THE EFFECT OF SPRAWN ANGLE AND WALL INCLINATION ON A BIPEDAL, DYNAMIC CLIMBING PLATFORM

J. D. Dickson and J. E. Clark*

Department of Mechanical Engineering,
Florida A & M University - Florida State University College of Engineering,
Tallahassee, FL 32310, USA
* E-mail: clarkj@eng.fsu.edu
www.eng.fsu.edu/stride

Animals have shown the ability to climb vertical surfaces with high speed and stability. Utilizing the underlying dynamics of these animals, robotic platforms have been developed that climb vertical surfaces with similar speed. It is hypothesized that the pre- incidence angle of the legs, commonly referred to as sprawl angle, for these robotic platforms can significantly affect vertical velocities, efficiency, and stability as well as passively controlling body oscillations. To date, little empirical work has been conducted on the effect of sprawl angle and wall inclination on the performance of dynamic climbing platforms. This paper presents initial research utilizing a biologically inspired dynamical climbing platform to understand the effect of sprawl angle and wall inclination on dynamic climbing. Simulations have shown that a sprawl angle of 30° maximizes vertical velocity overall, while experimental results show that a sprawl angle of approximately 10° maximizes vertical velocity, while in both increasing sprawl angle increases lateral velocities over all wall inclinations.

Keywords: Dynamic climbing; sprawl angle; bio-inspired robotics

1. Introduction

Animals have shown the ability to climb vertical surfaces with high speed and stability. Utilizing the underlying dynamics of these animals, robotic platforms have been developed that climb vertical surfaces with similar speed. The bio-inspired, dynamic scansorial platforms have shown capabilities of faster vertical velocities than previous, quasi-static climbers through active management of their kinetic energy.

Dynamic climbing platforms have drawn their inspiration from biological analogs including geckos and cockroaches. While these animals are vastly different morphologically, their ground reaction forces and velocity profiles
generated during climbing were found to be remarkably similar.\textsuperscript{1,2} This discovery led to the development of the Full-Goldman Template\textsuperscript{2,3} which utilizes two legs to generate similar force and velocity profiles as its biological progenitors. It is hypothesized that the pre-incidence angle of the legs, commonly referred to as sprawl angle, can significantly affect vertical velocities, efficiency, and stability as well as passively controlling body oscillations.\textsuperscript{2,3}

Current biological data indicates that cockroaches transition their legs from pushing during horizontal running to pulling for vertical climbing.\textsuperscript{4} To date, little work has been conducted on the effect of wall inclination on the performance of dynamic climbing platforms.

While biological data suggests that animals utilize an effective sprawl angle of approximately $10^\circ$ on vertical surfaces,\textsuperscript{2} only a cursory examination of the effect of sprawl angle on dynamic climbing platforms has been conducted.\textsuperscript{5,6} This paper presents the development of a small-scale, bipedal, dynamic climbing platform based on the Full-Goldman template with an adjustable shoulder sprawl angle. The effect of varying sprawl angle on vertical and lateral velocity is experimentally investigated on a variety of climbing inclinations.

### 2. Simulation

In order to study the effects of sprawl angle and wall inclination on dynamic climbing, a new simulation was developed in Working Model 2D capable of variable sprawl angle and wall inclination based on the Full-Goldman template.\textsuperscript{2} Considerations for the development of the physical platform led to a simulation mass of 200g. The dynamic properties of the Full-Goldman template were preserved through utilization of dynamic similarity. A thorough discussion of dynamic scaling is presented by Alexander\textsuperscript{7} and Clark et al.\textsuperscript{3} Scaling of the Full-Goldman template from 2g to 200g led to a simulation that utilizes a leg stroke of 5.1cm and runs at 4.2Hz.

The simulation utilizes a geared transmission system in which a single motor supplies torques to both gears. Each gear serves as a crank for the crank-slider mechanism which drives the linear arms angled at a prescribed sprawl angle. A wrist spring of $131 Nm^{-1}$ is incorporated into the system connecting the foot to the end of the arm. The foothold is approximated as a pin joint during stance and turned off during flight. The stance conditions are calculated based on the angular position of the gears driving the crank-slider mechanism. A torque-limited speed controller was implemented in the simulation in addition to the simple frequency controller.
The primary motivation for the addition of the torque-limited speed controller to the 2D simulation is the analysis of the effects of friction drag on the climbing surface when the wall inclination is reduced from vertical. The frictional force due to drag on the carpet was implemented as a force opposing vertical motion equal to the normal force of the robot, expressed as gravitational constant (9.81) multiplied by the mass of the robot and the cosine of the angle of the wall \( (\psi) \), on the wall multiplied by the coefficient of friction, as shown in (1). The coefficient of friction, \( \mu \), was empirically calculated for the carpeted climbing wall as 0.2650.

\[
F_f = \mu(9.81 \times \text{mass}) \times \cos(\psi)
\]  

(1)

2.1. Simulation Results

![Wall Inclination versus Vertical Velocity](image1)

![Wall Inclination versus Lateral Velocity](image2)

Fig. 1. Vertical and lateral velocities of the bipedal dynamic climbing simulation utilizing a mass of 200 g, a torque limited speed controller operating at 4.2 Hz, and wrist spring stiffness of 131 Nm\(^{-1}\) run on varying wall inclinations between 90° (vertical) and 50° incrementing by 10° with sprawl angle between −10° and 30° incrementing by the same amount.

