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High Speed Dynamic Climbing on Rough Exterior Surfaces

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HIGH SPEED DYNAMIC CLIMBING ON ROUGH EXTERIOR SURFACES

By

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Currently, few scansorial robots exist that are capable of operating on rough exterior surfaces. None of these platforms have, as of yet, been able to achieve high speed dynamic climbing on these surfaces. This thesis shows that through the use of compliant micro-spines, a miniature dynamic climber, BOB, is capable of climbing dynamically at high speed on rough exterior surfaces. A new manufacturing method for micro-spines is examined. The effects of micro-spine arrays onto a dynamic climber are examined and how the micro-spines affect compliance, roll, and yaw. Methods to mitigate the effects of these dynamic motions are also examined and presented.
CHAPTER 1
INTRODUCTION

Many animals have demonstrated abilities to rapidly traverse varying types of terrains. Cockroaches and geckos, for example, have been shown to climb vertical surfaces at multiple body lengths per second [8]. This natural capability for animals to perform well has lead to biologically inspired models such as the Full-Goldman (FG) model for climbing, the spring-loaded inverted pendulum (SLIP) model for running [2], and the lateral leg spring (LLS) model for running [4]. These biologically inspired models help to characterize the behavior of animals in simplified forms. Following these models can lead to robots that perform faster and more efficiently than a robot that may have been designed without such a model.

The past decade has seen vast improvements in climbing robots, particularly. These robots are envisioned to help in a variety of applications including surveillance over walls, through windows in tall buildings, search and rescue in partially collapsed buildings, inspections of bridges or hazardous work sites, and even for entertainment.

One domain of particular interest is persistent surveillance in urban settings. The typical solution today is to use a UAV, but these require constant actuation to maintain operation. They also may have trouble in dense urban settings where navigating between buildings can become a challenge. Along with these challenges, the necessity to maintain elevation/flight drains batteries quickly reducing possible mission duration. A climbing robot, like those discussed in this thesis, requires no actuation to provide persistent surveillance on stationary targets in urban settings, thus reducing the power requirements.

The research discussed in this thesis was performed on a dynamic bipedal climber, BOB, described in Section 2.4. This robot was developed as a research platform to explore multi-modal research, or a means of using more than one mode of transportation. Previous research explored the idea of a means of combining the perching and climbing capabilities of this robot with a fixed-wing airfoil. This concept allows the climber to safely detach from a wall and glide to another surface, the ground, or the operator. Fig. 1.1 demonstrates this design.
This research analyzed the dynamics behind the climber and some of the important characteristics used by dynamic climbers, which are reviewed in Section 2.1. It, however, did not address the problem of attachment to “real world surfaces,” which is a challenge that must be overcome to increase the robot’s practicality. This poses the question of what we define as the “real world”. Until recently, climbing experiments with BOB were performed on a prepared surface: a carpet covered wall. Throughout this thesis, a “real world” surface is defined as a rough, exterior wall surface such as cinder-block, stucco, stone-aggregate, or brick.

Other institutions have made varying levels of progress on attachment such as climbing smooth walls [3, 12], smooth curved surfaces [21], and trees [13, 10]. Stickybot [12] uses directional polymer stalks, or feet that behave similar to geckos. SpinybotII [11] and RiSE [1] make use of micro-spines to climb “real world” surfaces. One of the problems that the climbers discussed above share is that they are only capable of low climbing speeds using “quasi-static” gaits. This thesis addresses the challenge of integrating the attachment method of micro-spines with an under-actuated dynamic climber to achieve high-speed climbing on “real world” surfaces.
This thesis is organized as follows: Chapter 2 presents a review of biologically inspired design and climbing. A discussion of the challenges of climbing dynamically is presented in Chapter 3. Improvements and additions to the robotic platform are presented in Chapter 4. The importance of compliance and its effects on climbing is presented in Chapter 5. Chapter 6 and Chapter 7 discuss the yaw and roll motions that are common among dynamic climbers and how to mitigate their effects on attachment. A concluding discussion and future work are discussed in Chapter 8.
CHAPTER 2

BACKGROUND

2.1 Dynamic Climbing

Dynamic climbing robots such as DynoClimber [14], BOB (Bipedal Oscillating roBot) [5], and ROCR [18], shown in Fig. 2.1, climb efficiently at high speeds. These platforms are considered "dynamic" climbers as they accomplish this by using their natural dynamics while climbing rather than using a complicated control scheme to regulate the kinematics of multiple limbs. One method of dynamic climbing, discussed in Section 2.1.1, is based on the Full-Goldman model [8] mentioned earlier.

![Figure 2.1: A.) DynoClimber platform, picture provided by Jonathan Clark, B.) Bipedal Oscillating roBot, BOB, and C.) ROCR platform.](image)

Quasi-static climbers typically employ several legs or contact points, and move only one or two at a time with the use of multiple actuators. The center of mass of this style of robot is constrained to follow a specified path. This increased control often results in a loss of speed but can increase reliability. Dynamic climbers typically use fewer actuators, or under-actuated limbs, which results in some design challenges which are discussed in Chapter 3.

DynoClimber, BOB, and ROCR all demonstrate similar pendulum-like motion while climbing. ROCR uses an actuated mass to change the location of it’s center of mass. This then causes the
body to rotate and move the leg to a new foothold. DynoClimber’s design is based on the Full-Goldman model. This design uses two legs to pull the robot upward and to the side. BOB was inspired by the design of DynoClimber but is scaled down from DynoClimber in terms of size and mass and only uses one motor to rotate the two legs, however. BOB is discussed in more detail in Section 2.4.

