CLIMBING IN SPACE:
DESIGN AND IMPLEMENTATION OF A HEXAPOD
ROBOT USING DRY ADHESIVES

by

Michael Henrey
B.A.Sc., Simon Fraser University, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Applied Sciences

in the
School of Engineering Science
Faculty of Applied Sciences

© Michael Henrey 2013
SIMON FRASER UNIVERSITY
Spring 2013

All rights reserved.
However, in accordance with the Copyright Act of Canada, this work may be reproduced without authorization under the conditions for “Fair Dealing.” Therefore, limited reproduction of this work for the purposes of private study, research, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.
APPROVAL

Name: Michael Henrey
Degree: Master of Applied Sciences
Title of Thesis: Climbing in Space: Design and Implementation of a Hexapod Robot Using Dry Adhesives

Examinining Committee: Mike Sjoerdsma
Senior Lecturer
Chair

Dr. Carlo Menon, P. Eng.
Associate Professor
Senior Supervisor

Dr. Lesley Shannon, P. Eng.
Associate Professor
Supervisor

Dr. William Gruver
Professor Emeritus
Internal Examiner

Date Approved: March 18, 2013
Partial Copyright Licence

The author, whose copyright is declared on the title page of this work, has granted to Simon Fraser University the right to lend this thesis, project or extended essay to users of the Simon Fraser University Library, and to make partial or single copies only for such users or in response to a request from the library of any other university, or other educational institution, on its own behalf or for one of its users.

The author has further granted permission to Simon Fraser University to keep or make a digital copy for use in its circulating collection (currently available to the public at the “Institutional Repository” link of the SFU Library website (www.lib.sfu.ca) at http://summit/sfu.ca and, without changing the content, to translate the thesis/project or extended essays, if technically possible, to any medium or format for the purpose of preservation of the digital work.

The author has further agreed that permission for multiple copying of this work for scholarly purposes may be granted by either the author or the Dean of Graduate Studies.

It is understood that copying or publication of this work for financial gain shall not be allowed without the author’s written permission.

Permission for public performance, or limited permission for private scholarly use, of any multimedia materials forming part of this work, may have been granted by the author. This information may be found on the separately catalogued multimedia material and in the signed Partial Copyright Licence.

While licensing SFU to permit the above uses, the author retains copyright in the thesis, project or extended essays, including the right to change the work for subsequent purposes, including editing and publishing the work in whole or in part, and licensing other parties, as the author may desire.

The original Partial Copyright Licence attesting to these terms, and signed by this author, may be found in the original bound copy of this work, retained in the Simon Fraser University Archive.

Simon Fraser University Library
Burnaby, British Columbia, Canada

revised Fall 2011
Abstract

A legged, climbing robot that adheres to surfaces using dry adhesion is presented. This style of robot has potential applications in the space industry, as dry adhesives (unlike suction, magnets, or conventional pressure sensitive adhesives) have the potential to function effectively on orbiting spacecraft. Dry adhesives, fabricated by previous researchers, were tested in simulated space environments. No reduction in adhesive performance was found for pressures down to $1 \times 10^{-5}$ mbar or temperatures from $-50 ^\circ C$ to $75 ^\circ C$. The design of a robot, Abigaille-III, was optimized for vertical climbing. A custom computing architecture was developed on a Field Programmable Gate Array. A novel, open-loop preloading controller, and a closed-loop positioning controller were implemented. Abigaille-III was observed to climb smooth and uneven vertical surfaces, transfer from horizontal to vertical, loiter for nearly seven hours and climb vertically at a rate of 0.44 mm s$^{-1}$ for nearly four hours without detachment.

Keywords: Climbing robot; legged robot; dry adhesive; preloading; optimization; space
Acknowledgments

I would like to acknowledge some of the many people who helped me out during my research. Joana was unbelievably patient with me throughout my research and was always encouraging and understanding during the toughest times. Andrew helped me with countless hours of statistics discussions and explained the same concepts over and over to me until I actually understood the ideas fully. My family was consistently positive and optimistic about my research: always asking me how my robot was faring and never doubting that one day it would actually work. Kjetil and Laurent provided invaluable guidance and assistance at ESTEC, and kept me accountable with thoughtful comments on my research following my return to Canada. Lesley Shannon guided me through writing my first conference paper and gave me the chance to give a presentation in Oslo. My senior supervisor Carlo Menon gave me the opportunity to work on a climbing robot and go to ESTEC, and iterated with me tirelessly as we worked towards publishing our results. The entire MENRVA lab provided academic support and fruitful discussions, and our soccer team was legendary.
# Contents

Approval ii

Partial Copyright License iii

Abstract iv

Acknowledgments v

Contents vi

List of Tables viii

List of Figures ix

Glossary xi

1 Introduction 1
   1.1 Motivations ........................................ 1
   1.2 Objectives ........................................ 2
   1.3 Summary of Contributions .......................... 2
   1.4 Thesis Layout ...................................... 3

2 Literature Review 4
   2.1 Natural and Synthetic Dry Adhesives ................ 4
   2.2 Climbing Robots ................................... 8

3 Synthetic Dry Adhesives in Space Environments 11
   3.1 Materials and Methods .............................. 11
   3.2 Effects of Vacuum .................................. 19
   3.3 Effects of Temperature .............................. 22
   3.4 Summary ........................................... 23
## List of Tables

4.1 Motor options for the design of Abigaille-III ........................................... 27  
5.1 Computing system design criteria .................................................. 40  
5.2 Software resource usage ............................................................... 46  
5.3 FPGA resource usage ................................................................. 46  
5.4 Measured power consumption ....................................................... 47  
5.5 Steps for implementing the open-loop preloading controller ................. 49  
6.1 Manufacturing methods used in the fabrication of Abigaille-III ............... 57  
6.2 Joint specifications of Abigaille-III ............................................... 61  
6.3 Measured masses of Abigaille-III .................................................. 61  
6.4 Measured dimensions of Abigaille-III ............................................ 62  
7.1 Abigaille-III’s movement rates during various maneuvers ....................... 67  
7.2 Elapsed time for various maneuvers ............................................... 67
List of Figures

2.1 Foot of a climbing gecko. ...........................................  5
2.2 SEM micrographs of synthetic dry adhesives. ..........................  7
2.3 Examples of previous climbing robots. ................................  8
2.4 Examples of wheel-leg hybrid locomotion. ..............................  9
3.1 Optical image of the dry adhesive taken at two scales. ............... 12
3.2 Photos of the NST machine in its vacuum chamber. ................... 13
3.3 A schematic of the NST showing its sensors and actuators. .......... 14
3.4 Typical load-time curve for a dry adhesive. .......................... 14
3.5 Typical data collected from an adhesion experiment. ................. 15
3.6 Mounted and unmounted samples. .................................... 16
3.7 Pristine and poor adhesive samples. .................................. 16
3.8 Feasible testing range in the NST chamber. ........................... 17
3.9 Effect of PDMS to long term exposure to high temperatures. ...... 18
3.10 Synthetic gecko adhesion in atmosphere and vacuum. ............... 20
3.11 Stiffness of structured PDMS in vacuum and atmosphere. .......... 21
3.12 Estimates of $E^*$ plotted against time. ............................. 22
3.13 Estimates of $f_{a(sat)}$ plotted against time. ........................ 23
3.14 Synthetic gecko adhesion at various temperatures and preload forces. 24
4.1 Methodology used for the mechanical design of this robot. .......... 26
4.2 Diagram used for estimating required motor torques. ................. 27
4.3 Curves guiding motor selection in Abigiale-III. ....................... 29
4.4 Schematic of Abigaille-III on the wall showing forces and displacements. 30
4.5 The effect of changing front and middle foot contact locations. .... 34
4.6 Diagram used for computing minimum leg segment lengths. ........ 35
4.7 Feasible region of leg segment lengths. .............................. 37
5.1 Processor diagram of Abigaille-III’s computing system. .............. 41
5.2 Block diagram showing the coordinating controller. .................. 43
5.3 Block diagram showing the MicroBlaze leg processor.
5.4 Flow charts of the processor software.
5.5 Lab setup for conducting foot adhesion measurements.
5.6 Results from preload-pulloff tests.
5.7 Duty cycle and torque relationship in a 150:1 gear motor.
5.8 Computed and implemented duty cycles for a preloading controller.

6.1 Detailed view of Abigaille-III’s leg parts.
6.2 Detailed view of Abigaille-III’s macro-posts.
6.3 Detailed view of Abigaille-III’s foot.
6.4 Composite image showing design features of Abigaille-III.

7.1 Abigaille-III climbing a wall.
7.2 Abigaille-III transferring from a horizontal to a vertical surface.
7.3 Abigaille-III climbing along structured surfaces.
7.4 Normal direction foot forces in Abigaille-III.
7.5 Adhesion measured over 2000 cycles for a single foot of Abigaille-III.
7.6 Failure modes observed in Abigaille-III.

8.1 Evolution of the Abigaille robots.
### Glossary

#### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>2-Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3-Dimensional</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application Specific Integrated Circuit</td>
</tr>
<tr>
<td>BRAM</td>
<td>Block Random-Access Memory</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>CGR</td>
<td>Compliant Gecko Robot</td>
</tr>
<tr>
<td>CI</td>
<td>Confidence Interval</td>
</tr>
<tr>
<td>CNT</td>
<td>Carbon Nanotubes</td>
</tr>
<tr>
<td>COM</td>
<td>Center of Mass</td>
</tr>
<tr>
<td>DMM</td>
<td>Digital Multi-Meter</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree Of Freedom</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESTEC</td>
<td>European Space Research and Technology Centre</td>
</tr>
<tr>
<td>FF</td>
<td>Flip Flop</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>FIFO</td>
<td>First In First Out (buffer)</td>
</tr>
<tr>
<td>FIT</td>
<td>Fixed Interval Timer</td>
</tr>
<tr>
<td>FOS</td>
<td>Factor Of Safety</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>FSL</td>
<td>Fast Simplex Link (Xilinx FIFO)</td>
</tr>
<tr>
<td>GPIO</td>
<td>General Purpose Input/Output</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>I²C</td>
<td>Inter-Integrated Circuit</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LN₂</td>
<td>Liquid Nitrogen</td>
</tr>
<tr>
<td>LSB</td>
<td>Least Significant Bit</td>
</tr>
<tr>
<td>LUT</td>
<td>Look Up Table</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transformer</td>
</tr>
<tr>
<td>MCU</td>
<td>Microcontroller</td>
</tr>
<tr>
<td>MPMC</td>
<td>Multi-Port Memory Controller</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NST</td>
<td>Nano Scratch Tester</td>
</tr>
<tr>
<td>OS</td>
<td>Operating System</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
</tbody>
</table>
PDMS  Polydimethylsiloxane
PID  Proportional-Integral-Derivative (controller)
PMMA  Poly(methyl methacrylate)
PSA  Pressure Sensitive Adhesive
PWM  Pulse Width Modulation
RGR  Rigid Gecko Robot
SDRAM  Synchronous Dynamic Random-Access Memory
SEM  Scanning Electron Microscope
TBCP  Timing Belt Climbing Platform
UART  Universal Asynchronous Receiver/Transmitter

**Notation**

$\tau$  Vector of torques on the robot’s joints
$\tau^*$  Vector of optimal motor torques on the robot’s joints
$\tau_{ME}$  Motor torque (experimental)
$\tau_{MLit}$  Motor torque (literature)
$c$  Motor torque experimental offset
$d_x$  Vector of displacements from COM to robot’s feet in $x$
$d_y$  Vector of displacements from COM to robot’s feet in $y$
$d_z$  Vector of displacements from COM to robot’s feet in $z$
$E^*$  Effective Young’s modulus
$f$  Vector of forces at robot’s feet
$f^*$  Vector of optimal forces at robot’s feet
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_a$</td>
<td>Adhesion force</td>
</tr>
<tr>
<td>$f_B$</td>
<td>External forces acting on the robot’s body</td>
</tr>
<tr>
<td>$f_E$</td>
<td>Force applied by a leg (experimental)</td>
</tr>
<tr>
<td>$f_p$</td>
<td>Preload force</td>
</tr>
<tr>
<td>$f_x$</td>
<td>Vector of forces in $x$ on the robot’s feet</td>
</tr>
<tr>
<td>$f_y$</td>
<td>Vector of forces in $y$ on the robot’s feet</td>
</tr>
<tr>
<td>$f_z$</td>
<td>Vector of forces in $z$ on the robot’s feet</td>
</tr>
<tr>
<td>$f_{a(sat)}$</td>
<td>Saturation adhesion force</td>
</tr>
<tr>
<td>$f_{BN}$</td>
<td>External force on robot normal to the wall</td>
</tr>
<tr>
<td>$f_{BP}$</td>
<td>External force on robot parallel to the wall</td>
</tr>
<tr>
<td>$G$</td>
<td>Grasp matrix of the whole robot</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>$h$</td>
<td>Joint attachment to ground distance (height of robot)</td>
</tr>
<tr>
<td>$J$</td>
<td>Jacobian of a robot leg</td>
</tr>
<tr>
<td>$k$</td>
<td>Slope of force-distance motor-torque relationship</td>
</tr>
<tr>
<td>$l_1$</td>
<td>Length of first leg segment</td>
</tr>
<tr>
<td>$l_2$</td>
<td>Length of second leg segment</td>
</tr>
<tr>
<td>$l_{step}$</td>
<td>Step length of Abigaille-III</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass of entire robot</td>
</tr>
<tr>
<td>$M_B$</td>
<td>External moments acting on the robot’s body</td>
</tr>
<tr>
<td>$m_{LP}$</td>
<td>Mass of parts for 1 leg</td>
</tr>
<tr>
<td>$m_{TFM}$</td>
<td>Total fixed mass of robot</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of robot legs</td>
</tr>
<tr>
<td>$r$</td>
<td>Radius of spherical indenter</td>
</tr>
<tr>
<td>$s$</td>
<td>Depth of an indent</td>
</tr>
<tr>
<td>$w$</td>
<td>Wrench of forces on robot’s body</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Robotic systems are often used in applications where it is unsafe for humans to operate. On Mars, rovers such as Spirit, Opportunity and Curiosity have explored the hostile environment. On the International Space Station (ISS), the Canadarm2 and Dextre assist astronauts with inspection, repairs and Extra-vehicular Activities. However these current systems have their limitations. Exploring planetary surfaces requires dexterity and maneuverability. Current rovers can face difficulties with rough terrain, for example in 2009, Spirit was trapped in sand and had to continue its mission as a stationary laboratory. While the Canadarm2 is a suitable robot for the ISS, robotic systems for smaller satellites that are capable of performing repairs do not yet exist. If a critical part on a satellite fails then the entire mission is often compromised.