The velocities of the simulation, shown in Figure 1, show perceptible trends with the alteration of hip sprawl angle. The simulation shows a maximum vertical velocity utilizing a sprawl angle of 30° for most wall inclinations, as previous simulation studies conducted by Clark et al.\textsuperscript{5} and
Lynch et al. predict. For sprawl angles between 0° and 30° a minimum vertical velocity is shown at a wall inclination of approximately 70°. This wall inclination corresponds to a maximum resistive force on the platform through the combination of the gravitational force and drag force of the wall. Overall, the variation in vertical velocities is minute when compared to their overall magnitude. The lateral velocity shows an expected upward trend in maximum lateral velocity with increasing sprawl angle.

The trends shown in the simulation of sprawl angle show similarities to previous studies on the effect of sprawl angle on dynamic climbing. It is expected that a sprawl angle of 30° will maximize vertical velocity and max lateral velocity on the experimental platform. It is also expected that a sprawl angle of 0° will minimize the lateral velocities.

3. Platform Fabrication

The miniature bipedal dynamic climber utilized the same scale and drive system as the Working Model 2D simulation and borrowed design considerations from the initial dynamic climbing platform, Dynoclimber. A single DC motor was utilized to provide actuation for both arms leading
to an under actuated system for reduction of mass. The platform physically locks the arms 180° out of phase. Based on torque requirements determined utilizing the 2D simulation, a 6 V Faulhaber DC motor (# 1331 006 SR) with a Faulhaber Series 15/3 6.3:1 ratio spur gear head was chosen to drive the climber at the design target of 200g. The final physical platform weighed 187g.

A crank-slider mechanism utilizing 5 cm gears, leading to an additional gear reduction of 3.75:1, coupled with miniature linear guide rails and bearing blocks (Misumi #SSEB6-40) provide the necessary linear motion required based on the scaled Full-Goldman template. A slotted shoulder mount and guide block provide the ability to alter the sprawl angle at the shoulder and lock it during experimental runs. Marks on either side of the shoulder indicate pre-defined sprawl angles incrementing by 10°. The platform utilizes commercially available wrist springs of 131 Nm⁻¹ with a maximum extension of 2 cm. Simple hooks are rigidly attached to the slider block of each wrist mechanism, shown in Figure 2.

4. Experimental Setup and Procedure

To evaluate the performance of the platform’s scansorial motion, a 1.22m x 2.5m carpeted wall was built and oriented vertically, the wall is designed to be capable of adjusting its inclination between 90° and 50°. A motion capture system was implemented for tracking the location and orientation of the platform using two LEDs and a Casio Exilim Pro EX-F1 high-speed camera at 300 fps.

The platform was run 10 times for each sprawl configuration varying between 0° and 30° by 10° on the given wall inclination. The wall inclinations varied between 90° (vertical) and 50° incrementing by 10°. Each run extracted three strides at the top of the run to ensure steady state operation for numerical analysis utilizing MATLAB.

5. Experimental Results

The platform was first compared to the 2D Working Model dynamic simulation discussed in Section 2. The simulation utilized the same physical constraints as the platform including mass, wrist spring, frequency, and torque limitations. It was found that at a sprawl angle of 10° on a vertical wall the simulation predicted the platform’s trajectory and velocity profiles closely. Figure 3 shows the comparison of the platform run on a vertical wall with a sprawl angle of 10° and the Working Model simulation.
run with the same parameters. A limping gait is apparent in the vertical velocity of the platform, most likely attributable to a slight asymmetry in the drive mechanism of the platform. The experimental platform was shown to climb at a vertical velocity of $37.0 \pm 3.4 \text{cms}^{-1}$ approaching the scaled velocity of a cockroach climbing at the same mass and exceeding the predicted simulation velocity of $36.6 \text{cms}^{-1}$. This vertical velocity sets this miniature dynamic climbing platform as the second fastest climbing robot following the original dynamic climber, Dynoclimber, capable of velocities up to $66 \text{cms}^{-1}$.

After comparing the simulation to the physical platform, 200 individual climbs were run over the number of sprawl angles and wall inclinations. The results of these runs are shown in Figure 4a and Figure 4b. The overall trends found on the physical platform show a maximum vertical velocity at a sprawl angle of $10^\circ$ over all wall inclinations, as Figure 4a illustrates. Between $90^\circ$ and $50^\circ$ the maximum vertical velocity increases with decreasing wall inclination, as Figure 4b shows. As predicted by the simulation, and shown in Figure 4a, with increasing sprawl angle the maximum lateral velocity increases.
6. Conclusions and Future Work

A comparison of the Working Model 2D simulation results with previous simulation studies on the effect of leg sprawl on velocities shows similar trends including increasing vertical and lateral velocities with increasing sprawl angle and a 30° angle maximizing both.

While the simulation captures the effect of leg sprawl and slope for lateral velocities on the physical platform, it over predicts the vertical speed for large sprawl angles. The experimental data shows a maximum vertical velocity attained utilizing a 10° sprawl angle over all wall inclinations. The discrepancy in vertical velocity appears to be caused by increased lateral forces imparted to the linear guide block bearings as sprawl angle increases. The friction of the guide block increases as lateral force on it increases, thus reducing the overall vertical velocity. The sprawl angle of 10° represents the point where increased vertical velocity due to sprawl angle can still
overcome the increased friction due to the guide block, where as the benefit of increased sprawl angle on vertical velocity is lost after 10°. For wall inclinations of 90° to 50° the ideal sprawl angles do not seem to shift.

In order to address these discrepancies, the simulations utilized for dynamic climbing will need to incorporate a friction model for the legs and methods of reducing this friction should be investigated for the robot.

Future work will focus on analyzing the effects of sprawl angle and wall inclination on climbing efficiency and ground reaction forces utilizing simulation and experimental studies over wall inclinations between 0° and 90°. These studies will be compared to animals such as the cockroach *Blaberus discoidalis* and the gecko *Hemidactylus garnnotti* to gain insight on how biological systems utilize leg sprawl angle during high speed vertical running.

References