2.1.1 The Full-Goldman Model

![Figure 2.2: Plots of ground reaction forces and velocities of cockroach, A, gecko, B, and the template, C, where z represents the vertical direction and y represents the lateral direction. Reproduced with permission from [8].](image)

Certain animals, such as geckos and cockroaches are capable of climbing a variety of vertical surfaces very quickly and successfully even though they have very different physiology. Observations of these animals yielded a pattern to which each follows while climbing. While the number of feet and the attachment methods vary between the these two animals, the pattern between how their feet interact with the ground is similar. The ground reaction force exhibited by these animals is about twice their mass and in a smooth curve over the duration of the step. These observations led to the development of the Full-Goldman reduced-order model of climbing. With each step, there is a corresponding ground reaction force (GRF) with a vertical and horizontal component.
These forces, for which a representative sample is shown in 2.2A and B, were then used to create a corresponding model behavior, seen in 2.2 C. While following this model, the robot alternates its footholds and its weight from one freely rotating contact point to the other. This climbing scheme results in the center of mass following a pendulum-like motion as shown in Fig. 2.3. The model consists of a central body and two massless limbs with nominal length $l$ and a limb stiffness of $k$. The limbs are oriented with a sprawl angle of $\beta$ from the central body axis.

![Diagram of pendulum-like motion exhibited while climbing using the Full-Goldman model.](image)

Figure 2.3: Diagram of pendulum-like motion exhibited while climbing using the Full-Goldman model.

### 2.2 Directional Adhesives

Attachment is a common challenge among all climbing robots. There are designs that use magnets [20], suction cups [22], and low-pressure zones [23] to create or assist in attachment as shown in Fig. 2.4. These methods of attachment, however, are limited to specific surfaces such as metal or glass.

To climb other surfaces, some robots employ the use of directional adhesives. Directional adhesives can greatly assist in improving the efficiency and speed of climbing. Directional adhesives work by creating an adhesive force in the climbing direction, but allow the climber’s claw or foot to detach when unloaded. Similarly, a high amount of frictional resistance in the direction of gravity allows easy engagement with the surface. Via the hook and loop method, BOB uses a form of
directional adhesion while climbing on carpet as do ROCR and DynoClimber. Stickybot [12] uses gecko inspired directional adhesives to grip smooth surfaces via van der Waals forces as shown in Fig. 2.5.

![Figure 2.5: A.) Unloaded view of Stickybot foot and B.) Loaded Stickybot foot.](image)

An increasingly common directional adhesive involves micro-spines. SpinybotII [11] uses micro-spines to climb on surfaces that are rough or dirty such as stucco, concrete, cinder-blocks or brick. Micro-spines have also been implemented successfully on RiSE [1] while variations have been adapted to other platforms such as the Gravity-Independent Rock Climbing Robot and DROP [16, 17].
2.3 Micro-spine Arrays

![Image of micro-spine toes as seen on Rise](image)

Figure 2.6: Image of micro-spine toes as seen on Rise, from [9] edited by Gaurav S. Sukhatme, Stefan Schaal, Wolfram Burgard, and Dieter Fox, published by The MIT Press.

Micro-spines, shown in Fig. 2.6, developed for Spinybot II [11] are designed to engage the naturally existing asperities that are found in stucco, concrete, and many other rough surfaces. These asperities are often very small, on the scale of micrometers. Thus, the micro-spines used on RiSE have a tip radius between $15\mu m$ and $25\mu m$ depending on the toe generation [19].

The toes are often arranged in an array consisting of a number of toes on each foot. RiSE, for example, uses up to 30 toes per foot where robots such as the Gravity-Independent Rock Climbing Robot [16] use several arrays per foot for up to 256 toes. The toes are designed to act individually as separate multi-link mechanisms that can each engage the wall without interfering with the engagement of any other toes in the array. This allows for the possibility of multiple attachment points to distribute the load and increase attachment reliability.

The toes are typically fabricated from Innovative Polymers Urethane Liquid Plastic using a shore hardness of 20A for the soft components and 72DC for the hard components. They are manufactured through the Shape Deposition Manufacturing (SDM) method. This process involves milling the desired shape into a sacrificial support material and then pouring the model material into the support.
2.4 Platform

The Bipedal Oscillating Robot, shown in Fig. 2.7A has two legs driven by separate crank-slider mechanisms with each leg rigidly attached to the central body, a design similar to that of DynoClimber. A single DC motor is used, however, to drive the legs, which are locked 180° out-of-phase through the use of a pinion spur gear (SDP-SI #A 1P 2MYD08020A) driving a gear (SDP-SI #A 1P 2MYD08075A) with a 3.75:1 reduction. The gears serve as the crank to the slider crank mechanisms that make up the legs of BOB. The body and coupler are made of laser cut ABS while the slider consists of miniature linear guide rails (Misumi #SSEB6-40) through a slotted shoulder block that allows the shoulder angle to be adjusted. The dactyl claws used for attachment consist of de-barbed fish hooks. The claw is attached to a wrist spring that is used to soften the ground reaction force (see Section 5) so that it performs similarly to the Full-Goldman model. Based on the expected torque load and driving speeds, a 6V Faulhaber DC Motor (#1331-006-SR) with a Faulhaber Series 15/3 6.3:1 ratio spur gear head was chosen to drive the robot. The physical measurements of BOB are available in Table 2.1.

Table 2.1: Physical Measurements of Bipedal Climbing platform, BOB.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>0.19</td>
</tr>
<tr>
<td>Width (m)</td>
<td>0.91</td>
</tr>
<tr>
<td>Height (m)</td>
<td>0.110</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>0.200</td>
</tr>
<tr>
<td>Sprawl Angle (deg)</td>
<td>10</td>
</tr>
<tr>
<td>Shoulder Width (m)</td>
<td>0.097</td>
</tr>
<tr>
<td>Stiffness ($Nm^{-1}$)</td>
<td>131</td>
</tr>
</tbody>
</table>

Fig. 2.7B,C, and D depict the platform trajectory and velocity profiles of the climber for a run at an incline of 90° as recorded by a 10 camera VICON motion capture system at 120Hz and a stride frequency of about 3Hz. The position and velocity plots match the behavior of that demonstrated in Fig. 2.2 while the trajectory follows that of the template shown in Fig. 2.3.
Figure 2.7: A.) Image of the Bipedal Oscillating roBot, BOB, used in the experiments discussed in this manuscript, B.) X-Y Trajectory of the robot, C.) Vertical Velocity, and D.) Lateral Velocity.
CHAPTER 3

CHALLENGES OF CLIMBING DYNAMICALLY

As discussed in Section 2.1, dynamic climbers exhibit high speeds and efficient climbing schemes. To accomplish this though, there are some obstacles that must be overcome. This chapter attempts to identify and summarize the most pertinent challenges to climbing reliably on “real” surfaces. The high actuation speeds lead to increased ground reaction forces that can knock the climber off the wall. Body roll, coupled with yaw motion, create out of plane forces that can cause the climber to lose attachment. Another common challenge between dynamic climbers is attachment reliability. Robots with over two legs have the safety of extra attachment points. BOB and similar platforms rely on only one foot, or attachment point, engaging with the wall at any given time. This results in a duty factor approaching 50% whereas robots such as RiSE would have a duty factor of 83.3%.