1.1 Motivations

A legged robot for space applications has potential to be more mobile than current rovers, and more suitable for the inspection and repair of a small satellite than present robotic technology. However, designing a legged robot to walk on Mars, or scramble along the exterior of the International Space Station (ISS), poses a number of challenges not experienced by designers of terrestrial, legged robots. One key challenge is the design of a foot that can adhere the robot to the smooth spacecraft exterior and allow the robot to surmount various obstacles.

To achieve this goal, scientists have turned to nature, specifically the gecko, for inspiration. While geckos are not a space-faring species, the gecko sticks to surfaces using van
der Waals forces, and these forces are not affected by vacuum or temperature. A synthetic, gecko-inspired foot is an integral part of a climbing robot for space applications. To adhere to the exterior of an orbiting spacecraft, or operate on a planetary surface with low atmospheric pressure, an adhesive must be capable of functioning in a vacuum environment. Tests found in the literature give conflicting results: some authors find no effect of pressure (e.g. [1]), while others report that synthetic dry adhesives lose up to 25 percent of their adhesion strength when in vacuum (e.g. [2]).

A legged robot with gecko-like dry adhesives would also have applications in Earth environments. It is preferable to use robots for jobs that pose dangers to human lives, including painting of bridges, cleaning skyscraper windows, and inspection of hydroelectric dam walls and nuclear pressure vessels. A climbing, legged robot with gecko-inspired feet would have the dexterity and flexibility to excel in these dangerous environments.

1.2 Objectives

The objectives of this thesis are as follows:

1. Validate synthetic dry adhesive performance in a space environment.
2. Optimize a robot for climbing vertical surfaces.
3. Develop a computing architecture for the robot.
4. Propose and implement control software.
5. Construct the climbing robot.
6. Characterize the robot’s performance.

1.3 Summary of Contributions

Fabricating the synthetic dry adhesives and moulds was previous work [3]. The adhesive tests presented in Chapter 3 are my own work. In Chapter 6, macro-posts are discussed. I fabricated the macro-posts using the method of Li et al. [4] however my method of bonding the hierarchical foot structure was different.
Four robots (TBCP-I and II and Abigaille-I and II) had previously been developed in the MENRVA lab [5–8]. TBCP-II and Abigaille-II could both climb smooth surfaces and transfer between orthogonal surfaces. In 2009 and 2010, undergraduate students designed the first version of Abigaille-III during capstone and directed studies projects, with the output being a robot that could walk on horizontal surfaces, and had a Field Programmable Gate Array (FPGA)-based control system using seven soft-processors. In Chapter 4, I present physical equations that helped me discover the initial design of Abigaille-III was not strong enough to climb vertically. I redesigned the robot’s mechanical structure with a number of new sensors and actuators, optimized the leg mechanical subsystem, rewrote the control software and made changes to the computing architecture. The size, shape and mass of the robot is radically different from the first version of Abigaille-III. The computing architecture was altered with the addition of timers, motors, sensors, interrupts and software which met control system scheduling deadlines. An open-loop preloading controller was developed to actively preload the dry-adhesives and support the mass of the robot. The foot design of Abigaille-III was changed to include a passive ankle, and novel detaching mechanism.

1.4 Thesis Layout

Chapter 2 is a literature review, outlining the state of the art in both climbing robotics and testing of dry adhesives. Because the literature is conflicting on the low-pressure performance of synthetic dry adhesives, in Chapter 3 a characterization of dry adhesives in simulated space environments is presented. Optimization techniques used to design the robot’s mechanical structure are explained in Chapter 4. In Chapter 5, a computing architecture that is well matched to the robot’s mechanical design is presented. Additionally in Chapter 5, two control strategies are explained: an open-loop strategy was used for preloading and a closed-loop strategy was used for joint positioning. The robot is constructed using a variety of manufacturing techniques, which are outlined in Chapter 6. In Chapter 7, the results of testing the robot on various terrain, as well as failure modes are presented. This thesis concludes with a discussion of how the objectives were met and future work is proposed.
Chapter 2

Literature Review

In this chapter, a literature review of synthetic dry adhesives and climbing robots is presented. First, the properties of dry adhesives are outlined, and the mechanisms by which dry adhesives stick are explained. A discussion of adhesive testing corresponds to the first thesis objective: testing dry adhesives in vacuum. Next, the literature on climbing robots is examined, highlighting the various locomotion and adhesion styles used by climbing robots. This paves the way for the remaining objectives of this thesis.

2.1 Natural and Synthetic Dry Adhesives

The Tokay gecko (see Figure 2.1 (a)) sticks to a wall using van der Waals forces [9]. The gecko’s foot (see Figure 2.1 (b)) contains high aspect ratio hairs named setae (see Figure 2.1 (c)). Each seta branches into spatulae, which terminate in triangular tips about 200 nm in width (see Figure 2.1 (d)). Because the triangular spatulae tips come into very close contact (≤ 10 nm) with the surface the gecko is climbing, van der Waals interactions which typically occur between molecules, cause an adhesion between the gecko’s foot and the climbing surface. For the Tokay Gecko, up to 10 N of adhesive force can be generated by the sum of the gecko’s spatulae [10].

The functional properties of dry adhesives were described by Autumn in 2006 [12]:

...[T]he gecko adhesive is: 1) directional, 2) attaches strongly with minimal preload, 3) detaches quickly and easily, 4) sticks to nearly every material, 5) does not stay dirty, or 6) self-adhere, and 7) is nonsticky by default.
Many properties have been replicated in synthetic versions of the dry adhesive, paving the way for successful climbing robots. For example, directional adhesion (property 1) has been achieved in different manners. The gecko’s setae detach easily in one direction, so the gecko peels its toes to detach from a wall with minimal force [13]. Adhesives which mimic the shape of the gecko’s adhesives have been used by climbing robots [14], where microscale wedges detach easily in one direction, and grip in the other. Another approach was the manufacture of adhesives with offset caps [15].

Some alternate adhesion mechanisms include suction [16–20], magnets [21,22], and spines or claws [23,24]. Dry adhesives have advantages over these other mechanisms for use in space environments. Power consumption is low (properties 2 and 3 from [12]) because dry adhesives do not require pumps, electromagnets, or high detaching forces (which permanent
magnet systems require). Pressure Sensitive Adhesives (PSAs) outgas (boil off) in a vacuum, rendering them useless in space. The ability to stick to nearly every surface (property 4 from [12]) is very advantageous in space environments where it is expensive to upgrade a system to face a new and unforeseen environment [25]. In contrast, other adhesive mechanisms require very specific surfaces that may not be found in space environments: magnets require ferromagnetic surfaces, claws require rough surfaces and suction requires smooth surfaces and an ambient pressure.

Functional property 5 of gecko adhesives [12] is the self-cleaning ability. Gecko adhesive is thought to self-clean because it is energetically favorable dirt particles of most sizes to cling to the surface that a gecko is climbing, rather than the gecko’s foot [26]. Self-cleaning properties have also been developed for some synthetic adhesives [27]. The ability to self-clean adds to the system robustness, and is necessary for a truly autonomous robot.

Since the year 2000, various synthetic dry adhesives have been developed (e.g. [2,28,29]). A number of materials have been used as substrates including carbon nanotubes (CNT) and Polydimethylsiloxane (PDMS). PDMS has many desirable properties for use in synthetic dry adhesives: it has a fast cure time, is mouldable, and, for space applications, NASA has already characterized its outgassing properties [30]. Some examples of PDMS adhesives include the nanobumps by Sitti et al. [28], dual-level directional adhesives by Santos et al. [29], tape by Davies et al. [2], and the adhesives by Sameoto et al. used in this work [3]. Scanning Electron Microscope (SEM) images of dry adhesives are presented in Figure 2.2 to show the diversity of synthetic gecko adhesives.

Characterizing dry adhesives is commonly done by indenting a spherical probe (e.g. [31–36]) into the adhesive and subsequently retracting the probe. A load sensor on the probe resolves the preload and detachment forces (as in [37]), and displacement is often also resolved with an interferometer or other sensor (as in [33, 35]). While both Shargott et al. [37] and Long et al. [38] developed theory relating the preload and pulloff force of a synthetic dry adhesive tested with an indenter, no experiments have been conducted using the indenter geometry proposed by Long et al. [38]. The theory of Shargott et al. [37] has been used by other research groups (e.g. Greiner et al. [33]) to explain their data. The model in Shargott et al. [37] assumes each fibril of the dry adhesive acts as a spring, and a saturation adhesion is defined allowing for comparison of a single quantity between different adhesives, or the same adhesive in different environmental conditions.

A variety of tests have been conducted on dry adhesives. Previous tests include the
effect of post geometry and contact shape [35, 39], detachment speeds [40, 41], indenter geometry [39], Young’s modulus [33, 42], repeated measurements and time delays between measurements [33, 37]. Both gecko and gecko setae adhesion depend on ambient relative humidity [38, 43], however humidity has no effect on the adhesion of PDMS-based synthetic dry adhesives [1, 31]. Temperature has an effect on the adhesive ability of a live gecko [43], and on the Young’s modulus of PDMS [44], but no known studies of the effect of temperature on the adhesion of a synthetic dry adhesive have been found.

Studying the effect of pressure on dry adhesives allows insight into the mechanisms which cause adhesion. When inspecting dry adhesives with mushroom caps, Murphy et al. [34] observed that the ends of the adhesives take the shape of a suction cup. Because van der Waals forces are not affected by ambient pressure, any changes in adhesion observed in a low pressure environment suggest that suction may be in part responsible for the sticking capability of the adhesive. With flat-on-flat contact, Murphy et al. [34] found no effect of pressure on adhesion. A flat-on-flat test by Davies et al. [2] found up to 25 percent of the adhesion of their dry adhesives was due to suction. Multiple trials were reported by Heepe et al. [40] who found a 10 percent effect due to suction, and Sameoto et al. [1] who observed a drop in adhesion during some low pressure experiments but attributed it to adhesive damage rather than suction.
2.2 Climbing Robots

Climbing robots use various mechanisms, including dry adhesives [5–8, 45–53], suction [16–20], magnets [21, 22], and spines or claws [23, 24] for adhering to a wall. Within the category of robots that use dry adhesives, three primary locomotion mechanisms exist: continuous-track [7, 8, 45, 53], wheel-leg hybrids [46–49] and legs [5, 6, 50–52]. Examples of robots using each style of locomotion are presented in Figure 2.3. Robots with each locomotion technology have demonstrated the ability to climb vertically and transfer between orthogonal surfaces [6, 8, 49]. Overcoming small obstacles has been shown (e.g. by Unver et al. [45]), however, robots that can overcome complex terrain or uneven surfaces have not been demonstrated.

Continuous-track robots include Tankbot [45], MaTBot [53] and TBCP [7, 8]. A number of versions of Tankbot were designed and optimized for various situations including carrying payloads, overcoming obstacles and loitering [45]. Tankbot uses soft, flat elastomers for adhering to a surface. When MaTBot uses patterned dry adhesives it can only climb surfaces up to 60 degrees in slope [53], however, with magnets on a ferromagnetic surface it can climb vertically. Two robots, TBCP-I and TBCP-II, use PDMS as the substrate for their dry-adhesives [7, 8]. The second generation robot, TBCP-II, climbs at a rate of 34 mm s$^{-1}$ and has two modules connected by a center joint, making it capable of transferring between orthogonal surfaces. TBCP-II is controlled by a Digital Signal Processor (DSP) and applies an active preloading strategy using sensor feedback from distance sensors [8].
Because the contact area between a wheel and surface is small and, therefore, unsuitable for adhering a climbing robot to the wall, some climbing robots employ wheel-leg hybrid mechanisms for locomotion. The axles of a wheel-leg hybrid rotate like a wheel, but the contact areas are flat, providing more adhesion area for vertical climbing. Examples include Waalbot [46, 47] and the Mini-Whegs™ robots [48, 49]. A detailed view of wheel-leg hybrid locomotion systems is shown in Figure 2.4 for clarity. Because of its design with a large wheel-leg at the front, Waalbot can climb walls and transition between surfaces. A tail behind the robot passively preloads the adhesives at the front [47]. The second generation robot, Waalbot-II, includes an adhesion recovery system that detects reduced adhesion with force sensors on the tail. By rocking side to side, Waalbot-II cleans its adhesives to increase its adhesion on the climbing surface [46]. The Mini-Whegs™ robots have a different design; instead of the rigid Waalbot feet, the Mini-Whegs™ robots hold flaps of Pressure Sensitive Adhesives (PSAs) on their feet. These feet operate in a peeling mode: the flaps peel off the surface instead of suddenly unsticking [48]. A body joint was added to the second generation of Mini-Whegs™, allowing outside corner transitions [49].

While tank-tracked and wheel-leg hybrids demonstrate good performance on smooth surfaces, legged robots have potential to be more maneuverable and dexterous than robots
CHAPTER 2. LITERATURE REVIEW

with other locomotion styles. An additional advantage is the inherent safety factor of a legged robot: if one leg loses adhesion, the other legs are able to hold the robot to the surface while a recovery maneuver is performed [24]. Both maneuverability and redundancy are advantages in space environments. The first prototypes of legged robots using adhesives were published in 2006: the Rigid Gecko Robot (RGR) and the Compliant Gecko Robot (CGR) prototypes both mimic the gait of a climbing gecko [50]. While neither robot climbs vertically, they are capable of scaling 65 degree surfaces at $20 \text{ mm s}^{-1}$. Also published in 2006, Geckobot [51] uses elastomer adhesives and similar kinematics to the gecko for scaling up to 85 degree slopes. An interesting innovation was a mechanism for peeling the adhesive from the surface. Perhaps the most successful climbing robot, Stickybot [52], was the first legged robot to use dry adhesives and climb vertical surfaces. Its speed is $40 \text{ mm s}^{-1}$ while scaling vertical surfaces. Stickybot mimics the form and gait of a vertically climbing gecko, however it lacks the ground clearance and flexibility to perform transitions between orthogonal surfaces.

