:); obj.t3(i,:)];
        dirp = eye(3);
        % assemble rotation matrix
        for k = 1:3
            for l=1:3
                A(k,l) = dot(dirp(k,:),dirt(l,:));
            end
        end
        E = [obj.e11_face(i) obj.e12_face(i) 0; obj.e12_face(i) obj.e22_face(i) 0; 0 0 0];
        % rotate strain tensor
        E_rot = A*E*A';
        % store strain
        obj.e11_face(i) = E_rot(1,1);
        obj.e12_face(i) = E_rot(1,2);
        obj.e22_face(i) = E_rot(2,2);
        obj.e13_face(i,1) = E_rot(1,3);
        obj.e23_face(i,1) = E_rot(2,3);
        obj.e33_face(i,1) = E_rot(3,3);
    end
    % convert face data to point
    obj.faceToPointData();
end
end

% rotate strain from the local tangential coordinate system to the global coordinate system

% rotate strain from the global coordinate system to the local coordinate system
for i = 1:size(obj.faces,1)
  % tangential coordinate system
  dirt = [obj.t1(i,:);
          obj.t2(i,:);
          obj.t3(i,:)];
  dirp = eye(3);
  % assemble rotation matrix
  for k = 1:3
    for l=1:3
      % tangential unit vectors dotted with ... global unit
      % vectors
      A(k,l) = dot(dirt(k,:),dirp(l,:));
    end
  end
  E = [obj.e11_face(i) obj.e12_face(i) obj.e13_face(i);
       obj.e12_face(i) obj.e22_face(i) obj.e23_face(i);
       obj.e13_face(i) obj.e23_face(i) ...
       obj.e33_face(i)];
  % rotate strain tensor
  E_rot = A*E*A';

  % store strain
  obj.e11_face(i) = E_rot(1,1);
  obj.e12_face(i) = E_rot(1,2);
  obj.e22_face(i) = E_rot(2,2);
  obj.e13_face(i,1) = E_rot(1,3);
  obj.e23_face(i,1) = E_rot(2,3);
  obj.e33_face(i,1) = E_rot(3,3);
end
% convert face data to point
obj.faceToPointData();
end

% rotate strain tensor
function rotateStrain(obj, R)
for i=1:length(obj.x)
    % assemble strain as matrix
    E = [obj.e11(i) obj.e12(i) obj.e13(i);
         obj.e12(i) obj.e22(i) obj.e23(i);
         obj.e13(i) obj.e23(i) obj.e33(i)];
    % rotate strain tensor
    E_rot = R*E*R';
    % store strain
    obj.e11(i) = E_rot(1,1);
    obj.e12(i) = E_rot(1,2);
    obj.e13(i,1) = E_rot(1,3);
    obj.e22(i) = E_rot(2,2);
    obj.e23(i,1) = E_rot(2,3);
    obj.e33(i,1) = E_rot(3,3);
end

% save strain into face data
obj.pointToFaceData();
end
end

C.2 Principal Strain

This software calculates principal strain directions and directions of non-extension to be used by the streamline calculation of LoNEs.