3.1 Compliance

As discussed in 2.1.1, cockroaches and geckos exhibit a smooth curved ground reaction force (GRF). In order to match this behavior, a degree of limb compliance is added into BOB and DynoClimber. Fig. 3.1 shows a comparison of the GRF over a step with and without wrist compliance on BOB on a carpet surface.

As shown in Fig. 3.1B, the GRF profile during stance is reduced to a similar smooth curve rather than an impulse-like loading while the peak radial force is also decreased by 66%. The loading force applied from stiff limbs can cause damage to the toes or knock the climber off the wall. This force could also lead to destruction of the foothold asperity causing the robot to lose it’s attachment.

While using too little compliance results in large a GRF, too much compliance also reduces the climbing abilities of the robot. If the compliance is too soft, the extension of the limbs can exceed the stroke length. In this situation, the foot or claw would be unable to detach from the wall. It is also possible that with too soft of a wrist spring, the weight of the robot could exceed the spring’s maximum load capabilities, extending the spring beyond its maximum range of motion.
and permanently deforming the spring. Tuning of compliance is discussed in more detail in Section 5.1.

### 3.2 Roll and Yaw

The Full-Goldman model describes a 2-dimensional model for climbing dynamically, but designing a robot that is capable of performing purely in 2-dimensions with any success proves to be a challenging design issue. BOB uses a pitched-forward design to prevent backward pitching off the wall. This pitch, combined with the motion of the legs, creates a body roll as the robot pulls itself up with each stroke. In conjunction with this roll, as the robot’s foothold changes from foot to foot, an inherent yaw motion causes a gravitationally induced roll by creating a moment about the attached foot and the point at which the rear limbs make contact with the wall. This yawing motion also creates a torque at the point of attachment that can damage the foot or the surface of the foothold.

To mitigate the effects of gravitational roll, both BOB and DynoClimber use passive rear limbs, however, there is little research into the necessary design characteristics of these rear passive limbs. Chapter 6 examines a means of mitigating the effects of yaw while Chapter 7 examines two methods to mitigate the effects of roll.
3.3 Attachment

Compliance, roll, and yaw all play a key role in attachment capability. Too much compliance creates a significant loss in stroke length while too little compliance creates impulsive loading forces that can knock the climber off the wall. Over-rolling can cause the flight foot to miss the surface. Further roll can cause the attached foot to peel away from the wall as the directional adhesives used on BOB (for example) are only designed to be loaded along the vertical orientation. These directional adhesives lose their effectiveness under significant yawing motion. Dactyls with a single point of attachment perform similar to a pin-joint with negligible rotational GRF, but a micro-spine array is more resistant to rotation and will experience a higher rotational GRF, or a torque as shown in Fig. 3.2. This torque causes the spines on the toward the center of the robot to extend further and hold more of the weight the robot while the spines closer to the outside of the robot rotate upward resulting in the release of any loading. This causes uneven wear of the spines and wears out the inner spines faster. This can also cause the inner spines to extend to the overload protection pins designed to purposefully disengage the toe in an overload situation; leading to a failed foothold and possible disengagement from the wall. Using stiffer toes would reduce the yawing motion but the compliance challenges related to loading dynamics still apply. Reducing the yaw creates higher rotational GRF that could damage the toes or the foothold.

![Figure 3.2: Micro-spine array shown with rotational loading force. The outer spines are extended while the inner spines see loading.](image)
CHAPTER 4
PLATFORM DEVELOPMENTS

In order to improve performance on “real” surfaces, a number of modifications were made to the bipedal platform, BOB. These modifications are discussed in the following subsections, involving the addition of a wireless control circuit and proportional control loop and the integration of micro-spines for improved attachment performance.

4.1 Micro-spine Design and Manufacturing

The dactyls that allow the climber to perform on carpet do not perform well on hard or smooth surfaces. These dactyls provide high strength and resist wear at the cost of size. The dactyl tip is too large to properly engage asperities in common exterior surface materials. Using micro-spines with a much smaller tip radius, closer to $20\mu m$, allows for engagement of significantly smaller asperities.

The micro-spines used on robots such as RiSE are manufactured via the Shape-Deposition Manufacturing method. While this method allows for multiple material types to be combined into one finished product, the process is time consuming and requires seven days for the polyurethane to cure. For increased manufacturing time of small batches a new process would be developed.

The new process involves the use of a 60 Watt Universal Laser Systems Laser Cutter. The entire shape of the toes is cut from pre-manufactured polyurethane with a Shore rating of 20A (McMaster #9010K41). This shape alone, however, is too soft to provide support for the climber. Certain sections of the toe must maintain a rigid shape, such as where the toe attaches to the mounting pins and where the spine is embedded. To increase the stiffness around these sections, a stiff but thin, 0.003in. plastic sheet (McMaster #9513K115) is adhered to the sides of the toes. Once the plastic is adhered, the spine (Umpqua #TMC100SP-BL) is embedded between the plastic sides into a precut groove and bonded in place. The steps of the toe assembly process and the final array of micro-spines are shown in Fig. 4.1. This assembly process requires a 24 hour cure time for the epoxy used to bond the toe to the polyurethane.
The first generation of spines used the same plastic for both sides. This provided a sufficient bending stiffness, resisting deflection out of the 2-dimensional plane of the toe. However, this plastic appeared to have poor tensile strength leading to tensile failure in some of the toes. Fig. 4.2 demonstrates these two types of failure. Another challenge of this design exists in the assembly process. The urethane sheet that used to form the structure of the toes is coated with an adhesive backing. This backing simplifies assembly for one side of the toe by removing the need to apply an adhesive. However, only one side of the sheet is adhesive-backed requiring a layer of adhesive to be applied to the other side during toe manufacturing.