Abigaille-I [5] and Abigaille-II [6] are the precursors to the work in this thesis. Abigaille-I does not walk or climb, as it is only a development platform for proving the potential for a legged robot with dry adhesives. During the design of Abigaille-I, the authors derived the inverse kinematics for the joint structure of a 3-Degree Of Freedom (DOF) robotic leg which was used in future Abigaille versions. Each joint position is sensed with a Hall-effect sensor. Abigaille-I had a microcontroller-based processor, and shift registers were used to meet the pin count requirements of the control system. Each foot of Abigaille-I consists of a rigid plastic element, and a flexible silicone element. The flexible silicone element forms a 3-DOF rotational joint, allowing the foot to attach and detach using trajectory-based methods. Abigaille-II climbs vertically and transfers between surfaces. Each joint position is sensed using a potentiometer. It uses a servo controller to command its motors. Abigaille-II has flaps of adhesive on its feet, which, like the feet of Abigaille-I, attach and detach from the wall with trajectory-based preloading and detaching methods.
Chapter 3

Synthetic Dry Adhesives in Space Environments

The first objective of this thesis is to validate the use of synthetic dry adhesives in space environments. Adhesives were tested at the European Space Research and Technology Centre (ESTEC) to characterize the performance of dry adhesives in a vacuum and at various temperatures. This was done with a focus on space applications, however, from a materials-science perspective, the experiments in vacuum also explored whether the adhesive mechanism of a dry adhesive includes a suction component.

3.1 Materials and Methods

During all of the tests, a quartz sphere was used to contact the adhesive. The PDMS dry adhesives had been fabricated between March and April 2012, and kept in a dust free environment. The tests were conducted between July 2012 and August 2012. Images of the adhesives are provided in Fig. 3.1.

A Nano Scratch Tester (NST) was used to take the measurements. The NST is shown in Figure 3.2, and a schematic of the equipment is shown in Figure 3.3. Roughing and diffusion pumps (Edwards) were connected to the system. Vibrations were dampened using an air table and compressor (Jun-Air), and a damping block (Edwards) on the roughing pump hose. The sample was mounted inside the chamber on a 3-axis positioner (Maxon). An electric heating element and Liquid Nitrogen (LN$_2$) cooling tube controlled the sample
temperature. The probe was a quartz sphere (maximum roughness 0.22µm) of 1.5 mm diameter, glued with cyanoacrylate to a 2 mm diameter steel pin. The NST cantilever holding the probe had a measurement resolution of 0.15µN in load and 0.3 nm in depth. Displacement was measured with a Linear Variable Differential Transformer (LVDT) at the end of the cantilever and at a fixed reference attached to the chamber. The load was computed from the LVDT measurement and spring constant of the cantilever (0.6820 mNµm$^{-1}$). A microscope was mounted inside the chamber. The sample was moved between the probe and the microscope for inspection.

During a normal testing cycle, the quartz sphere was brought into contact with the adhesive, and preloaded to the desired depth. Once preloaded, the adhesive was unloaded until detachment, completing a single measurement. Repeating the cycle allowed more measurements to be obtained at the same location. A force-time plot of a single measurement is provided in Fig. 3.4. After the indenter contacted the sample (A), the load increased to a maximum (B, constant rate of motion). Next the probe retracted (constant rate of motion), until detachment (C). In this case, the final value (D) was slightly above the zero load line due to the automatic contact detection, requiring a load offset to be computed during data analysis.

Typical data had the form shown in Figure 3.5, which shows a series of four attachment and detachment cycles, over the course of one minute. The NST software output a tab-delimited text file containing a header and the time-load-displacement information at each sample point. It was post-processed to identify the peak preload forces, preload depths and adhesion forces using MATLAB. A typical file from 5 min of testing at 100 Hz was between 4 MB and 40 MB.

Two procedures were adopted to reduce measurement variance. Bonding the samples
Figure 3.2: The NST machine in its vacuum chamber (A). A microscope (B) is provided for imaging samples. The sample is mounted under the NST cantilever (C), on a heating/cooling stage (D). Behind the machine sits a roughing pump (E), diffusion pump (G) and LN$_2$ dewar (F).

to a substrate which was clamped under the indenter resulted in sharper detachments as shown in Figure 3.6. The samples were bonded to a copper block using a silicone compound (Bison), which had a temperature rating of up to 300°C. Sample quality was important. A small area of adhesive with pristine caps was identified using a microscope and tests were performed in this pristine area. The difference between pristine and poor adhesives is shown in Figure 3.7 where a variety of locations were tested in both a poor region and a pristine region. In the pristine region, the variance was lower, and overall adhesion was higher.

During pumpdown, chamber movement caused a relative shift between the sample and the indenter. This was characterized under a microscope to be 5\(\mu\)m in the x and y (planar) directions and 100\(\mu\)m z-direction (vertical) through inspection of the features on a sample during pumpdown and refocusing them using the stage. A similar test during sample
Figure 3.3: A schematic of the NST showing its sensors and actuators. © 2009 CSM [55].

Figure 3.4: Typical load-time curve for a dry adhesive. A is the contact point, B is the maximum preload force, C is the maximum adhesion and the zero load force is D which will need to be corrected to zero using an offset. Positive forces are preload, while negative forces are adhesive.
heating showed a movement of $0.01 \mu m \, ^{\circ}C^{-1}$ in the planar directions and $1.0 \mu m \, ^{\circ}C^{-1}$ in the z-direction. These relative shifts meant that testing the same sample location in both vacuum and atmosphere, or between different temperatures (pairwise comparisons) was not feasible because absolute location of indentation was not known. One cause of measurement uncertainty was found to be variance between locations on a sample. To reduce variability, a number of locations were tested.

Testing at arbitrary temperatures and pressures was not possible. A schematic of the feasible testing zone is the area enclosed in Figure 3.8. At low temperatures, to avoid condensation on the sample or probe, low pressure was required. This was because the use of a vacuum reduced water vapor in the chamber. The lowest pressure achievable was $1 \times 10^{-5}$ mbar at room temperature, or $1 \times 10^{-6}$ mbar when the LN$_2$ was cooling the stage because additional vapors condensed onto the LN$_2$ tube (the tube acted as a cold plate). When using temperatures below $0 \, ^{\circ}C$, a low pressure was necessary to avoid excessive sensor heating which affected results. Thermal transfer from the stage to the sensor was reduced
CHAPTER 3. SYNTHETIC DRY ADHESIVES IN SPACE ENVIRONMENTS

Figure 3.6: Mounting a sample increases the peak adhesion, and eliminates the secondary detachment seen for a floating sample. Only the adhesive (negative) portion of the unloading plot is shown, but both samples had equal preload forces.

Figure 3.7: Testing in poor and pristine locations. When using a pristine region of adhesive, the overall adhesion is higher.
in low pressure because convection transfer was negligible.

The effect of vacuum and temperature on measurements was characterized. This was done by indenting with the quartz probe onto a fused silica sample. Because fused silica is a very hard material, and the probe is blunt, the indentation depth was expected to be negligible. By indenting to a constant force at ambient conditions, and observing the measured displacement, and then comparing this displacement to the displacement obtained under low pressure and various temperatures, the effect of changing environmental conditions on the apparatus was found. From this experiment, an error estimate of $14 \text{ nm \cdot mN}^{-1}$ was obtained between atmospheric and low pressure trials. By varying the temperature at a pressure of $1 \times 10^{-5} \text{ mbar}$, an error of $0.6 \text{ nm \cdot mN}^{-1} \circ C^{-1}$ was obtained. These correction factors were applied to all the data collected so that they could be properly compared against room temperature data. Note that the correction factors are expressed in units of nm mN$^{-1}$ because a cantilever was used to convert forces into distances measurable by the LVDT: measurement
Figure 3.9: Effect of PDMS to long term exposure to high temperatures. After exposure to high temperatures, the PDMS becomes stiffer (indentation depth for a given force is reduced).

Because heat is used to cure PDMS, as a result of spending time at elevated temperatures (during testing) the material properties of PDMS changed permanently. As seen in Figure 3.9, the sample permanently stiffened as a result of exposure to elevated temperatures for extended times (order of hours). The stiffening was manifested as an increased preload force for a constant depth (similar to a spring with a stiffer spring constant). The tests were all conducted below 75°C to limit this stiffening, and the highest temperature tests were conducted first, so that any stiffening was seen in all the tests. However for a robot application, the effect of a stiffer adhesive substrate should be characterized in future work.

The tests were conducted in a vacuum, limiting convection thermal transfer. The sample was heated but the probe temperature was unregulated, causing concern that the temperature difference between the sample and the probe caused erroneous measurements following a sample temperature change. To reduce the effect of changing probe temperatures, during thermal testing the probe was brought into contact with the sample for an extended period of time, bringing the temperatures to equilibrium before taking measurements.


CHAPTER 3. SYNTHETIC DRY ADHESIVES IN SPACE ENVIRONMENTS

3.2 Effects of Vacuum

To test the effect of a vacuum on adhesion, measurements were conducted at atmospheric pressure (980 mbar) and vacuum (1 $\times$ 10$^{-5}$ mbar) pressure. Data was fit to the model presented by Shargott et al., who defines a saturation adhesion as the maximum adhesion possible for a given indenter geometry, independent of the preload force [37]. If the saturation adhesion has not been reached, adhesion can be modeled as a function [37] of the preload according to:

$$f_a = 2\sqrt{f_{a(sat)}f_p} - f_p,$$

where $f_a$ is the adhesive force, $f_{a(sat)}$ is the saturation adhesion force, and $f_p$ is the preload force. 488 data points in vacuum and 408 data points in atmosphere (where one data point is a preload and detachment pair) were collected (see Figure 3.10a). This represented one day of data collection. To compare the results obtained in this research, estimates of $f_{a(sat)}$ were computed for both the atmosphere and vacuum tests, and the estimated were compared to each other. The estimates were computed by transforming (3.1) into a form suitable for linear regression:

$$Y = bX,$$

where $Y$ was equal to $f_a + f_p$, X is equal to $\sqrt{f_p}$ and $b$ is defined as:

$$b = 2\sqrt{f_{a(sat)}},$$

Using the regression toolbox in MATLAB, $b$ and its 95 percent Confidence Intervals (CIs) were computed. The transformation:

$$f_{a(sat)} = \frac{b^2}{2},$$

was applied to both $b$ and its 95 percent CIs to transform the estimate of $b$ into an estimate of $f_{a(sat)}$ in the vacuum and atmosphere conditions. For the measurements in a vacuum, an estimate of 18.57 mN was obtained and in atmosphere an estimate of 18.31 mN was obtained for the saturation adhesion. The 95 % confidence intervals (CIs) of these estimates overlap, as shown in Figure 3.10b, demonstrating that there was no significant
Figure 3.10: Original data points (left) and 95% CIs (right) for saturation adhesion values of synthetic gecko adhesives in atmosphere and vacuum.

Because the NST also resolved displacement measurements, it was possible to examine the preloading curves for each measurement. Applying the method in Greiner et al. gave estimates of the effective Young’s modulus ($E^*$) of the structured adhesive [31]. The equation used from Greiner was:

$$f_p = \frac{4}{3} E^* \sqrt{rs^3}, \quad (3.5)$$

where $r$ is the indenter radius (750µm), $s$ is the indentation depth, and $f_p$ is the applied force as before. Fitting the data to (3.5) gave estimates of $E^*$ of 2.260 MPa ($n=488, \sigma=0.1324$) in a vacuum and 2.395 MPa ($n=408, \sigma=0.2122$) in atmosphere. Using a t-test, these estimates were found to be significantly different at the p-value of $p=0.05$, meaning that the vacuum had an effect on sample stiffness, even though no effect was found on adhesion. This difference was likely due to outgassing in vacuum, or a reduced humidity in vacuum (laboratory humidity was 70% and humidity in vacuum was negligible). The data used, and estimates
of $E^*$ generated are shown in Figure 3.11.

Because a change was noted in $E^*$ resulting from pressure change, the data was examined to see if a time-dependent effect could be detected. A time dependent effect may result from continued outgassing of the sample under vacuum, but was not expected to occur in atmosphere where conditions were not changing. Indentation tests were conducted over 8 hours in both atmosphere and vacuum, and estimates of $E^*$ and $f_{a(sat)}$ were computed. These estimates were divided into two groups, for measurements in the first and second four hours. In Figure 3.12, the effect of time on $E^*$ is shown, and in Figure 3.13 the effect of time on $f_{a(sat)}$ is presented. A t-test was conducted to look for the effects of time on both quantities. At a confidence level of 95%, only the effect of time on $E^*$ in vacuum was significant ($p = 0.0011, n = 464$). As expected, the effect was not seen in atmosphere ($p = 0.2228, n = 267$). No effects of time on $f_{a(sat)}$ were noticeable in the eight hour tests conducted in either vacuum ($p = 0.0705, 35$) or atmosphere ($p = 0.3100, n = 16$).
CHAPTER 3. SYNTHETIC DRY ADHESIVES IN SPACE ENVIRONMENTS

Figure 3.12: Estimates of $E^*$ for indentations in vacuum and atmosphere plotted against time. Trials were conducted over eight hours, and divided into 2 groups, those in the first 4 hours ($0 \leq t \leq 4$) and those in the last 4 hours ($4 \leq t \leq 8$) for vacuum and atmosphere environments.