Listing C.2: Principal Strain Calculation

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% calcPrincipalDirections - LoNE Calculator v 4
% ------------------------------------------------------------- %
% Eddie Obropta - MIT Man-Vehicle Lab
% Professor Dava Newman
```
% Summary: Calculate principal strain directions as well as ...
% directions of
% non-extension

function [ data_new ] = calcPrincipalDirections( data )
% Calculate principal strain and directions of non-extension
[rows, cols] = size(data.e11_face);
% transpose data
if cols > rows
    data.e11_face = data.e11_face';
    data.e22_face = data.e22_face';
    data.e12_face = data.e12_face';
end

e11 = data.e11_face;
e22 = data.e22_face;
e12 = data.e12_face;
% Lagrangian Strain Tensor
E11 = data.e11_face;
E22 = data.e22_face;
E12 = data.e12_face;
% compute eigenvectors and eigenvalues
for i = 1:length(E11)
    [V,D] = eig([E11(i) E12(i); E12(i) E22(i)]);
e1p_eig(i) = D(2,2);
e2p_eig(i) = D(1,1);
e1p_eig_x(i) = V(1,2);
e1p_eig_y(i) = V(2,2);
e2p_eig_x(i) = V(1,1);
e2p_eig_y(i) = V(2,1);
end
% Principle Direction from Mohr's Circle
\[
\theta_p_{\text{mohr\_lag}} = \frac{1}{2} \text{atan2}(2E_{12}, (E_{11} - E_{22}));
\]

% LoNE Direction from Mohr's Circle
% Radius of Mohr's Circle
\[
R = \text{sqrt}((0.5*(E_{11}-E_{22})).^2 + E_{12}.^2);
\]
\[
e_{1p} = 0.5*(e_{11}+e_{22}) + R;
\]
\[
e_{2p} = 0.5*(e_{11}+e_{22}) - R;
\]
\[
e_{p1\_x} = \text{ones}(\text{length}(e_{11}),1);
\]
\[
e_{p1\_y} = \text{tan}(\theta_{p\_mohr\_lag}) .* e_{p1\_x};
\]

\textbf{for} i = 1:\text{length}(E_{11})
\[
\textbf{if} \ \theta_{p\_mohr\_lag}(i) < 0
\]
\[
e_{p1\_x}(i) = -1;
\]
\[
e_{p1\_y}(i) = \text{tan}(\theta_{p\_mohr\_lag}(i)) \times e_{p1\_x}(i);
\]
\textbf{end}
\textbf{end}

\[
e_{p1\_xu} = e_{p1\_x} ./ \text{sqrt}(e_{p1\_x}.^2 + e_{p1\_y}.^2);
\]
\[
e_{p1\_yu} = e_{p1\_y} ./ \text{sqrt}(e_{p1\_x}.^2 + e_{p1\_y}.^2);
\]

% second direction is orthogonal
\[
e_{p2\_xu} = -e_{p1\_yu};
\]
\[
e_{p2\_yu} = e_{p1\_xu};
\]

% center of Mohr's Circle
\[
c = (E_{11} + E_{22}) / 2;
\]
% angle to 0 extension line
\[
\phi = \text{acos}(c./R);
\]
% angle from 0 extension line to principle direction
\[
\theta_{\text{lone\_mohr\_lag1}} = (\pi - \phi)/2 + \text{abs}(\theta_{p\_mohr\_lag});
\]
\[
en_{1\_x} = \text{ones}(\text{length}(e_{11}),1);
\]
\[
en_{1\_y} = \text{tan}(\theta_{\text{lone\_mohr\_lag1}}) \times en_{1\_x};
\]
\[
\theta_{\text{lone\_mohr\_lag2}} = (\pi + \phi)/2 + \text{abs}(\theta_{p\_mohr\_lag});
\]
en2_x = en1_x;
en2_y = \tan(\theta_{\text{lone mohr lag2}}) \times en2_x;

% compute LoNE direction unit vectors
en1_xu = en1_x ./ sqrt(en1_x.^2 + en1_y.^2);
en1_yu = en1_y ./ sqrt(en1_x.^2 + en1_y.^2);
en2_xu = en2_x ./ sqrt(en2_x.^2 + en2_y.^2);
en2_yu = en2_y ./ sqrt(en2_x.^2 + en2_y.^2);

% match eigenvalues from eigenvalue calculation to mohrs circle ...
calculation
% for consistency
tol = 1e-5;
for i = 1:length(E11)
    % if inconsistency make a switch
    if (abs(e1p_eig(i) - e1p(i)) > tol)
        disp('EIG SWITCH');
        disp(i);
        % confirm the inconsistency
        if (abs(e2p_eig(i) - e1p(i)) < tol)
            e1p_eig(i) = e2p(i);
            e2p_eig(i) = e1p(i);
            % store directions to make value switch
            e1p_x_temp = e1p_eig_x(i);
            e1p_y_temp = e1p_eig_y(i);
            e2p_x_temp = e2p_eig_x(i);
            e2p_y_temp = e2p_eig_y(i);
            e1p_eig_x(i) = e2p_x_temp;
            e1p_eig_y(i) = e2p_y_temp;
            e2p_eig_x(i) = e1p_x_temp;
            e2p_eig_y(i) = e1p_y_temp;
        else
            disp('EIG SWITCH FAILED')
        end
    end
% Check for tangent inconsistency when theta_lone_mohr_lag1 > 90 ... and < 270
for i = 1:length(E11)
    if theta_lone_mohr_lag1(i) > pi/2 && theta_lone_mohr_lag1(i) < 3*pi/2
        en1_x(i) = -en1_x(i);
        en1_y(i) = tan(theta_lone_mohr_lag1(i)) .* en1_x(i);
        en1_xu(i) = en1_x(i) ./ sqrt(en1_x(i).^2 + en1_y(i).^2);
        en1_yu(i) = en1_y(i) ./ sqrt(en1_x(i).^2 + en1_y(i).^2);
        disp(['SWITCHED LoNE 1 Direction of i=' num2str(i)]);
    end

    if theta_lone_mohr_lag2(i) > pi/2 && ...
        theta_lone_mohr_lag2(i) < 3*pi/2
        en2_x(i) = -en2_x(i);
        en2_y(i) = tan(theta_lone_mohr_lag2(i)) .* en2_x(i);
        en2_xu(i) = en2_x(i) ./ sqrt(en2_x(i).^2 + en2_y(i).^2);
        en2_yu(i) = en2_y(i) ./ sqrt(en2_x(i).^2 + en2_y(i).^2);
        disp(['SWITCHED LoNE 2 Direction of i=' num2str(i)]);
    end
end

data_new.en1_xu = en1_xu;
data_new.en1_yu = en1_yu;
data_new.en2_xu = en2_xu;
data_new.en2_yu = en2_yu;
data_new.elp = e1p;
data_new.e2p = e2p;
data_new.elp_xu = ep1_xu;
data_new.elp_yu = ep1_yu;
data_new.e2p_xu = ep2_xu;
data_new.e2p_yu = ep2_yu;
data_new.elp_eig = e1p_eig;
C.3 From Local to Global Directions

This code transforms the local strain principal directions to the global strain directions in the global frame. This treats the principal directions as vectors.

Listing C.3: Convert from Local to Global