To overcome these two challenges, a revision of the toe design was made to use the 0.003in plastic (McMaster #9513K115) on one side while using a separate, adhesive-backed, 0.002in thick plastic film (McMaster #8689K42) that was rated for a high tensile strength compared to the previously used plastic. Using the adhesive-backed plastic on the "dry" side of the urethane, and the low tensile strength plastic on the adhesive-backed side of the urethane maintained the desired bending stiffness while increasing the tensile stiffness. This also increased the manufacturability of the laser-cut toes by decreasing the complexity and assembly time.
4.2 Micro-spine Experimentation

Dactyls on carpet have been shown to climb at speeds of 40 cm/s but are unable to perform on any “real” world surface. Direct implementation of micro-spines onto the platform yielded positive results. To compare the performance of dactyls against micro-spines, each attachment method was attempted on carpet, fine stone aggregate, rough stone aggregate, cinder block, and brick wall. The results of these preliminary tests are presented in 4.1.

<table>
<thead>
<tr>
<th>Attachment Method</th>
<th>Surface Type</th>
<th>Mean Vertical Speed (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dactyl Claws</td>
<td>Carpet</td>
<td>37.0 (±3.4)</td>
</tr>
<tr>
<td>Dactyl Claws</td>
<td>Fine Stone Aggregate</td>
<td>–</td>
</tr>
<tr>
<td>Dactyl Claws</td>
<td>Rough Stone Aggregate</td>
<td>–</td>
</tr>
<tr>
<td>Dactyl Claws</td>
<td>Cinder Block</td>
<td>–</td>
</tr>
<tr>
<td>Dactyl Claws</td>
<td>Brick</td>
<td>–</td>
</tr>
<tr>
<td>Micro-Spine Array</td>
<td>Carpet</td>
<td>38.5 (±0.01)</td>
</tr>
<tr>
<td>Micro-Spine Array</td>
<td>Fine Stone Aggregate</td>
<td>17.0 (±1.1)</td>
</tr>
<tr>
<td>Micro-Spine Array</td>
<td>Rough Stone Aggregate</td>
<td>12.2 (±0.6)</td>
</tr>
<tr>
<td>Micro-Spine Array</td>
<td>Cinder Block</td>
<td>10.2 (±0.7)</td>
</tr>
<tr>
<td>Micro-Spine Array</td>
<td>Brick</td>
<td>–</td>
</tr>
</tbody>
</table>

For each surface, a maximum reliable speed was found using a feed-forward method relying on voltage control. During these preliminary trials, 10 trials were performed on each surface except for the fine stone aggregate surface. During the 4th trial on this surface, the micro-spine toes were too far damaged to continue testing.
While the micro-spines improve performance in the “real” world, BOB was still unable to climb brick as the surface appears to be too smooth to allow engagement. While climbing on carpet, there appears to be no loss in speed as the attachment with micro-spines may perform even better than the dactyls in the sense that there are more attachment points created by the additional toes. Top speeds on stone aggregate and cinder block are less than half of the speed achievable on carpet. This is likely due to the loss in asperity density and the change in dynamics related to micro-spines discussed in Chapter 3. In the following chapters, methods to increase reliability and performance will be examined.

4.3 Wireless Control

The initial design of the climbing platform, BOB, used a tether to provide power and only used a feed-forward control method. With this method, a specified voltage was given to the motors and the motor would attempt to rotate as fast as that voltage would allow. However, this provided little control of the robot’s stride frequency. If a low stride frequency was desired, this could lead to the motor stalling. To overcome this, a proportional feedback loop was implemented. To increase functionality and eliminate the need for a power tether, a wireless controller was also added.

These tasks were accomplished through the use of the Pololu Wixel (#1336), a board based on the Texas Instruments CC2511F32 microcontroller. This microcontroller unit (MCU) contains an integrated radio transceiver. Using a pair of these MCUs allowed for a variety of stride frequencies to be used depending on the command from a remote host.

![Figure 4.3: Diagram of Wixel control scheme](image)
Velocity feedback would be controlled through the same MCU. The Faulhaber motors that were originally implemented on BOB were not equipped with encoders, however. Therefore, Maxon RE-13 DC motors (#118632) with a Maxon 17:1 planetary gearhead (#110314) was selected as the drive actuator with a Type S quadrature encoder (#224702). This motor provided similar torque and velocity characteristics to the previously employed Faulhaber motor. The encoder provides 16 pulses per revolution of the motor on two 90° phase-shifted channels. By counting the rising and falling edge of both channels, the resolution of the encoder is increased to 64 “ticks” per revolution of the motor.

The control scheme is demonstrated in Fig. 4.3. As the Wixel does not have a motor driver integrated, Pololu’s Motor Driver Carrier (#713) equipped with a Toshiba Motor Driver (#TB6612FNG) was also incorporated into the design. This motor driver’s low power consumption, small size, and high output capabilities make it an appropriate choice for pairing with the low current and voltage output of the Wixel. Using these components, a proportional control law was implemented on BOB operating in a feedback loop at 366Hz. This control algorithm allows for a variety of stride frequency’s to be programmed, however, stride frequency’s above 5Hz require a higher voltage supply than the 11.1V Li-Po battery used currently and stride frequency’s under 0.9Hz do not produce enough encoder “ticks” per iteration of the feedback loop. For simplicity, the current program uses a command prompt connected over the Wixel’s respective COM port via a program such as Putty. The program accepts an integer value between 1 and 5 as a commanded stride frequency. The input of the “w” character corresponds to a stride frequency of 4.1Hz for comparison to the model discussed in Chapter 6. The “s” character commands a stop-action that returns the electronics to an idle state awaiting a starting command.