3.3 Effects of Temperature

A total of 219 measurements were performed at temperatures between $-50 ^\circ C$ to $75 ^\circ C$. The results are presented in Figure 3.14a where the colors of the points represent the sample temperature during the measurement. In Figure 3.14b, the 95 % CIs are shown for each temperate tested. No clear relationship was observed, however, Schneider et al. noted that the stiffness of PDMS changes linearly with temperature [44]. To test if temperature also affected adhesion in a linear manner, linear regression was performed on:

$$f_a + f_p = b_1 + b_2 \sqrt{f_p} + b_3 T + b_4 \sqrt{f_p} T,$$

where $b_{1-4}$ are parameters to be estimated, and $T$ was the temperature in $^\circ C$. At a confidence level ($\alpha$) of 0.05, the terms involving $T$ ($b_3$ and $b_4$) were not significant. Therefore no significant effect of temperature was detected with our experiment. The increased variance seen in this plot compared to the tests involving only pressure and not temperature likely stemmed from thermal effects on the equipment, for example expansion or contracting of
CHAPTER 3. SYNTHETIC DRY ADHESIVES IN SPACE ENVIRONMENTS

Figure 3.13: Estimates of $f_{a(sat)}$ for indentations in vacuum and atmosphere plotted against time. Trials were conducted over 8 hours, and divided into 2 groups, those in the first 4 hours ($0 \leq t \leq 4$) and those in the last 4 hours ($4 \leq t \leq 8$) for vacuum and atmosphere environments.

the chamber walls during testing.

3.4 Summary

The testing at ESTEC using the NST revealed three primary findings. Adhesion of PDMS dry adhesives was not found to change in pressures down to $1 \times 10^{-5}$ mbar, or with temperatures between $-50^\circ$C and $75^\circ$C. This completed the first thesis objective, validating the use of synthetic dry adhesives in space environments. The tests revealed further interesting results. An observed reduction in the measured $E^*$ of the PDMS adhesives when in vacuum is suspected to have resulted from either outgassing or a change in ambient humidity. In vacuum, a change in $E^*$ due to outgassing of the PDMS over time was observed. This effect was not observed in the atmosphere tests for the same time duration. However, because no decrease in adhesion was noted, it appears that the adhesive capability of a PDMS dry adhesive is robust to changes in $E^*$. These findings support the use of PDMS dry adhesives in space environments, for example as a method of holding robots to the exterior of satellites.
Figure 3.14: Synthetic gecko adhesion at various temperatures and preload forces. In (a), the adhesion measurements at various temperatures and preload forces are shown. In (b), the estimates of $f_{a(sat)}$ (and error bars showing the 95% CI of $f_{a(sat)}$) are presented for each temperature tested.
Chapter 4

Mechanical Design of a Climbing Robot

The second thesis objective is to design a climbing robot that uses synthetic dry adhesives for scaling smooth vertical surfaces. Optimization of the design of a climbing robot is presented in this chapter. A legged robot was built because, as discussed in Section 2.2, this locomotion style has advantages over other styles in space environments (namely dexterity and an inherent factor of safety). Dry adhesives were used because they have more potential for sticking in space environments than other mechanisms (suction, magnetism or PSAs).

The design process is presented in Figure 4.1. First, the design constraints and goals were identified. A study of reference models allowed motor selection and body sizing, as well as an estimate of the robot’s mass. Using an estimate of the robot’s mass, the robot’s leg was optimized. This subsystem was chosen for detailed analysis because it had many variable parameters including size and nominal position. Foot design and a complete Computer-Aided Design (CAD) model of Abigaille-III will be presented later in the manufacturing chapter (Chapter 6).

4.1 Problem Definition and Constraints

This robot was an upgrade of the previous robot, Abigaille-II. The control system of Abigaille-II was an off-the-shelf unit and did not allow the user to build and test custom control systems. In addition, Abigaille-II under-performed predicted climbing rates by
four times, due to bending of parts [6]. To solve these problems, a robot using a FPGA and custom Printed Circuit Board (PCB) for control system implementation and with sufficient strength to support its own mass and the mass of the controller was needed. The six leg (hexapod) design was selected, in order to take advantage of an inherent factor of safety while climbing. The application of this robot is for space environments, so minimizing mass and size, while retaining dexterity were primary objectives.

4.2 Mass Estimate and Motor Selection

The tasks of estimating the robot’s mass and selecting appropriate motors were conducted in parallel because motors with larger torque generally have a higher mass, and the robot’s mass affected the required motor torque to move the robot. First the fixed masses were calculated. These are masses that are the same for any mechanical design. The FPGA and PCB together weighed 105 g. The cables and fasteners for a six leg prototype had an estimated mass of 160 g (this estimate assumed 120, 100 mm length wires), leading to a Total Fixed Mass ($m_{TFM}$) of 265 g.

Next the variable masses were computed. From two reference designs, the mass of the leg parts ($m_{LP}$, units of g) as a function of motor torques ($\tau$, units of N·m) was estimated using CAD tools to be $75 \text{ g N}^{-1} \text{ m}^{-1}$. A table of motor options with masses in the 5 g to 45 g range, appropriate for Abigaille-III, is provided (Table 4.1). The Gizmozone motor has the lowest mass, and is used in Abigaille-II, however the torque is also quite low. The highest torque motor investigated, Pololu 150:1, has a torque to mass ratio that is almost 6.5 times superior to the Gizmozone motor. To evaluate whether any of these motors were suitable, one additional equation was needed.
CHAPTER 4. MECHANICAL DESIGN OF A CLIMBING ROBOT

Table 4.1: Motor options for the design of Abigaille-III

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (g)</th>
<th>Torque (N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gizmozone</td>
<td>5.1</td>
<td>0.025</td>
</tr>
<tr>
<td>Pololu 100:1</td>
<td>10</td>
<td>0.177</td>
</tr>
<tr>
<td>Micromo brushless</td>
<td>27</td>
<td>0.18</td>
</tr>
<tr>
<td>ISL motor</td>
<td>32</td>
<td>0.18</td>
</tr>
<tr>
<td>DFRobot</td>
<td>45</td>
<td>0.19</td>
</tr>
<tr>
<td>IG-22</td>
<td>35</td>
<td>0.2</td>
</tr>
<tr>
<td>Pololu 150:1</td>
<td>10</td>
<td>0.318</td>
</tr>
</tbody>
</table>

Because the design of this robot was complex, it was necessary to refine certain parameters and equations during course of the design. Later (Section 4.3), a more precise equation will be derived, but for motor selection, it was assumed that only one motor per leg is used for lifting the robot’s body vertically up the wall, and the leg segment actuated by this motor was perpendicular to the wall, as shown in Figure 4.2 (in this diagram, Motor 2 is used for lifting the body up the wall).

When moving the robot’s body vertically, the motors had to support the robot’s mass. Assuming the mass was equally distributed about the robot legs, an equation was found for $f_{BP}$, the force on the robots body parallel to the wall:
where $m$ is the total robot mass including that of 24 motors and $g$ is the force due to gravity (9.81 m s$^{-1}$). Assuming all the legs were working together, the motors must supply at least enough torque to support the force on the robot’s feet:

$$f_{BP} \leq \frac{T_{MLit}}{h} n,$$

where $n$ is the number of legs (six for Abigaille-III) and $h$ (see Figure 4.2) is the distance of the robot from the climbing surface.

Combining (4.1) and (4.2), and applying a safety factor of two, provided minimum torque-mass curves for the motor, as a function of the robot’s distance to the wall ($h$) (see Figure 4.3). As the length of the leg segments are not yet defined, three values of $h$ between 25 and 100 mm are plotted for reference. The Pololu 150:1 motor was optimal (highest torque to mass ratio) from the considered motors, though the Pololu 100:1 motor also appeared suitable, assuming the leg lengths were kept below 0.1 m which was a reasonable assumption. The Gizmozone motor was not an option for this robot, as the leg lengths would have be too constrained, step sizes too small and robot speeds too slow. The heavier motors would have been possible, but because of the design goal of keeping mass low, they were not selected. The Pololu 150:1 was chosen for implementation on the robot.

A number of parameters about the robot have been determined. An estimate of the mass of 550 g which can be used for future design calculations was obtained by adding the leg parts mass ($m_{LP}$) to the fixed mass ($m_{TFM}$) and adding the mass of 24, 10.0 g motors. To keep the robot’s overall size small, the body frame size was designed to be the same as the PCB and FPGA (120 mm x 200 mm).

### 4.3 Robot Leg Optimization

To improve climbing performance and limit failures, the leg size and foot placement were optimized. A climbing gecko pulls its head towards the wall to counteract the tendency to pitch-back [56]. In a similar fashion, a pitch-back failure is defined as a fall caused by the front or middle feet of the robot detaching during vertical climbing. To minimize the risk of a pitch-back failure when Abigaille-III climbed vertically, optimal leg attachment
Figure 4.3: Curves guiding motor selection in Abigaille-III. Black lines are the minimum torque for a given motor mass at specific body distances $h$. Grey dots mark selected motors available for purchase. A motor is feasible for any $h$ that falls below it (at a lower torque) on the graph.

positions were found. First a kinematic analysis was performed which identified the climbing configuration that minimized the tension forces at the front and middle feet.

The equation of static equilibrium for Abigaille-III was:

$$Gf = w,$$  \hspace{1cm} (4.3)

where $f$ is the set of forces at the robots feet, $G$ is the grasp matrix, and $w$ is the wrench. $w$ is comprised of two vectors:

$$w = \begin{bmatrix} \begin{bmatrix} f_B \end{bmatrix}_{3\times1} & \begin{bmatrix} M_B \end{bmatrix}_{3\times1} \end{bmatrix},$$  \hspace{1cm} (4.4)

where $f_B$ and $M_B$ are respectively the external forces and moments acting on the robot’s body. The vector $f$ has eighteen elements, comprising the 3-Dimensional (3D) forces at the robot’s feet, which can be separated into components along each of the coordinate axis (see reference frame in Figure 4.4a):
Figure 4.4: Diagram of the robot on the wall, in 3D (a) and 2D (b). For clarity, in the 3D schematic, only forces for leg 3 and distances from the COM for leg 4 are shown.

\[
f = \begin{bmatrix} f_x[1 \times 6] & f_y[1 \times 6] & f_z[1 \times 6] \end{bmatrix}^T,
\]

where each of \( f_x \), \( f_y \) and \( f_z \) are vectors containing one element for each foot on the robot, (e.g. \( f_{x1} \), \( f_{x2} \), ..., \( f_{x6} \)), as shown in Figure 4.4a. Referencing Figure 4.4a, which shows the displacements for a single leg, the grasp matrix for the entire robot is given by:

\[
G_{[6 \times 18]} = \begin{bmatrix}
1_{[1 \times 6]} & 0_{[1 \times 6]} & 0_{[1 \times 6]} \\
0_{[1 \times 6]} & 1_{[1 \times 6]} & 0_{[1 \times 6]} \\
0_{[1 \times 6]} & 0_{[1 \times 6]} & 1_{[1 \times 6]} \\
0_{[1 \times 6]} & d_z[1 \times 6] & d_y[1 \times 6] \\
d_z[1 \times 6] & 0_{[1 \times 6]} & d_x[1 \times 6] \\
d_y[1 \times 6] & d_x[1 \times 6] & 0_{[1 \times 6]}
\end{bmatrix},
\]

where \( d_x \) is the vector of the six displacements from the Center Of Mass (COM) of the robot to each of its feet in the \( x \) direction (\( d_{x1} \), \( d_{x2} \), ..., \( d_{x6} \)), and \( d_y \) and \( d_z \) are the vectors of six displacements in the \( y \) and \( z \) directions respectively.

Abigail-III was symmetric from its head to rear. Assuming vertical climbing, this allowed a 2-Dimensional (2D) analysis to be conducted. In this case, the forces in the \( y \) axis and moments around the \( x \) and \( z \) axes of (4.4) are neglected, and the displacements and forces at legs 3, 4 and 5 are equal to those at legs 2, 1 and 6 respectively (see Figure 4.4b).
CHAPTER 4. MECHANICAL DESIGN OF A CLIMBING ROBOT

In this simplification, \( f \) is reduced to a six by one vector:

\[
f = \begin{bmatrix} f_x[1 \times 3] & f_z[1 \times 3] \end{bmatrix}^T,
\]

where \( f_x \) and \( f_z \) consist of the forces only on three legs (e.g. \( f_{x3}, f_{x4} \) and \( f_{x5} \)). \( G \) simplifies to a three row by six column matrix,

\[
G = \begin{bmatrix} 1_{[1 \times 3]} & 0_{[1 \times 3]} \\ 0_{[1 \times 3]} & 1_{[1 \times 3]} \\ d_x[1 \times 3] & d_z[1 \times 3] \end{bmatrix},
\]

and \( w \) simplifies to a one by three matrix,

\[
w = \begin{bmatrix} f_B[1 \times 2] & M_B \end{bmatrix}^T.
\]

The external force \( f_B \) on the robot’s body (see Figure 4.4b) is separated into two components: \( f_{BN} \), which is normal to the wall and \( f_{BP} \), which is parallel to the wall. Since it is assumed that the robot is climbing vertically, the external force due to gravity is in the direction of \( f_{BP} \), yielding:

\[
f_{BP} = mg,
\]

and

\[
f_{BN} = 0,
\]

where \( m \) is the robot’s mass and \( g \) is the acceleration due to gravity. There was no net torque on the body (because the only contact the robot had to the surface was through its feet), reducing the external wrench vector, \( w \), to its 2D form:

\[
w = \begin{bmatrix} mg & 0 & 0 \end{bmatrix}^T.
\]

The robot’s body was assumed to be parallel to the wall, so that the distance from each leg to the wall is constant. While this is not the worst case, it was chosen for this optimization because vertical climbing was to be the most frequent use of Abigail-I. The variables \( d_{x3}, d_{x4} \) and \( d_{x5} \) are therefore equal, and for the rest of this section they are referred
to as the height \( h \). Equation (4.3) has infinite solutions, as the rank of \( G \) is less than the number of columns in \( G \) [57]. The Moore-Penrose Pseudoinverse \((^\dagger)\) is used to compute an analytical solution,

\[
f = G^\dagger w,
\]

which yields:

\[
f = \begin{bmatrix} \frac{mg}{3} & \frac{mg}{3} & \frac{mg}{3} & -hmga_1 & -hmga_2 & -hmga_3 \end{bmatrix}^T,
\]

\[
a_1 = \frac{0.5(-2d_{x3} + d_{x4} + d_{x5})}{D},
\]

\[
a_2 = \frac{0.5(d_{x3} - 2d_{x4} + d_{x5})}{D},
\]

\[
a_3 = \frac{0.5(d_{x3} + d_{x4} - 2d_{x5})}{D},
\]

\[
D = d_{x3}d_{x4} + d_{x3}d_{x5} + d_{x4}d_{x5} - d_{x3}^2 - d_{x4}^2 - d_{x5}^2.
\]

The forces at each foot in the normal direction \( f_{z3}, f_{z4} \) and \( f_{z5} \) are functions of the values \( d_{x3}, d_{x4}, d_{x5} \) and \( h \). It can be shown that the denominator, \( D \), of (4.15-4.17) is always less than or equal to zero. To do so, the following relationship (4.19) is assumed:

\[
d_{x3} \geq d_{x4} \geq d_{x5}.
\]

The following re-parameterizations are made:

\[
d_{x4} = d_{x3} - A,
\]

and

\[
d_{x5} = d_{x3} - B.
\]

Substituting (4.21) and (4.21) into (4.19) and simplifying, an expression for \( D \) is obtained:

\[
D = -(A - B)^2 - AB.
\]
From (4.19), both $A$ and $B$ are greater than zero, so the denominator, $D$ is less than or equal to zero. The inequality $D$ equal to zero corresponds to all the feet placed at the same position, which is not feasible on this robot. Since $d_{x5}$ is of the opposite sign to $d_{x3}$ and $d_{x4}$ (the rear foot was placed on the opposite side of the COM to the front and middle feet), and the denominator is less than zero, $a_3$ is always negative. The consequence is that the rear foot was always in compression during vertical climbing. This is a similar principle to a rock climber, who uses their hands to pull their body towards the surface, and their feet to push away from the surface.