```matlab
function [ data_new ] = convertDirectionsTo3D( data )
% This functions converts local strain data to the global coordinate frame

% Global coordinate system
dirp = eye(3);
% loop over points
for i = 1:length(data.en1_xu)
    % initialize en1_xu_3D
```

```
% convertDirectionsTo3D - LoNE Calculator v 4
% ------------------------------------------------------------- %
% Eddie Obropta - MIT Man-Vehicle Lab
% Professor Dava Newman
% (C) 2014
% ------------------------------------------------------------- %
% Summary: Convert local strain directions to global frame
% $\texttt{convertDirectionsTo3D}(\texttt{data})$ converts local strain data to the global coordinate frame.
```
data.en1_xu_3D(i) = 0;
data.en1_yu_3D(i) = 0;
data.en1_zu_3D(i) = 0;
data.en2_xu_3D(i) = 0;
data.en2_yu_3D(i) = 0;
data.en2_zu_3D(i) = 0;

% initialize elp_xu_3D
data.elp_xu_3D(i) = 0;
data.elp_yu_3D(i) = 0;
data.elp_zu_3D(i) = 0;

% tangential coordinate system
dirt = [data.t1(i,:), data.t2(i,:), data.t3(i,:)];

for k = 1:3
    for l=1:3
        A(k,l) = dot(dirp(k,:),dirt(l,:));
    end
end

% only consider principle points that have tangential coordinate system
% compute principle strain directions
elp_3D = A*[data.elp_xu(i) data.elp_yu(i) 0]';
elp_3D = A*[data.elp_xu(i) data.elp_yu(i) 0]';

% store global coordinate Principle vectors
data.elp_xu_3D(i) = elp_3D(1);
data.elp_yu_3D(i) = elp_3D(2);
data.elp_zu_3D(i) = elp_3D(3);
data.e2p_xu_3D(i) = e2p_3D(1);
data.e2p_yu_3D(i) = e2p_3D(2);
data.e2p_zu_3D(i) = e2p_3D(3);

% only consider points that have a local coordinate system
% and LoNEs exist
if data.elp(i)*data.e2p(i) < 0

% convert from local tangential frame to global frame
en1_3D = A*[data.en1_xu(i) data.en1_yu(i) 0]';
en2_3D = A*[data.en2_xu(i) data.en2_yu(i) 0]';

% store global coordinate LoNE vectors
data.en1_xu_3D(i) = en1_3D(1);
data.en1_yu_3D(i) = en1_3D(2);
data.en1_zu_3D(i) = en1_3D(3);
data.en2_xu_3D(i) = en2_3D(1);
data.en2_yu_3D(i) = en2_3D(2);
data.en2_zu_3D(i) = en2_3D(3);
end

data_new = data;
end
Bibliography


[43] Noah Rayman. This is nasa’s spacesuit of the future, 2014.


N. Wolfrum, Newman D.J., and K. Bethke. An automatic procedure to map the skin strain field with application to advanced locomotion space suit design, July 2006.