The integration of a MCU also added the ability to incorporate additional actuators such as a servo, or an additional DC motor, for future studies or platform expandability. The updated platform is shown in Fig. 4.4 with the micro-spine arrays, microcontroller, battery and motor. While the components discussed here remove the need for a power tether and increase the climbing reliability by reducing the chance of stalling the motor, the components increase BOB’s weight by 50%, to 0.295kg.
Figure 4.4: Robot with updated hardware such as micro-spine arrays, wireless MCU, battery and motor.
CHAPTER 5

COMPLIANCE

Section 3.1 outlined the importance of using compliance while climbing dynamically. The following sections discuss the modeling and experimentation of the compliance levels involved in transitioning from dactyls to micro-spine arrays.

5.1 Compliance Modeling

While climbing prepared surfaces, such as carpet, the dactyls perform well because of their resistance to bending and a single engagement point that behaves like a pin-joint. A single linear extension spring in each wrist can provide the necessary compliance to reduce the ground reaction force (GRF). When moving to a "real" surface, the dactyls are too large to engage the surface and too stiff. When the dactyl’s tip engage the surface they can either destroy the asperity or bounce off the surface.

The prepared carpet surface used in previous research has a soft nature and low stiffness that acts in series with the robot’s compliance. The use of micro-spines as a form of attachment adds another compliant source in series between the surface and the wrist. The resulting system stiffness, \( k_{\text{system}} \), can be expressed as

\[
k_{\text{system}} = \left( k_{\text{surface}}^{-1} + k_{\text{wrist}}^{-1} + \left( \sum_{i} k_{\text{toe}_i} \right)^{-1} \right)^{-1},
\]

where \( k \) represents the spring constant of the respective component and \( N \) represents the quantity of toes engaging the surface. While climbing on most "real" surfaces, the \( k_{\text{surface}} \) approaches infinity, but while climbing on carpet, or other soft surfaces, this value becomes more relevant.

5.2 Compliance Experimentation

To examine the benefits of using the hierarchical compliance provided by the micro-spines over dactyls, varying compliance levels were examined on BOB while climbing at 90° using the speed
controller developed in Section 4.3. For this experimental setup, the carpet compliance was found to be approximately $500\,N/m$, the toes manufactured in Section 4.1 were found to have an approximate spring stiffness of $200\,Nm^{-1}$ when loaded vertically and the micro-spine arrays consisted of 15 toes each.

Examination under high speed video footage revealed that approximately 33% of the toes engage the surface and carry the load during a given step, which corresponds to an approximate foot stiffness of $1000\,N/m$. Experimental tuning found that a wrist spring with stiffness of $141\,N/m$ yields a GRF similar to the model behavior. This leads to a system compliance, from Equation 5.1, of $124\,Nm^{-1}$. The results of experimental trials with varying compliance types are tabulated in Table 5.1.

Table 5.1: Effect of compliance on reliable attachment to real surfaces

<table>
<thead>
<tr>
<th>Case</th>
<th>$k_{\text{system}},(N/m)$</th>
<th>$F_{\text{peak}},(N)$</th>
<th>$V_{\text{y,mean}},(m/s)$</th>
<th>Success (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Compliance</td>
<td>$\gg 1000$</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>No Toe Compliance</td>
<td>141</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>No Wrist Compliance</td>
<td>1000</td>
<td>7.5</td>
<td>0.206</td>
<td>60</td>
</tr>
<tr>
<td>Compliant Wrist and Toes</td>
<td>124</td>
<td>5.6</td>
<td>0.157</td>
<td>100</td>
</tr>
</tbody>
</table>

To eliminate the limb compliance, the toes and wrists were pinned in place. In this configuration, the robot was unable to climb the wall at all. Despite having 15 potential attachment points on each foot, the toes are unable to engage the asperities. Maintaining the constraint on the toes but introducing wrist compliance leads to the same results. One of the benefits of micro-spine arrays is the ability of each toe to act individually. By pinning them in place, the toes behave more like a sharp edge on the wall instead of individual points. This can cause certain toes to prevent neighboring toes from engaging the surface.

With the wrist motion constrained and the toes allowed to behave independently, the robot was able to climb the wall with a success rate of only 60%. The climber was also able to achieve speeds up to $0.206\,m/s$. Re-introducing wrist compliance, from Eq. 5.1, the system stiffness drops to $124\,N/m$. This low stiffness leads to a 25% decrease in the vertical GRF and a success rate of 100%. This increase in compliance, causes a loss in stroke length leading to a 25% slower vertical climbing speed at only $0.157\,m/s$. These results show that using micro-spines and tuned limb compliance, reliable dynamic climbing on “real” surfaces is possible.
CHAPTER 6

YAW

While tuning the limb stiffness of the robot improved its reliability at vertical speeds under 0.2\(ms^{-1}\), compliance tuning alone did not allow higher vertical speeds on “real” surfaces. One potential reason for this is the fact that BOB’s dactyl claws behave like pin-joints when engaged with the wall allowing rotation about the attachment point, matching the Full-Goldman template. On the other hand, the micro-spine arrays behave more like square-joints resisting rotation and potentially causing the spines near the array edge to disengage or fail. This chapter examines the effects of yaw on attachment forces for high speed climbing and introduces a method to mitigate these effects.

6.1 Modeling and Simulation of Climber

To analyze the change in behavior of the climber between the two attachment methods, a two-dimensional computer model of BOB was developed and examined in Working Model 2D. A previous model had been developed [5] during the design of the robot climber, BOB, which simulated the climber’s performance with a pin-joint foothold. This model was modified to account for the changes that were made to BOB for implementation in the “real” world including the motor characteristics, the additional compliance level provided by the micro-spines, a reduced sprawl angle, and the square-joint foothold. The original and modified model are presented in Fig. 6.1.

As expected, the use of micro-spine arrays prevent the pendulum-like motion that is characteristic of the Full-Goldman model. A position plot of the original and modified models are presented and compared in Fig. 6.2.