When the tension forces at the feet of the robot exceeded the adhesive capability of the synthetic dry adhesives, detachment and climbing failure was risked. Thus, while climbing, one goal was to reduce the normal tension forces in the front and middle feet. From (4.14), this can be done by reducing $a_1$, $a_2$ and/or $h$. In terms of mechanical design, reducing $h$ involved selecting gaits which kept the robot’s body close to the climbing surface, and placing the electronics (which were heavy) as close to the surface as possible (while retaining sufficient body clearance for negotiating terrain). The placement of feet during a gait affects $a_1$ and $a_2$. Referencing (4.15) and (4.16), moving the rear feet further rearward (decreasing $d_{x5}$) decreases $a_1$ and $a_2$ (and correspondingly the magnitude of tension force that each foot experienced). This is a similar principle to the function of the tail of a climbing gecko, which stretches behind the gecko to prevent it from falling [56].

The effect of foot placement is shown in Figure 4.5a, where the rear feet are stretched rearwards, and the front foot positions are varied. Contour lines represent the maximum tension force experienced by any foot. Tension forces are reduced when the feet are at equal distance from the COM, and as far forward as possible. The position used for Abigail-III is marked in Figure 4.5 (a) as the point marked 1, corresponding to a maximum tension force of 0.29 N. In Figure 4.5b, a schematic of the robot assuming the chosen configuration is shown. This specific position was selected as increasing the foot placement distances from the COM, while decreasing the tension forces, required a larger body frame size or longer leg segment. Increasing the body frame size was undesirable because it would have increased the mass and size of the entire robot.

The effect of leg segment lengths is now discussed. Assuming the robot was placed in its optimal configuration, namely four legs forward and two legs rearward [6], a feasible region for the leg sizes was desired. To find the feasible region, first the Jacobian of the leg, $J$, which relates the force at each foot of the robot, $f$, and torque at the robot’s joints, $\tau$, of
Abigaille-III is defined according to [58],

\[ \mathbf{f} = (\mathbf{J}^T)^{-1} \tau, \quad (4.23) \]

where \( \mathbf{f} \) is comprised of \( f_x \) and \( f_z \) as in (4.7). To find the specific Jacobian for each leg of this robot, in reference to Figure 4.6, where a schematic robot leg is shown taking a vertical step, first the forward position kinematics for a single leg are written:

\[
\begin{bmatrix}
  x \\
  z
\end{bmatrix} =
\begin{bmatrix}
  l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) \\
  l_1 \sin(\theta_1) + l_2 \sin(\theta_1 + \theta_2)
\end{bmatrix}.
\quad (4.24)
\]

Taking the partial derivatives of these equations gives the Jacobian of a single leg:

\[
\mathbf{J} =
\begin{bmatrix}
  -l_1 \sin(\theta_1) - l_2 \sin(\theta_1 + \theta_2) & -l_2 \sin(\theta_1 + \theta_2) \\
  l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) & l_2 \cos(\theta_1 + \theta_2)
\end{bmatrix}.
\quad (4.25)
\]

In a 2D case, as when computing optimal leg positions, \( \mathbf{f} \) is a vector comprised of \( f_x \), the shear direction force, and \( f_z \), the normal direction force. To simplify the analysis, it is
assumed that the weight of the robot was equally distributed over each foot. This means each leg must support its mass while climbing vertically or walking horizontally:

\[ f_x = f_x \geq \frac{mg}{n}, \tag{4.26} \]

where \( n \) is the number of legs on the robot. Abigaille-III is a hexapod, so \( n \) is six. Equations (4.25) and (4.26) are substituted into (4.23), and solved for \( l_1 \) and \( l_2 \), which, due to the inequality in (4.26), are the maximum lengths that the leg segments can be while supporting the robot’s mass.

To obtain the minimum bound on the leg segment lengths, the typical gait of Abigaille-III was considered. Referring to Figure 4.6, which schematically represents a leg, the leg had two segments: the first segment had length \( l_1 \) and second segment had length \( l_2 \). The angles \( \theta_1 \) and \( \theta_2 \) were the joint angles. Two constraints were imposed on the gait: the step length was \( l_{step} \), and the joint attachment to ground distance was at least \( h \) in order to keep the robot’s body off the ground.

For the robot to take a step forward, the contact point moved from position \( P_1 \) to position \( P_2 \), which had a separation of \( l_{step} \) (see Figure 4.6). The situation where \( \theta_1 + \theta_2 = \frac{3\pi}{2} \) was considered. In this position, the leg of the robot was centered around the normal to the surface. At \( P_1 \), the angle of the second joint was represented as a nominal angle \( \theta_2 \) with an offset of \( -\alpha \) (see Figure 4.6). Similarly at \( P_2 \), the angle was \( \theta_2 + \alpha \). An equation
relating $h$ to the joint lengths and angles was written:

$$ l_1 \sin(\theta_1) + l_2 \sin(\theta_1 + \theta_2 + \alpha) + h \leq 0. $$

(4.27)

The step length and second segment length are related by:

$$ l_2 \sin(\alpha) - \frac{l_{\text{step}}}{2} = 0. $$

(4.28)

Together, (4.27) and (4.28) give two equations with three unknowns, which can be solved for $l_1$ giving:

$$ l_1 \geq \frac{1}{\sin(\theta_1)}(h - l_2 \cos(\arcsin(l_{\text{step}}/2l_2))). $$

(4.29)

From (4.29) $l_2$ must be at least $l_{\text{step}}/2$ due to the bounds on the arc sine function; physically, this limit corresponds to the minimum segment length required to produce a step of length $l_{\text{step}}$.

At present, these equations are general for a climbing robot with a hexapod configuration. To set specific bounds on the segment lengths for Abigaille-III, numerical parameters were required. A minimum step size ($l_{\text{step}}$) of 0.01 m was selected, which is the step size used in Abigaille-II. The joint attachment height, $h$, had a value of 0.021 m, which was dictated by the thickness of the populated PCB and chosen to allow some clearance to the ground or wall. Typical motor torques were 18.0 g.m (found experimentally when characterizing the motors in Section 5.2.2) and nominal joint angles of $\theta_1 = 10^\circ$ and $\theta_2 = 260^\circ$ were used.

Combining these parameters with (4.23) and (4.29) allowed the generation of a feasible space for the leg segments (shown as the region inside the solid line in Figure 4.7). Specifically, segments A and B result from (4.23), and represent the maximum leg lengths for a given motor size, while segments C and D result from (4.29) which represent the minimum leg lengths to take a step forward of length $l_{\text{step}}$. Next, the limits of fabrication were considered: empirically, it was observed that leg segments longer than 0.07 m deflected and twisted excessively under load. Segments shorter than 0.01 m were of insufficient length to construct a joint. These manufacturing limits were dictated by the use of 3D printer material; if another manufacturing method were selected it may have been possible to choose from a different set of segment lengths. The grey lines on Figure 4.7 represent contours of equal force that the robot can apply at its foot.
The region inside both the solid and dotted lines represent the feasible space for leg segment lengths. For the front and middle legs, 0.03 m segments were used (design point I in Figure 4.7), and for the rear legs, a 0.03 m first segment and 0.05 m second segment (design point II in Figure 4.7) were used. The longer second segment of the rear leg allowed this leg to extend further and better counter-act the tendency to pitch-back, as previously analyzed.

4.4 Summary

In this chapter, the motors for the robot were selected and justified, the robot’s mass was estimated, and mechanical optimization was conducted. The methodology and equations presented in this chapter were deliberately introduced in a general form, and then applied to the specific design constraints and goals of Abigaille-III. This completes the second thesis objective: designing a climbing robot that uses synthetic dry adhesives for scaling smooth
vertical surfaces.
Chapter 5

Control System

In this chapter, the control system of Abigaille-III is outlined. Two thesis objectives are addressed: the implementation of a computing architecture suitable for use with the climbing robot, and the development of control strategies for (a) moving the feet and robot’s body between climbing positions, and (b) preloading the robot’s feet firmly to a vertical surface. The computing system for Abigaille-III was implemented on an FPGA [59]. This affected the robot’s mechanical design because the electronics payload is larger and heavier than in previous Abigaille versions. In this section, this design choice is explained and justified. An outline of the hardware and software comprising the computing system is provided. Some system tests were conducted to evaluate the architecture. Two controllers were implemented in software: an open-loop controller was used for preloading and a closed-loop controller was used for leg joint positioning.

5.1 Computing Architecture

In other works (e.g. [48, 54, 60]), embedded robots use a small computer, microcontroller or multiple microcontrollers for their computing system. For Abigaille-III, which is a laboratory platform for future experimentation, the design goals in Table 5.1 were set. The first goal, encapsulating levels of control, could be achieved with software (i.e. a multi-threaded program) or hardware (with multiple processors, or even hardware blocks for the lowest control levels). Minimizing size and mass meant that reducing component count is ideal; for this criteria a FPGA or single Microcontroller (MCU) performed better than multiple MCUs. A MCU is an easier development platform than an FPGA because no hardware


Table 5.1: Computing system design criteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design criteria</th>
<th>Ideal System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Encapsulation</td>
<td>Each level of control is encapsulated</td>
<td>Any</td>
</tr>
<tr>
<td>Size and mass</td>
<td>Minimized</td>
<td>MCU, FPGA</td>
</tr>
<tr>
<td>Ease of use</td>
<td>Usable by non-computer engineers</td>
<td>MCU</td>
</tr>
<tr>
<td>PID frequency</td>
<td>1 kHz</td>
<td>FPGA</td>
</tr>
<tr>
<td>Coordination loop-frequency</td>
<td>100 Hz</td>
<td>FPGA</td>
</tr>
<tr>
<td>I/O Pins</td>
<td>8 PWM + 3 ADC + 1 GPIO per leg</td>
<td>FPGA</td>
</tr>
</tbody>
</table>

Table adapted from [59] © 2012 IEEE.

design skills are needed. However, with a proper architecture (i.e. implementing in software the aspects of the system that will be changed often) this can be alleviated. Alternately, high-level design tools like the National Instruments (NI) LabVIEW FPGA module can simplify hardware implementation tasks. Loop frequencies will be higher on an FPGA than on one or many MCUs, because of the option to implement time-critical algorithms in hardware instead of software. Considering the number of Input/Output (I/O) pins, and especially when specialty I/O pins are considered (Pulse Width Modulation (PWM) or Analog to Digital Converter (ADC)), the FPGA was the preferred choice. While a multiple MCU system provides many I/O pins, the communication rate between processors was found to be slower. Transferring 32 bits (typical package size in the implementation on Abigaille-III) over a First-In First-Out buffer (FIFO) takes 4 clock cycles at 50 MHz, while an I²C data transfer between MCUs at 100 kHz required 96 clock cycles, (11750 times slower) [59].

 Compared to an Application Specific Integrated Circuit (ASIC), the FPGA also has advantages. The cost of manufacturing an ASIC is very high, and the flexibility to redesign the FPGA to meet changing design goals is a significant advantage. For example, if an extra level of control (i.e. a path planner) was added to the robot in the future, a computing system on a FPGA could be modified more easily to meet this demand than an ASIC.

5.1.1 Computing System Implementation

The system implemented on the FPGA contained seven soft-processors, as shown in Figure 5.1. One processor, the coordinating processor, was responsible for high-level decisions about the robot. It kept the other processors synchronized. The six leg-control processors were responsible for running low level controllers, each for a single leg. This involved reading
sensor data and updating actuator control signals.

Also on the development board was a 16 MB Synchronous Dynamic Random-Access Memory (SDRAM), which was accessed by the coordinating processor. The SDRAM was used for storing trajectory tables, which commanded the individual joints where to go to perform complex motions. To execute a trajectory, a portion of the table was loaded to Block Random-Access Memory (BRAM), and individual commands were sent by the coordinating processor to the corresponding leg processor. The trajectory tables had a size on the order of 1 kB, which could fit in BRAM, however the implemented tables were quite simple. More complex tables, or storing multiple tables, necessitates the future use of off-FPGA storage, so the capability was built into this version. SDRAM was also used for coordinating processor code, code profiling and storing state information during testing. When detailed information about the control system during operation was desired, the control system state was logged in SDRAM, and uploaded to a PC via RS-232 following operation. This technique avoided
issues with a slow RS-232 communication interfering with the real-time operation of the system.