Fig. 6.2 demonstrates a significant loss in horizontal motion when transitioning to a more rotationally rigid attachment type, such as the micro-spines. While the lateral velocity is decreased significantly, the vertical velocity seems to only decrease by about 0.05\(m/s\). The small change in vertical velocity but large change in lateral velocity suggests the vertical GRF should not change very much, but the rotational GRF should increase greatly.
Figure 6.1: A.) Original model of BOB with pin-joint footholds. B.) Model of BOB with simplified micro-spine compliance and square-joint footholds.

Figure 6.2: Model data over four strides for original BOB model and the modified model demonstrating A.) 2-Dimensional Position, B.) Vertical Velocity, and C.) Lateral Velocity.
The modeled rotational GRF over a stride is presented in Fig. 6.3 for a square joint and for a pin joint. While the rotational GRF for the pin joint remains at a constant level of zero, the rotational GRF on the wall as modeled is $0.2\text{Nm}$. Assuming that only 33%, or 5, linearly spaced toes are engaging the surface and that there is a linear distribution across the toes, the individual force on each toe can be solved for. Solving the system as a simply supported beam with yields the forces as shown in Fig. 6.4.

The model assumes that the foothold is a rigid ON or OFF connection and does not consider the fact that the toes provide little friction when traveling upwards. Therefore, a toe with a GRF of less than zero would actually be closer to zero. This, however, means that vertical load on the
remaining toes would also increase. While Fig. 6.4 may not provide an accurate measurement of the forces on each toe, it implies that certain toes will see significantly higher forces than other toes leading to overloading on those toes. The overload pins in the micro-spine arrays forcefully disengage toes that undergo forces above 1N to prevent damage to the toes, but also causes loss of attachment.

Two possible methods to compensate for these forces include the following: 1.) Increase the size of the micro-spine to include more toes, or 2.) Add a rotational degree of freedom (DOF) to the wrist to allow the body to rotate independent of the foot.

Option one provides less complexity as it only requires a new and slightly larger 3D printed wrist and additional toes. By distributing the moment across a higher number of engagement points, the individual forces seen on each toe decrease as does the potential for damage to each toe. This approach, however, does not reduce the rotational GRF, it merely compensates for it.

Option two requires a redesign of the wrist into a two-piece design: one piece to maintain the sliding DOF and a secondary that rotates on this slider to create the rotational DOF. To accomplish this task, a torsional spring could be required to reset the foot to the proper orientation during flight phase.

Because the rotational GRF, or reaction torque, could not only damage the toes, but the surface asperities, option two was chosen for further study since it reduces the rotational GRF instead of merely compensating for it. To examine the effect of using a torsional spring at the foot the Working Model simulation was modified to include a torsional spring at the foothold. The rotational GRF over various springs stiffnesses are shown in Fig. 6.5.

In Fig. 6.5, the rotational GRF increases sharply with increasing spring stiffness then approaches the reaction force of the rotationally stiff wrist as the spring stiffness approaches infinity. Fig. 6.6 represents a closer view of the rotational GRF with springs that are very soft. The spring to be used for BOB’s wrists would need to be soft enough to reduce the rotational GRF but stiff enough to reset the foot to the vertical orientation, resisting the gravitational load on the foot. The necessary spring stiffness is dependent on the location of the center of mass of the foot relative to the point of rotation.

A proposed design is presented in Fig. 6.7. The stiffness required to maintain the orientation of the foot during flight phase was found empirically to be $k = 0.03 Nm/rad$. Therefore, a spring
(McMaster #9271K17) with this stiffness was chosen. Torsional springs with a higher stiffness should also work but as Fig. 6.5 shows, increasing the spring stiffness also increases the rotational GRF.

6.2 Experimental Results

To establish an experimental baseline, a six-axis force plate was used to measure the GRF of BOB while climbing with micro-spines. The data was sampled at 2500 Hz. The average GRF over
Figure 6.7: 3D-Printed prototype rotational wrists with a torsional spring, $k = 0.03N\text{m/}rad$.

5 steps on a stone aggregate surface is presented in Fig. 6.8.

![Figure 6.8: Plot of baseline ground reaction forces over one step.](image)

The data shown from the experimental trials follows closely with the model shown in Fig. 6.3 with a peak rotational moment at about $0.2N\text{m}$. The experimental data appears to have a slightly lower reaction torque which is likely caused by the slower operating speed than that of the model. The modeled robot climbs with a stride frequency of $4.1Hz$ but the maximum operating frequency in BOB’s current configuration is only $3Hz$ on stone aggregate.
To reduce the rotational GRF, or torque, a redesigned wrist with a rotational DOF could be designed and implemented on BOB as discussed in the previous section. A plot of the GRF after implementing wrists with a rotational DOF is presented Fig. 6.9.

Figure 6.9: Plot of ground reaction forces over one step after implementing a rotational DOF in the wrists.

Comparing the measured torques between Fig. 6.8 and 6.9 shows very little difference. The maximum command-able climbing speed also remained the same at 3Hz suggesting that there was no real gain to attachment capability.

The rotational DOF in these experiments was located at the base of the foot, offset from the point of attachment by approximately the length of a toe. To collocate the pin at the point of attachment would require a tedious redesign of the wrists. Moving the foot under the wrists, also changes the geometry of the climber, requiring the rear limbs to be modified to compensate for the change in body pitch. This data, though, suggests that these modifications may be desirable to decrease the effects of a rotational GRF on attachment.
CHAPTER 7

ROLL

7.1 Gravitational Body Roll

In order to reduce their pitch-back moment, climbers try to keep their center of mass as close to the wall as possible. For BOB, however, a slight body pitch is necessary to ensure that the flight foot engages with surface when the limb is fully extended. This design allows the robot to climb with only a single drive motor, but contributes to gravitational roll that occurs about the vector created from the engaged forward foot to the outer most point of the rear as shown in Fig. 7.1.

![Figure 7.1: Schematic of climbing platform with parameters for addressing roll with passive rear limbs.](image)

Figure 7.1: Schematic of climbing platform with parameters for addressing roll with passive rear limbs. The parameters $d_1, d_2, l_{\text{max}}, w, \psi, \vec{g}$ and $\vec{barf}$ represent the shoulder width, rear leg offset, extended leg length, rear leg width, maximum body yaw, gravitational vector and foot-contact vector, respectively, for the climber.

To counter gravitationally induced roll, BOB employs the use of passive rear limbs. Previous iterations of BOB used excessive spreading of the rear limbs to counter this roll. While using this design prevented the detached foot from rolling away from the wall, the design increased the robot’s size and weight.
Direction of the roll is determined by the location in which the gravity vector, \( \hat{g} \) and the foot-contact vector, \( \hat{f} \), intersect. If the intersection occurs above the center of mass, COM, then the body will roll toward the detached foot and assist in attachment. If the intersection of the vectors is below the center of mass, however, the body will roll the detached foot away from the wall decreasing the chance of attachment.

To optimize the design of BOB and increase the reliability of design, the tail should be long enough to cause the intersection of \( \hat{g} \) and \( \hat{f} \) to be above the COM without using excessive material and weight. While climbing dynamically, the body’s yaw constantly changes the point at which \( \hat{g} \) and \( \hat{f} \) intersect. To compensate for the body’s yaw, the minimum distance between the two rear feet, \( w \), becomes a function of the maximum yaw as well as the body’s geometry as described in Equation 7.1.

\[
w \geq 2 \left( d_1 + (l_{\text{max}} + d_2) \tan \Psi_{\text{max}} \right),
\]

(7.1)

In Equation 7.1, \( d_1 \), \( l_{\text{max}} \), \( d_2 \), and \( \Psi \) represent the shoulder width, the maximum extended length of the leg, the offset between the shoulder and rear legs along the body centerline, and the maximum expected yaw, respectively.

### 7.2 Passive Rear Limb Width Experimentation

Using high-speed video, the maximum yaw that BOB’s body undergoes was found to be 21° on stone-aggregate with micro-spines at a stride frequency of 2Hz. (Note: This low climbing speed was used because BOB and similar dynamic climbers exhibit the largest yaw motions at slower speeds.) With BOB’s dimensions and this yaw angle, Equation 7.1 gives a minimum rear width of 0.357m. In order to test this prediction, a series of experimental runs with various width passive limbs were run. Table 7.1 shows the % of successful runs out of 10 trials a range of rear widths.

Using active rear legs, such as seen on the SCARAB platform [15], can also provide the stabilizing effects shown here, but at the cost of adding an actuator to each limb, requiring additional control and feedback. The approach discussed above maintains a simple methodology with low control. Tuning of the rear limb width as discussed above proposes a reduction in the width of the limbs to 0.357m from the previous 0.91m or a reduction of 0.553m and a weight savings of 13g. This however suggests operating at the minimum rear limb width. Using a safety factor of 1.4,
Table 7.1: Climbing success rates with varying rear widths.

<table>
<thead>
<tr>
<th>Splay Width (m)</th>
<th>Success Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.600</td>
<td>100</td>
</tr>
<tr>
<td>0.500</td>
<td>100</td>
</tr>
<tr>
<td>0.400</td>
<td>100</td>
</tr>
<tr>
<td>0.357</td>
<td>90</td>
</tr>
<tr>
<td>0.300</td>
<td>0</td>
</tr>
</tbody>
</table>

or a width of 0.500\(m\), allows for occasional missed steps where the yaw may exceed the predicted maximum and still results in a weight loss of 10\(g\) and a reduction of over 0.400\(m\) from the previous value.

### 7.3 Stroke-Induced-Roll

While the four-bar drive mechanism that BOB and similar dynamic climbers employ is simple and effective, when combined with the body’s pitch, it causes the leg stroke to have a component that acts normal to the climbing surface instead of in the 2-dimensional plane that parallels the climbing surface. This motion causes the body to roll about the body’s centerline. To quantify this force, the robot was run 5 times over a force plate while data was recorded at 2500\(Hz\). Data from a commanded stride frequency of 3\(Hz\) on stone aggregate is shown in Fig. 7.2 which shows an average peak force of 1.1\(N\) being exerted in the normal direction by the limb during a step.

Running the same 5 trials with BOB at stride frequency of 2\(Hz\) results in a peak normal force of 0.9\(N\) while trials on a carpet surface at 5\(Hz\) yield a normal force of 3\(N\), shown in Fig. 7.3. This data suggests that as the stride frequency increases, the normal GRF also increases.

To understand the impact of this normal force while climbing, the maximum allowable normal attachment force for the robot’s feet was examined. To find the maximum allowable normal force for a given foothold, one of the robot’s feet was placed on the force plate while the other was detached from the surface. Since the allowable normal (adhesive) force for micro-spines (and other directional adhesives) is a function of the loading (downward) force on the foot, three separate pre-loads were examined: 1) the robot’s weight, 2) twice the robot’s weight, and 3) three times the robot’s weight. During testing, a normal force was exerted on the foot until the foothold failed. The maximum forces sustained by the foothold under the 3 separate preloads are tabulated in Table 7.2.
Figure 7.2: Plot of averaged force plate readings shown over one step for the vertical forces and the normal force at 3Hz on stone aggregate.

Table 7.2: Maximum normal force before foothold failure on stone aggregate.

<table>
<thead>
<tr>
<th>Vertical Force Applied (N)</th>
<th>Mean Normal Force at Failure (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>1.5(±0.9)</td>
</tr>
<tr>
<td>5.0</td>
<td>1.5(±0.6)</td>
</tr>
<tr>
<td>7.5</td>
<td>3.1(±0.4)</td>
</tr>
</tbody>
</table>

From Table 7.2, the average normal force exerted by BOB (1.1N) during a step on stone aggregate is shown to be close to the maximum sustainable fore-aft force. This suggests that a method to reduce the out of plane motion of the limbs is necessary to achieve higher reliability while climbing dynamically on “real” surfaces.

Some robots such as the RiSE platform, use an additional actuator in the limb to achieve the desired foot trajectory, thus reducing the normal reaction force. For a bipedal platform, such as BOB, the torso can be actively rotated using the rear limbs to achieve a similar effect. This can be done by redesigning the drive mechanism to additionally activate a mechanism that performs this counter-rolling motion, or by the implementation of a single additional actuator which would require the use of a controller such as that developed in Section 4.3.