Each processor has its own address space because if the processors all shared a bus, the bus would be overloaded and slow. In addition, there is no need for all the processors to be accessing all the system resources; each processor only needs to talk to its own sensors and actuators and communicate to the coordinating processor. Communications are all routed through the coordinating processor, preserving the distinct levels of control and design goal of encapsulation.

With this architecture, scalability is ensured. The computing hardware corresponds to distinct mechanical elements; if a new leg is added to the robot, a new soft processor and leg control system is built. This is simple to implement on the FPGA: each processor is running identical code, so duplicating one of the existing leg control processors is possible. Scaling to new levels of control is also possible. A path planner with its own suite of sensors and feedback could be implemented on top of the controlling processor. This hypothetical path planner could have its own soft processor, as well as some peripherals for interfacing with its sensors. Implementing such a path planner was outside of the scope of the current work.

This design was implemented on a Spartan-3A, using Xilinx MicroBlaze soft processors. The FPGA has a 4-Look-Up Table (4-LUT) architecture, and the design operated at a system clock frequency of 50 MHz. In Figure 5.2, the coordinating processor block diagram is presented. For communicating to a Personal Computer (PC), a Universal Asynchronous Receiver/Transmitter (UART) and Debug Module were provided. The UART was used to provide limited feedback during operation, or extended feedback following operation to the user regarding the control system. A manual mode was also implemented to allow the user to control individual joints. This was used to test the effect of applying extra preload while climbing. The General Purpose Input/Output (GPIO) and Light Emitting Diode (LED) provided feedback to the user about the system health of the robot. The coordinating processor had a small BRAM, however the program software was stored in SDRAM, and accessed via cache link and a Multi-Port Memory Controller (MPMC). Interrupts were generated by a 1 kHz timer, which synchronized the coordinating processor with the leg processors. There were also six bi-directional Fast Simplex Link (FSLs), which provided communication between the leg control processors and the coordinating processor. These operate in non-blocking mode from the coordinating processor side, and generated interrupts
when data was available.

In Figure 5.3, a processor block diagram is provided for one of the leg controllers (all six are identical). These controllers had a set of sensors and actuators, which communicated to the FPGA through ADCs and PWM generators respectively. A FSL connected the leg processor to the coordinating processor, and it operated in non-blocking mode. A fixed interval timer (FIT) ensured the control loop ran at 1 kHz and if it did not complete in time, a warning was sent back to the coordinating processor. On every interrupt of the FIT, all the ADCs were polled, control parameters were updated and signals were output to the PWM generators. The ADCs and PWM generators were implemented as hardware peripherals; the PWM generators generated 20 kHz signals.

### 5.1.2 Software Design

There were two programs running on Abigaille-III’s computing system. The coordinating processor software controlled the high-level operation of the robot, including selecting and
Figure 5.3: Block diagram showing the MicroBlaze leg processor, used for each of the six leg controllers. Figure adapted from [59] © 2012 IEEE.

sending appropriate trajectories to each leg control processor. It looked for signs that a foot was not detaching and ensured that the foot detached fully before moving on to the next trajectory. The leg control processors were responsible for low level control functions. Due to the parallel nature of the system, each processor was only responsible for four joints (four PWM signals and reading four sensor values), making the 1 kHz loop frequency quite feasible.

Using an Operating System (OS) for this design was unnecessary. While an OS could abstract the low level functions of the system (e.g. by providing hardware drivers, scheduling tasks or handling memory allocation), only one program was running on the system and the program complexity was low, making scheduling and memory allocation simple. In addition, the OS would have used resources that were best allocated elsewhere. An example of an OS is the PetaLinux product [61], which recommends 16 MB of space to run; this would have used all available SDRAM on the development board.

The software on the leg control processor is given as a flowchart in Figure 5.4(a). This processor ran a 1 kHz loop in which it polled the sensors, updated the Proportional-Integral-Derivative (PID) values and generated duty cycles for the motors. In addition, it ran a 100 Hz loop which received new positions from the coordinating processor and returned
feedback on its status. The coordinating processor ran a 100 Hz loop, in which it checked the positions of each leg joint, and compared them to the set-points to decide if the legs were stuck or not. Then it made the decision whether or not to send new trajectories, or wait for legs to reach their target positions or unstick themselves. Because the coordinating processor communicated with six leg control processors, running its control loop at 100 Hz ensured that there was adequate processing time.

### 5.1.3 Computing System Tests

The software resource usage of the system is presented in Table 5.2. In each leg control processor, 73 percent of the code space was used, allowing flexibility for developing alternate control systems. In addition, because a FPGA was used, the ability to reallocate BRAM is possible should a more complex control system be required. The coordinating software was cached and stored in SDRAM, leaving lots of space for more complex code in the coordinating processor.

In Table 5.3, the resource usage of the FPGA is outlined. The user I/Os were the most critical element; if this architecture and FPGA are to be used for a scaled up system, either
with additional levels of control or with additional legs, some consideration should go into PCB design to reduce the pin count. One option would be an off-chip ADC, which can poll eight or sixteen channels in parallel, and communicate to the FPGA serially using a two digital pins at high-speed. In fact, due to the slow speed of the ADCs on the FPGA, this would also improve sampling rates and low level loop frequencies (though with the slow robot speed this would be unnecessary). The next critical element was BRAM. To handle the BRAM shortage, connecting some of the leg processors to the MPMC would allow them to store their code in SDRAM and free up space. One potential downside of this strategy is overloading the MPMC with too many read or write requests. Additional design complexity could also be handled with a larger FPGA.

With regards to response time, the leg processors were capable of running PID loops up to 12 kHz, however the ADC sample rate was limited to 2 kHz. This might be improved using lower ADC resolution (as the Least Significant Bits (LSBs) are noisy anyway, and may not be necessary for closing the loop on the control system). For more significant improvements in control loop frequency, a high sample rate, parallel ADC should be implemented on the PCB.

Power consumption was measured with a Digital Multi-Meter (DMM), and estimated using the Xilinx XPower Analyzer. As seen in Table 5.4, the FPGA and development
### Table 5.4: Measured power consumption

<table>
<thead>
<tr>
<th>Component</th>
<th>Power consumption (W)</th>
<th>Power consumption (% of total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPGA (including development board)</td>
<td>1.215</td>
<td>17.9</td>
</tr>
<tr>
<td>PCB</td>
<td>0.710</td>
<td>10.4</td>
</tr>
<tr>
<td>Sensors</td>
<td>0.880</td>
<td>12.9</td>
</tr>
<tr>
<td>Motors (at peak)</td>
<td>4.0</td>
<td>58.8</td>
</tr>
</tbody>
</table>

Table from [59] © 2012 IEEE.

board were responsible for 17.9 percent of the total power consumption when the robot was moving. The power consumption was estimated at 1.215 W and measured to be 1.30 W. Since the measured and estimated values were close, validating the use of the XPower Analyzer, different scenarios were examined. It was estimated that reducing the system clock frequency to 25 MHz (which allows the ADCs to sample at just over 1 kHz) reduces power consumption of the FPGA to 0.860 W. Further reductions could be obtained by clocking the leg control processors at 5 MHz which would still be sufficient to meet control loop timing. Power consumption was also compared to a multiple MCU system (using seven PIC 24FJ64GA004 family microcontrollers [62]). The PIC system had a power consumption of 0.4 W, however this was an underestimate because it did not include power consumption at the I/O pins of the MCU. A low power FPGA, for example the LatticeECP3 Low Power device could be used for further reducing system power consumption [63].

### 5.2 Control Software

Each of Abigaille-III’s joints operated a closed loop position controller. However no additional sensors were implemented on the robot, creating two problems. First, because no optical or tilt sensors that could provide feedback about the robot’s body-position in the world were incorporated, the robot was programmed with a trajectory specific for climbing and released on the wall to climb. There was no method for the robot to correct its trajectory in the case of disturbances. The second problem observed was that the robot spontaneously detached and fell from the wall. This was determined to be a problem of insufficient preloading, so an open loop preloading method was developed, t could preload the robot without the use of force sensors on its feet.
5.2.1 Positioning (Closed-Loop) Controller

Various controllers were tested with the robot. Because only position feedback was available from the potentiometers, (and not force feedback) the control system was designed to reject disturbances in position, but was unable to reject force-disturbances. The control system responsible for moving the joints between various positions was a proportional controller: when a joint received a target angle to rotate to, the corresponding motor was operated with a duty cycle which was proportional to the angular distance the joint needed to rotate (with a gain $K_p$):

$$\delta = K_p(\theta_t - \theta_a)$$  \hspace{1cm} (5.1)

No integral or derivative terms were used in this control system. The potentiometers did not have sufficient to resolve meaningful measures of joint speed, and the integral term led to limit cycles (oscillations) in the presence of joint friction. The motor duty cycle could not exceed ±100 percent, so the duty cycle $\delta$ had an inherent saturation when the motor was fully on in the forward or reverse directions. During testing, it was determined that a fully on motor was too powerful, and the saturation levels were reduced to ±80 percent to avoid damaging collisions with the climbing surface:

$$\delta = \begin{cases} 
K_p(\theta_t - \theta_a) > 80, & 80 \\
-80 \leq K_p(\theta_t - \theta_a) \leq 80, & K_p(\theta_t - \theta_a) \\
K_p(\theta_t - \theta_a) < -80, & -80 
\end{cases}$$  \hspace{1cm} (5.2)

However, due to the use of a proportional-only controller, the actual joint position tended to undershoot the target joint position due to friction. Because an integral term was found to be cause limit cycles, a knocker, or pulse train, was introduced to combat the friction. The knocker was implemented as a series of pulses added to the control action every 20 ms. The pulses had a duration of 2 ms and height of $\delta = 20$ percent. The knocker had a dead zone of 2 degrees around the target position $\theta_t$.

5.2.2 Preloading (Open-Loop) Controller

This robot was not equipped with force feedback on its feet, however, controlling the preloading force was desired in order to ensure the robot was properly adhered to the wall. Therefore, an open-loop preloading controller was implemented, in order to preload each foot to a
CHAPTER 5. CONTROL SYSTEM

target level, without the use of force feedback. To implement the open-loop preloading controller, a number of steps were taken (see Table 5.5). A desired target adhesion was selected based on the previous leg design computations (Section 4.3). Adhesion experiments were performed in order to determine the required preload to support these adhesion forces. An optimization was performed in order to find the forces that each foot must apply in order to meet this preload. Through the Jacobian of each leg, there is a one-to-one mapping of forces to motor torques, and through motor experiments another one-to-one mapping was found between the motor torques and PWM duty cycles. While climbing, these duty cycles were applied to preload each foot of the robot to the target force without the use of a force sensor in the foot.

Table 5.5: Steps for implementing the open-loop preloading controller

<table>
<thead>
<tr>
<th>Step</th>
<th>Input</th>
<th>Method</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Desired adhesion (Fig. 4.5)</td>
<td>Adhesion experiments</td>
<td>Minimum required preload</td>
</tr>
<tr>
<td>2</td>
<td>(a) Required preload</td>
<td>Optimization</td>
<td>Optimal foot forces during preload</td>
</tr>
<tr>
<td></td>
<td>(b) Static robot equations (eq 4.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(a) Optimal foot forces</td>
<td>Inverse Jacobian (eq 4.23)</td>
<td>Motor torques</td>
</tr>
<tr>
<td></td>
<td>(b) Leg dimensions and configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Motor torques</td>
<td>Duty cycle-torque relationship characterization</td>
<td>Optimal duty cycles during preload</td>
</tr>
</tbody>
</table>

**Adhesion Experiments**  Adhesion experiments were performed using a complete foot of Abigail-III, shown later in Section 6.1. The foot was mounted to a table, and a linear stage with load cell was attached to the same table. A glass microscope slide was attached to the load cell, so that when the stage moved downwards, it brought the slide into contact with the foot. The load cell measured the forces, and once the slide was preloaded to the foot to a certain force, it was detached and the adhesion was measured. LabVIEW software was used to control the system and read the sensor value at 1 kHz. The load cell output was conditioned using a custom amplifier with a 250x gain. A schematic of this system is shown in Figure 5.5.

The experimental data collected was at least five measurements, on four feet, at eight
preload forces. The result of an individual test is shown in Figure 5.6a and the result of the combined tests is shown in Figure 5.6b. Two main observations are noted: the ratio of pulloff to preload decreases at higher preloads, and the variance between measurements (error bars) at higher preloads is lower than at lower preloads. The ratio of pulloff to preload decreases with higher preloads because the adhesion force is saturating, in a similar fashion to the observations in Section 3.2. Variances between samples are suspected to be due to manufacturing differences between the feet structure, which is to be expected because each is a custom device.

The target preload selected for Abigaille-III was 4 N per foot. This target preload corresponded to a detachment force of about 4 N. While this represented over a 10x Factor Of Safety (FOS) compared to the 0.29 N predicted when computing the leg placements (see Figure 4.5), dynamic movements and situations when not all the legs are on the surface created conditions justifying such a high factor of safety.

**Optimization of Foot Forces** Using the target preload of 4 N, the forces at the other feet were optimized in order to attain this preload. First the optimization constraints and goal were defined. Avoiding the detachment of the feet performing the preload was a concern, so this was used as the goal. Physically this corresponded to minimizing the tension forces
Figure 5.6: Results from preload-pulloff tests. (a) Shows a single representative trial on sample 1. Point A is where the sample comes into contact with the substrate, B is the maximum preload of 4 N, C is start of detachment 2 s later, D is the maximum pulloff force and E is when the sample is fully pulled off the substrate. Positive forces are tension, while negative forces represent compressions. The dashed lines indicate stage commands: the stage first approaches the sample, holds and then retracts. The combined results of trials on 4 samples are given in (b).

felt at any of the feet:

$$\min(\max(f_{zi}), i \in [1, 6], i \neq j),$$  \hspace{1cm} (5.3)

where $j$ is one of the front or middle feet ($j \in 1, 2, ..., 4$). The rear feet did not need preloading because they were be in compression against the climbing surface as demonstrated in Section 4.3. The first constraint was that the foot being preloaded must reach a preload of at least 4 N:

$$f_{zj} \geq 4.$$  \hspace{1cm} (5.4)

Next limits were applied to the forces in the shear and friction directions for the feet on the wall. While the forces in these directions were not observed to cause failure as easily as in the normal direction, they were still of concern:
\[-5 \leq f_{xi} \leq 5, i \in [1, 6], \quad (5.5)\]

\[-5 \leq f_{yi} \leq 5, i \in [1, 6]. \quad (5.6)\]

The final constraint was that the robot obeyed the equation of static equilibrium (4.3). This optimization problem was solved using a genetic algorithm [64] and cross-checked using a patternsearch algorithm [65]. Over 100 runs were conducted with random starting values for each algorithm, and the most optimal result was saved. The output of this optimization was a set of optimal foot forces, \( f^* \), with the same components as in (4.5).

**Leg Jacobian and Motor Experiments** By inverting (4.23), the output of the previous optimization, \( f^* \), was used as an input to find the unique joint torques that provided these optimal forces:

\[\tau^* = Jf^*. \quad (5.7)\]

Next, a mapping between the optimal torques (\( \tau^* \)) and the duty cycles (\( \delta \)) applied to the motor controller was needed. This was because the control system commands the motor power using PWM. To find this mapping, the gear motors were characterized experimentally using a load cell and a piece of the leg structure. Various duty cycles from 20 to 80 percent were applied to the motor, causing it to rotate a piece of leg structure into contact with a load cell. The length of the leg structure from shaft to load cell (\( l_{leg} \)) was measured, and because the contact was perpendicular to the load cell, the experimental torque (\( \tau_{ME} \)) was computed from the measured force (\( f_E \)):

\[\tau_{ME} = f_E l_{leg}. \quad (5.8)\]

The experimental results are summarized in Figure 5.7. A linear mapping was found for the range of measurements tested, with the model:

\[\delta = k\tau + c, \quad (5.9)\]

where \( k \) is the slope of the line in Figure 5.7 (19.8 g cm\(^{-1} \)), \( \tau \) is the torque found from applying the Jacobian to the result of the foot force optimization, and \( c \) is an offset (116.4 g cm).
Applying this mapping allowed the duty cycles to be computed from the optimal torques. These duty cycles corresponded to the theoretical duty cycles that applied optimal forces, $f^*$, at the robot’s feet to preload each foot and are shown as the blue bars in Figure 5.8. During implementation, the duty cycles were tuned further (red bars in Figure 5.8). Note that because the motor did not turn on for duty cycles below 20 percent due to gearbox friction, these were rounded to either 0 percent or 20 percent for implementation on the robot.

### 5.3 Summary

In this chapter, a computing architecture and two controllers were presented. The architecture comprised a FPGA with seven soft-processors, with each processor running custom software. This architecture was matched to the mechanical design of the robot, meeting the requirement of implementing a computing architecture suitable for use with the climbing robot. A closed-loop positioning controller used joint positions as feedback. Force-controlled preloading was desired, but no suitable force sensors were available for integration with a
Figure 5.8: Computed (blue) and implemented (red) duty cycles for an open-loop preloading controller. To read this plot first select the leg to be preloaded along the left side. For the hip and shoulder motors, the preloads that each leg must apply are given by the blue (theory) or red (implemented) bars.
650 g robot, so an open-loop preloading controller was implemented. Experiments and optimization mapped the desired preloads to appropriate motor control signals, and these were implemented in software. These controllers satisfied the objective of developing control strategies for (a) moving the feet and robot’s body between climbing positions, and (b) preloading the robot’s feet firmly to a vertical surface.
Chapter 6

Robot Platform Development

The fifth thesis objective is to construct the climbing robot. To meet this objective, in this chapter, the various manufacturing technologies used for different parts of the robot are justified and explained. Then the manufacturing details of the subsystems of the robot (frame, legs and adhesive) are presented. Finally, the CAD model and implemented prototype are shown.

6.1 Fabrication Technologies

Fabrication processes are divided into additive processes (processes in which a material is built up or moulded) and subtractive processes (starting with a block of material, the parts are carved out). Subtractive processes are feasible for simple parts, especially ones with a planar geometry and round corners, as tools can access the areas to be cut or removed. However, for parts with more complex geometry, an additive process is often necessary because tools cannot reach the material to be cut without damaging other areas of the part.

The additive processes available for this project (for reasons of fabrication time and cost) were 3D printing and polymer moulding. Moulds require the construction of a negative, which can be made either on the 3D printer, CO\textsubscript{2} laser cutter, or from a positive mould (i.e. an existing part). The additional steps required when moulding (making the negative) were only justified when there was a benefit to using a mould, for example the ability to use materials that can only be moulded. In contrast, 3D printing is a single step procedure, and produced usable parts in less than 12 hours.

3D printing, laser cutting and moulding were all used in the manufacture of this robot.
In Table 6.1, the parts which were manufactured are listed, as well as the drivers for selecting a manufacturing technology and material, and the material and technology selected.

<table>
<thead>
<tr>
<th>Part</th>
<th>Drivers</th>
<th>Material</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>Low mass, high strength</td>
<td>PMMA</td>
<td>Laser cutter</td>
</tr>
<tr>
<td>Legs and joints</td>
<td>Complex shapes</td>
<td>Fused plastic</td>
<td>3D printer</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Existing moulds</td>
<td>PDMS</td>
<td>Polymer moulding</td>
</tr>
<tr>
<td>Macro-posts</td>
<td>Existing moulds, flexibility</td>
<td>PDMS</td>
<td>Polymer moulding</td>
</tr>
</tbody>
</table>

**Frame** The frame of the robot was cut from Poly(methyl methacrylate) (PMMA) on a CO$_2$ laser cutter (VersaLASER VLS 3.60). PMMA was chosen over 3D printed fused plastic for the body frame, due the comparable density of PMMA (1.17 g cm$^{-3}$ vs. 1.14 g cm$^{-3}$), and superior ultimate strength (48 MPa vs. 24 MPa). The frame consisted of two parts, 6 mm of PMMA on the top, and 3 mm of PMMA on the bottom. These two frame parts sandwiched the legs and provided rigidity to the robot body. A series of holes equally spaced around the frame allowed the legs to be mounted in various positions, creating flexibility in robot configurations. The PCB was mounted below the frame in order to keep the COM close to the climbing surface, which was found to be optimal in Section 4.3.

**Leg Parts** The leg parts of the robot (see Figure 6.1) were printed using the 3D printer (InVision HR). They were too complex to be cut on a laser cutter, or machined. While this technology was suitable for the printing of leg parts, damage and wear to the joints, as well as permanent deformation of the leg parts after sufficient time under load, was noticed. The use of nylon hubs, adhered with epoxy to the fused plastic and cyanoacrylate to metal motor shafts, was found to reduce joint wear. Linear, rotary potentiometers were incorporated into each joint to provide joint-angle feedback.

**Adhesive** A synthetic dry adhesive was manufactured by polymer moulding [3]. PDMS was mixed 10:1 and poured onto a previously manufactured mould [3]. It was degassed for at least 10 min in vacuum and then cured for at least 3 h at 60$^\circ$. Once cured, it was demoulded by hand and kept in a dust free environment until it was ready for use.
Macro-posts  The PDMS adhesive was about 1 mm thick, which had some compliance. However, more compliance was desired to compensate for misalignment between the feet and the climbing surface, which could cause ineffective preloading. A layer of posts, called macro-posts [4], were fabricated. The macro-posts (see Figure 6.2) added additional compliance to the foot system. PDMS was mixed 10:1 and poured into a laser cut PMMA mould containing an array of 1-by-1 mm square posts with 3-by-3 mm inter-post spacing. A vacuum was used to extract air from the mould cavities and ensure proper PDMS coverage.

Robot’s Foot  Each robot foot (Figure 6.3(a)) contained two subsystems: a dry adhesive structure for attaching, and a cam mechanism for detaching. A motor was held by a housing in the plastic foot. An Infrared (IR) sensor was mounted on the housing to detect the position of a rotating cam which was attached to the motor shaft. To detach the adhesive, the motor rotated the cam into contact with the ground, prying the adhesive up. To return the cam to a neutral position and allow preloading of the foot at a new position, the cam was rotated in reverse until detected by the IR sensor, indicating that it was out of the way. A white mark was painted on the black cam to increase contrast and improve detection by the IR sensor. An elastic band between the robot leg and foot ensured that the adhesive on
the robot foot faced the wall at the start of preloading.

The dry adhesive structure (see Figure 6.3(b)) was formed by first bonding the macro-posts to the dry adhesive (see Figure 6.3(c) for a micrograph of the dry adhesive posts) with the post-ends contacting the unstructured side of the adhesive. A silicone compound (Dow Corning 732 [66]) was used between the adhesives and macro-posts. Next this two-part structure was cut to be the same shape as the robot’s foot, and bonded to the foot using additional silicone compound. Previous work [8] had used PDMS to bond two parts of a PDMS-based adhesive, which was also attempted in this work. Empirically, it was observed that the adhesive capability of the dry adhesives was degraded over time when additional PDMS was used (possibly non-crosslinked oligomers seeped through the foot and fouled the adhesive surface). Cyanoacrylate (super-glue) was also tested as a method of bonding the PDMS layers, however, this was also observed to degrade the adhesive, and was, therefore, not used on any part of the robot near the adhesives.

6.2 CAD Model and Implemented Robot

Abigaille-III (shown climbing a whiteboard in Figure 6.4(b)) was a climbing robot with six legs and 24 motors. Each leg (Figure 6.4(a)) was comprised of three active joints (two Degree-of-Freedom (DOF) for the hip and one DOF for the knee, note: only one hip joint is visible in this image), a 1-DOF passive ankle joint and an extra motor on the foot for
Figure 6.3: Detailed view of Abigaille-III’s foot assembly (a), showing the cam, IR sensor, elastic band and detaching motor. In (b), the adhesive micro-posts (c) are shown mounted on macro-posts and the rigid plastic foot.

detachment. The use of the detaching motor to rotate the cam is shown in Figure 6.4(a). To climb (Figure 6.4(b)), Abigaille-III moved its legs in the order shown in (Figure 6.4(c)), followed by a whole-body movement where every motor was used to pull the body vertically. This gait was chosen empirically, and was partially based on the observation that the front feet supported more tension force than the rear feet and therefore were moved first. The body was rectangular, in order to compactly hold the rectangular PCB. The legs were mounted around the body near the optimal configuration identified in [6](see Figure 6.4(c)), however a series of mounting holes on the frame allowed for different leg positions. Abigaille-III had a versatile and modular control system, making climbing with either five or six legs possible. During five-legged climbing, different holes in the rectangular body were used as shown in Figure 6.4(d). On the body, a custom-designed PCB was mounted. The PCB contained electronics for motor control, as well as an FPGA, containing the custom, seven soft-processor control system.

The joint ranges of Abigaille-III are summarized in Table 6.2. Additional physical parameters are summarized in Tables 6.3 and 6.4.
Figure 6.4: Composite image showing design features of Abigaille-III. (a) The front foot and cam mechanism as it detaches and reattaches to the wall; (b) The 6-legged configuration of Abigaille-III climbing a vertical wall; (c) CAD model of the body, where letters beside legs on the CAD model indicate order that the legs are moved during operation; and (d) the 5-legged configuration of Abigaille-III climbing a vertical wall.

### Table 6.2: Joint specifications of Abigaille-III

<table>
<thead>
<tr>
<th>Joint</th>
<th>Sensor</th>
<th>Range (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder, front legs</td>
<td>Potentiometer</td>
<td>135</td>
</tr>
<tr>
<td>Shoulder, middle and rear legs</td>
<td>Potentiometer</td>
<td>110</td>
</tr>
<tr>
<td>Elbow</td>
<td>Potentiometer</td>
<td>110</td>
</tr>
<tr>
<td>Ankle (passive)</td>
<td>None</td>
<td>105</td>
</tr>
<tr>
<td>Detaching cam</td>
<td>IR</td>
<td>360</td>
</tr>
</tbody>
</table>

### Table 6.3: Measured masses of Abigaille-III

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (gram)</th>
<th>Total mass (gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPGA and PCB</td>
<td>105.0</td>
<td></td>
</tr>
<tr>
<td>24 motors and sensors</td>
<td>249.6</td>
<td></td>
</tr>
<tr>
<td>Leg structure and frame</td>
<td>117.4</td>
<td></td>
</tr>
<tr>
<td>Cables, fasteners and glue</td>
<td>162.6</td>
<td></td>
</tr>
<tr>
<td>Robot’s total mass</td>
<td></td>
<td>634.6</td>
</tr>
</tbody>
</table>
Table 6.4: Measured dimensions of Abigaille-III

<table>
<thead>
<tr>
<th>Body subsystem</th>
<th>Length (m)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body envelope (width)</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Body envelope (length)</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Body envelope (height)</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Body envelope volume</td>
<td></td>
<td>3.78 × 10⁻³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Leg subsystem</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First leg segment length</td>
<td>0.03</td>
</tr>
<tr>
<td>Second leg segment length (front and middle legs)</td>
<td>0.03</td>
</tr>
<tr>
<td>Second leg segment length (rear legs)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### 6.3 Summary

In this chapter, the objective of constructing the climbing robot was addressed. Various manufacturing techniques were discussed and applied to different subsystems of the robot. The adhesive foot was discussed in detail, explaining how an adhesive layer of PDMS micro-posts mounted on macro-posts added compliance to help the robot adhere to surfaces. The robot was constructed and characterized in terms of size, mass and joint ranges. CAD images and photos of the final, implemented prototype were presented.
Chapter 7

Results and Tests

The final thesis objective, characterizing the robotic platform, was done by testing the system performance in a variety of conditions. The tests included climbing, transferring between orthogonal surfaces, and endurance tests of the robot and the adhesives. A validation of the preloading method was conducted by monitoring foot forces with an external sensor during climbing. Failure modes were also examined, giving an idea of how the robot can be improved in the future.