The magnitude of this rotation is dependent on certain geometric parameters of the climber’s body, displayed in Fig. 7.4. First of these parameters to calculate are the nominal shoulder heights,
Figure 7.3: Plot of averaged force plate readings shown over one step for the vertical forces and the normal force at 5Hz on carpet.

\[ h_R = l_R \sin \phi \]  
\[ h_L = l_L \sin \phi \]  

(7.2)  
(7.3)

where \( l_R \) and \( l_L \) are the lengths of the right and left legs, respectively, with a given leg at full extension. These values can be used to determine the difference in height of the shoulders from the centerline using the equation,

\[ \Delta h = \frac{h_R - h_L}{2}, \]  

(7.4)

from which the required body roll angle \( \theta \) to keep the feet in the climbing plane can be found as

\[ \theta = \arcsin \left( \frac{\Delta h}{d_1} \right) . \]  

(7.5)

Equation 7.5 can be rewritten and to include the terms from Equations 7.2, 7.3 and 7.4 as

\[ \theta = \arcsin \left( \frac{(l_R - l_L) \sin \phi}{2d_1} \right) . \]  

(7.6)
Figure 7.4: Schematic for a bipedal dynamic climber with the parameters relevant to addressing leg-stroke-induced roll labeled. The parameters $d_1$, $d_2$, $d_3$, $l_R$, $l_L$, $l_c$, $\theta$, and $\Phi$ represent the shoulder width, rear leg offset, wall offset, right leg length, left leg length, distance to the surface along the centerline, body rotation angle and leg incidence (pitch) angle, respectively.

From the equations presented here, and the known geometric parameters of BOB, the angle required to rotate BOB’s torso was found to be $11^\circ$. Using this angle, a controller, such as that discussed in 4.3 can be programmed to control an additional actuator, such as shown in Fig. 7.5, to reduce the out of plane forces and keep the feet in a 2-dimensional plane that parallels the climbing surface.
Figure 7.5: Picture of the proposed hip-actuator for BOB to reduce out of plane forces.
CHAPTER 8

CONCLUSIONS

8.1 Summary

While biological inspired designs have been proven to perform efficiently and at high speeds, there is still a great deal of research that can improve the field further. Few robots have been designed that are capable of climbing at high speed while BOB is the first climber to be capable of climbing at high speed on a rough exterior surface.

This thesis included a new method for the manufacturing of laser cut micro-spines as an alternative to the SDM method. Using these micro-spines, BOB became the first dynamic climber to successfully employ micro-spines in the “real” world achieving a speed of 17.0\text{cm/s} on stone-aggregate and 10.2\text{cm/s} on cinder block. While other robots have shown an ability to perform in the “real” world using micro-spines, their quasi-static gaits limit their climbing speeds significantly.

A minimum level of compliance was proven to be needed to prevent the climber’s feet from knocking itself off the wall. More specifically, the use of a hierarchical compliance is shown to be more beneficial than using a single source of compliance by distributing the loading over several toes. While increasing the level of compliance in the limbs increases the reliability of the climber, it also decreases the speed of the climber as the stroke length is limited by the size of the crank and the extension of the spring.

The yaw and roll motions that are coupled to dynamic climbing present some of the largest challenges to “real” world dynamic climbers. Both motions can create undesired effects that cause the loss of a foothold. A 2D simulation was presented that showed the effects of yaw on attachment along with experimental verification of the model. Two types of roll were examined along with methods to compensate for both. Gravitational roll that occurs due to the climber’s yaw was modeled as a function of the climber’s geometry and then a specified rear splay width was found. While using a rear splay width at, or near, the specified width presented only a 90% success rate in climbing, using a safety factor of just 1.4 increased the success rate to 100%. Additionally, stroke-induced roll was modeled as function of the 3-dimensional geometry of the climber including
the body’s pitch. This pitch is necessary to ensure engagement of the feet with the surface. To compensate for this roll about the body’s centerline, an equation representing a counter-rolling hip-angle was presented along with a proposed mechanism to accomplish this task.

8.2 Future Work

Using the principles outlined in this thesis, combined with some of the tasks outlined in this section, further work on BOB should yield reliable high-speed climbing on a variety of “real” surfaces.

While the controller presented in Section 4.3 provided adequate control for a single actuator without the need for an additional decoder chip, future work with the controller may require an external decoder to reduce the processing load on the MCU allowing for better control of multiple actuators. Migrating the components to a printed circuit board will allow for better routing of signal lines allowing for control with a board of the same size as that used here.

Using this updated controller, countering roll with active rear limbs can be further examined. Because the hip motor would be back-driven at speeds up to $5Hz$, a motor or servo with adequate gear material and nominal speeds would need to be implemented. Testing done for this thesis with Power HD DSM44 servos resulted in gear teeth failure.

Using the counter-rolling mechanism, a method of climbing down a wall can also be investigated. The nature of BOB’s initial design only allows for climbing upward. Actively rolling the torso $180^\circ$ with the motor should allow for a downward climbing scheme. Previous work has shown methods for maneuvering laterally [7] that can be combined with the active rolling mechanism to greatly increase the robot’s maneuverability.

Future work also includes the exploration of other surfaces than those discussed here. While this thesis demonstrated results on two types of stone-aggregate and cinder block, other surfaces such as stucco and brick should be examined. Other robots, such as Rise, use a controlled stroke length to grip the top of individual bricks as the actual bricks are too smooth to attach to with current micro-spines. BOB’s stroke length is too short to accomplish this task. This leads to the idea of a slightly larger BOB employing physically larger gears to increase it’s stroke length.
The future work proposed here can also be integrated into the ICAROS platform discussed in Chapter 1 to create the first multi-modal platform that can climb at high-speeds on “real” surfaces operating in the scansorial regime and the aerial regime.
APPENDIX A

PERMISSIONS FOR THE REPRODUCTION OF IMAGES

Title: Design of a Multimodal Climbing and Gliding Robotic Platform
Author: Dickson, J.D.; Clark, J.E.
Publication: Mechatronics, IEEE/ASME Transactions on
Publisher: IEEE
Date: April 2013

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