7.1 Climbing, Transferring and Endurance

During implementation, the robot was placed on the wall and allowed to climb vertically. Overlaid still images extracted from video of the robot climbing are given in Figure 7.1. These stills show the change in robot position after 12 min of climbing. During climbing, the robot used a pentapedal gait: each of its feet moved in sequence and then a final whole-body movement completed one gait cycle. The robot repeated the gait cycle continuously until commanded to stop climbing.

Two endurance tests were conducted: in the first test Abigaille-III climbed up a whiteboard for 20 min until the top of the whiteboard was reached. Then Abigaille-III was removed and replaced at the bottom and the cycle repeated. This tested the fouling behavior of the adhesives, and Abigaille-III was shown to climb for 3 h 55 min, (a distance of approximately 6 m) before adhesive failure. The next test was a loitering test: Abigaille-III was commanded to take five steps upward to self-preload, and then hold that position on the wall. After 7 h, no adhesive failures were observed and the test terminated.
CHAPTER 7. RESULTS AND TESTS

Figure 7.1: 6 Legged configuration of Abigaille-III climbing a vertical wall. Two overlaid stills are extracted at 0 at 12 minutes from video footage. The distance traveled during this time was approximately 0.28 m. A hanging mass indicates the direction of gravity.

Abigaille-III is shown to transfer in Figure 7.2. In this figure, three still frames from a video taken during transferring at 10 s, 45 s and 60 s are overlaid. The position of the front feet is marked with a white arrow at each time instance. A transferring motion takes Abigaille-III approximately 60 s and 31 steps to complete. The robot started with its feet on the wall because it had no distance or positioning sensors and therefore needed to localize itself against the wall when starting the transfer sequence.
CHAPTER 7. RESULTS AND TESTS

7.2 Uneven Terrains

Tests were also conducted to show the dexterity of the robot. While ascending a vertical wall (Figure 7.3 (a)), Abigaille-III climbed onto a ledge protruding 5 mm from the wall. Abigaille-III climbed vertically along a ledge of 18 mm height in two different configurations, as shown in Figure 7.3 (b) and (c). In Figure 7.3 (d) and (e), Abigaille-III is shown climbing along a ditch and a ridge, both of 18 mm height.

The rate of motion for some representative tests is given in Table 7.1. During a 550 s climbing test, Abigaille-III was observed to climb a total of 240 mm, or 0.44 mm s$^{-1}$. Abigaille-III was also capable of walking on a horizontal surface with a tripod gait at
Figure 7.3: Abigaille-III climbing over a ledge (a) and along a ledge with one foot (b) and two feet (c). Abigaille-III can also climb along a ridge (d), and ditch (e).
1.1 mm s\(^{-1}\), along a horizontal ledge with a tripod gait at 1.0 mm s\(^{-1}\) and rotate while on a vertical surface (up to 20° from the vertical without detachment). Walking speeds along a ledge were slightly slower than along flat surfaces because the step length was reduced to compensate for the terrain. Performance during the endurance tests and transferring tests are summarized in Table 7.2.

### Table 7.1: Abigaille-III's movement rates during various maneuvers

<table>
<thead>
<tr>
<th>Walking (horizontal surface)</th>
<th>Rate (mm s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tripod gait</td>
<td>1.1</td>
</tr>
<tr>
<td>Tripod gait, ledge</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Climbing (vertical surface)</th>
<th>Rate (mm s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 legged configuration</td>
<td>0.44</td>
</tr>
<tr>
<td>6 legged configuration, ledge</td>
<td>0.35</td>
</tr>
<tr>
<td>5 legged configuration</td>
<td>0.34</td>
</tr>
</tbody>
</table>

### Table 7.2: Elapsed time for various maneuvers

<table>
<thead>
<tr>
<th>Test</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transferring from horizontal to vertical</td>
<td>60 s</td>
</tr>
<tr>
<td>Endurance: vertical climbing</td>
<td>3 h 55 min</td>
</tr>
<tr>
<td>Endurance: loitering on wall</td>
<td>7 h 0 min*</td>
</tr>
</tbody>
</table>

*The loitering test was stopped after 7 h because no signs of failure were noted. The maximum loitering capability of the robot is not known.

### 7.3 Foot Forces During Climbing

To validate the preloading strategy, forces generated at each of the front and middle feet during the climbing cycle were measured. A part of a PMMA climbing wall was cut out and replaced with a load cell so the forces of a single foot could be measured as the robot passed over it. The robot was made to climb over the load cell multiple times in different positions to capture the forces at each foot.

The forces in the normal direction of the front and middle feet are shown in Figure 7.4. This test showed the repeatability of the forces during a climbing step, and verified the effectiveness of the preloading strategy. The front feet (2 and 3) generally supported a
larger range of forces than the middle feet (1 and 4). When a foot detached, it preloaded the adjacent feet (for example in gray box A, feet 1 and 2 are preloaded by foot 1 in Figure 7.4). Preloading a foot required a detaching force by the adjacent feet (see B in Figure 7.4). Moving the feet at the rear (5 and 6) had a very minimal effect on the forces observed at the front and middle feet.

7.4 Adhesive Degradation and Failure Analysis

Kroner et al. observed PDMS synthetic dry adhesive to degrade with use [36], and it appeared during the endurance test that the robot detached from the wall because its feet became less sticky over time. A controlled experiment was, therefore, conducted on a single foot of Abigaille-III to investigate if the adhesives used on Abigaille-III degraded over time. The experiment setup was similar to the one described in section 5.2.2, with one foot of Abigaille-III pressed against a glass slide 2000 times to a preload of 2.0 N while recording the peak preload and adhesion forces. The peak preload, time of preload and duration between preloads were all controlled using a force-feedback controller implemented in Labview. The maximum adhesive force was found, and plotted against the indentation number in Figure 7.5. A degradation in adhesive ratio can be seen from the plot, and there appears to be about 12 percent reduction in adhesion over 2000 cycles. This is less degradation than observed by Kroner et al. [36]. However, in the endurance test, the robot was observed to fail after about 570 cycles. This can be explained by the extra contamination that occurred when the robot’s foot contacted a different PMMA location on each step when climbing a wall (during the controlled test, the robot stepped in the same location each time).

To investigate the causes of failure of this robot, 19 videos of climbing were reviewed. Failures were divided into mechanical and adhesive modes. Mechanical failures included parts breaking, joints wearing out or leads detaching. Adhesive failures were instances where the robot was not able to support its own weight on the wall and fell. The 19 videos were sorted by duration (elapsed climbing time before failure). Graphically represented in Fig. 7.6, adhesive failures were most common near the start of climbing, while mechanical failures appeared after a few minutes into the test. During later stages of climbing, adhesive failures became more common again. This can be explained considering that adhesive failures generally result from surface contamination (either the surface was pre-contaminated and failure is early, or contamination occurs after a large number of steps). Mechanical
CHAPTER 7. RESULTS AND TESTS

Figure 7.4: Normal direction forces in foot 1 (a), foot 2 (b), foot 3 (c) and foot 4 (d). Positive forces indicate preloads, while negative forces are detaching forces. Two cycles are overlaid to indicate the degree of repeatability of forces in each foot. Numbers at the bottom indicate which foot is moving at the time that forces are recorded. In region of interest A, foot 3 detaches, and in B, foot 3 is preloaded.
Figure 7.5: Adhesion measured over 2000 cycles for a single foot of Abigaille-III. A degradation of the adhesive was noted, however it was not as severe as the degradation found in [36].

failures occurred after the robot had taken a few steps, and parts that were under excessive stress had a chance to fail.

7.5 Summary

In this chapter, the thesis goal of characterizing the robot platform in various climbing situations was completed. Performance while climbing in both five and six legged configurations was identified, and tests to examine loitering and endurance performance were conducted. The robot was tested in various environments and situations including transferring between orthogonal surfaces and vertical climbing along a ledge, ridge and cliff. Foot force measurements validated the preloading method and failure mode analysis provided some insight into areas of future improvement for the robot.
Figure 7.6: Failure modes from video analysis of 19 climbing trials. The trials were sorted by duration, showing that mechanical failure modes were most common in the mid-length tests, while adhesive failures were more common in short and longer tests.
Chapter 8

Conclusion

In this thesis, a climbing robot equipped with synthetic dry adhesives to stick to smooth vertical surfaces, was presented. This robot had potential applications in space environments, as the dry adhesives used showed no difference in adhesive strength between laboratory and simulated space environments. To enable vertical climbing, mechanical optimization, computing system development, and control software implementation were all performed. The robot, Abigaille-III showed strong performance in endurance and loitering tests, and showcased the dexterity of its hexapod configuration by climbing uneven vertical surfaces.

8.1 Summary of Objectives

The first objective of this work was to validate the use of synthetic dry adhesives in space environments (thermal and vacuum). Through testing with instrumented indentation apparatus at ESTEC, it was found that neither pressures to $1 \times 10^{-5}$ mbar nor temperatures between $-50^\circ$C and $75^\circ$C had a statistically significant effect on the adhesive capability of a PDMS dry adhesive.

The second objective was to design a climbing robot that used synthetic dry adhesives and was capable of climbing vertically. To achieve this objective, first the fixed parameters of the robot (electronics payload mass) were determined. Reference models assisted in predicting how motor sizing would affect robot mass, and motors which would be strong enough to support the robot’s mass were selected. The leg subsystem design was optimized considering static forces during climbing, and desired step parameters.

The third objective of this work was the implementation of a computing architecture,
which was suitable for use with the climbing robot mechanical design. The advantage of a computing architecture, which closely paralleled the mechanical design (one processor per leg) was demonstrated when the robot climbed successfully with either three or four motors, and five or six legs. Implementing the control systems in software made changing the control strategy easy, for example to test out friction compensation strategies. Low inter-processor latency, in combination with sufficient loop frequencies were other traits of this design.

The design of suitable controller software for (a) executing joint trajectories and (b) preloading feet, was the fourth objective of this thesis. The preloading controller was designed in an open-loop configuration. First, the adhesives and motors were characterized, and then an optimization was performed to find a combination of forces that each foot could apply during the preloading phase to avoid accidental detachment. A closed loop proportional control system with saturation and a knocker was used for positioning the joints.

The fifth objective of this thesis was the development and construction of the complete robot system. Multiple fabrication methods were employed, including polymer moulding, 3D printing and laser cutting.

The sixth and final objective was testing and characterizing the robot platform in various environments. Abigaille-III was designed and optimized for climbing vertically with six legs, but was fully capable of walking, rotating, climbing with five legs, transferring, and climbing on uneven surfaces with six legs. Endurance tests showed that nearly four hours of continuous climbing were possible on a single set of adhesives, and that the adhesive degradation of a single foot over 2000 attaching and detaching cycles was only 12 percent. Loitering in-place for seven hours on a vertical wall was also shown. Failure analysis showed that mechanical failures were most common between three and eight minutes into a climb, while adhesive failures dominated the other time periods, suggesting that both mechanical and adhesive improvements would contribute towards increasing the reliability of future Abigaille robots (see the following section on Future Work).

Compared to previous Abigaille-series robots, Abigaille-III has a number of new features. In Figure 8.1, Abigaille-II is shown beside Abigaille-III at the start and end of this project. Abigaille-III boasts a versatile, FPGA-based, control system, in contrast to Abigaille-II’s off-the-shelf parts. Abigaille-I was only a testing platform and never capable of vertical climbing. Abigaille-II had poor reliability, and was only capable of vertical walking on flat surfaces. Abigaille-III climbed for nearly 4 h in an endurance test, traversed multiple types
of structured surfaces, and could operate with five or six legs.

8.2 Future Work

Miniaturization of the Robot  The robot presented in this thesis had a $3.78 \times 10^{-3} \text{ m}^3$ body envelope and mass of 634.6 g. A number of steps could be taken to miniaturize the robot, desirable for space applications where size and mass are constraints. The wiring accounted for about 20 percent of the robot’s mass, printing or embedding wiring traces
for potentiometer signals and motor power onto the 3D printed parts could substantially reduce mass. For the robot presented in this thesis, the body volume was not decreased for two reasons: the PCB and FPGA development board were a fixed size, and the legs were placed far apart from each other because the body flexed like a spring, reducing the effects of leg positioning errors. Reducing leg positioning errors, for example with lower backlash in the motor and joint assembly, would allow the legs to be placed closer together. Electronic size could be reduced if a smaller FPGA development board were used, and the PCB was redesigned.

**Electronics Upgrades** For a fully-autonomous or partially-autonomous robot, control system and electronics upgrades will be necessary. Sensors, for example a camera or range sensors, can be used to collect data for collision avoidance and navigation. A processor on the FPGA could be instantiated to process the sensor data and generate trajectories. This would allow a human to command the robot with high-level directorates (e.g. move left, right or climb a wall) and the robot could automatically find the wall and climb. To deal with FPGA pin-count limitations, high-speed parallel-to-serial ADCs could be placed on the next generation PCB. Wireless serial radios, for example XBee transceivers, could communicate between the robot and the user controls. A battery, and battery charging circuit, would permit tetherless operation.

**Mechanical Upgrades** Mechanical failures generally resulted from parts snapping, or joints wearing out. In this research, fused plastic from a 3D printer machine was used for many parts because it allowed quick development iterations. Building the robot from stronger and harder materials would substantially reduce mechanical failures. One option is using a 3D printer technology suitable for printing metals. Care must be taken not to increase (and ideally to decrease) the mass of the robot if new materials are selected.

**Adhesive Improvements** Abigaille-III was capable of climbing smooth vertical surfaces. However, to overcome more general terrain, including rough surfaces, a foot incorporating both adhesive and claw elements could be designed. On rough surfaces, the claws would grip the surface roughness, while on smooth surfaces the dry-adhesives would provide adhesion. In this thesis, tests were only conducted on uniform surface types. In the future, it would be interesting to observe robot performance as it transfers between surfaces of different materials or roughness scales. In controlled experiments, 12 percent adhesive degradation
over 2000 attaching and detaching cycles was observed, likely due to surface contamination of the adhesive. Cleaning mechanisms will, therefore, be necessary for autonomous operation, where actively cleaning the adhesives with PSAs is not possible.
Bibliography


