Phase Overlap for Bounding Gait

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***Abstract*—This study presents the design and evaluation of a quadrupedal robot that uses a bounding gait and is optimized for navigating deformable terrains, focusing on the critical locomotion parameter, i.e., phase overlap/difference. Addressing the unique challenges posed by such terrains, which are often encountered in search and rescue missions and extraterrestrial explorations, this research aims to enhance robotic capabilities beyond the limitations of traditional wheeled or tracked systems. Through empirical experimentation and adaptation of the Buehler clock parameters, it was hypothesized and demonstrated that the robot's velocity increases to an optimal point with phase overlap before decreasing, identifying the optimal phase overlap that balances stability and propulsive efficiency. This investigation provides valuable insights into the adaptive locomotion of robots, shedding light on the complex dynamics of quadrupedal movement and informing future designs for robust and versatile robotic platforms in real-world applications.**

I. INTRODUCTION

The ability to navigate challenging terrains with precision and efficiency has been a longstanding pursuit in robotics. Deformable terrains, characterized by their variability and unpredictability, pose unique challenges for robots. Addressing these challenges requires innovative design approaches that can adapt to the ever-changing nature of the terrain. Bounding gait was the chosen locomotion type as it is optimal for robots traversing on deformable terrains. In a bonding gait, the robot's front legs contact the ground (briefly) while the rear legs straddle. When the rear legs are about to hit the ground, the front legs lift off, propelling the robot forward. Therefore, the robot is constantly in motion, and experimentally, the bonding gait makes the robot travel in a straight line and at a fast pace.

The primary motivation behind this endeavor lies in the practical applications of such a robot. From search and rescue operations in disaster-stricken areas to exploration missions on unknown extraterrestrial landscapes, the ability to navigate deformable terrains efficiently can significantly enhance the capabilities of robotic systems. As such, this project aims to contribute to developing robots that can operate effectively in real-world scenarios where traditional wheeled or tracked systems may fall short.

The research question focuses on the design of a quadrupedal robot with a bounding gait that exhibits optimal phase overlap/difference. Phase overlap/difference is a critical parameter in the locomotion of quadrupedal robots, as it dictates the timing and coordination of leg movements. Achieving an optimal phase overlap/difference ensures stability and efficiency during traversal on deformable terrains. To guide this research, a hypothesis was formulated that suggests the robot's velocity will follow a specific pattern as a function of phase difference. Specifically, it is proposed that the robot's velocity will increase linearly until it reaches a phase difference of 0.4, after which it will decrease linearly. This hypothesis was developed because a phase difference of 0.4 would represent a midpoint between synchronized leg movements (phases 0 and 1); it is expected that this phase difference will strike an optimal balance between maintaining stability through coordinated leg lifting and achieving forward propulsion through efficient linear velocity increase and decrease. This hypothesis serves as a foundation for the experimental approach and data analysis.

Fig. 1: Quadrupedal Robot on Deformable Terrain

This research builds upon the work of numerous scientists and engineers who have contributed to quadrupedal robotics. The comprehensive literature review draws upon the research findings from diverse sources, each contributing a unique facet to understanding quadrupedal robot locomotion and deformable terrain traversal. In the realm of snake-like robots, Fu and Li (2020) explored the stability benefits of body compliance for robots traversing enormous, smooth obstacles, presenting a robot with a unique gait that combines lateral undulation and cantilevering. This approach showcased the robot's ability to travel steps as high as a third of its body length, providing valuable insights for developing snake robots in applications like search and rescue and building inspection [1]. On the quadrupedal front, Lee et al. (2021) introduced a neural network-based controller for legged locomotion, demonstrating remarkable zero-shot generalization from simulation to challenging natural environments. The controller maintained robustness across various terrains, including steep slopes, rocky grounds, and even in the presence of dynamic footholds and overground impediments. This contribution signifies a leap towards achieving animal-like robustness and adaptability in robotic locomotion [2].

In the paper by Li and Lewis [4], the authors address the need for alternative ground robots to traverse sandy and rocky extraterrestrial terrains effectively. They highlight the challenges such environments pose and advocate for developing innovative robotic systems with diverse locomotion mechanisms to overcome these obstacles. This paper provides valuable insights into the limitations of traditional ground robots in extraterrestrial exploration scenarios and underscores the importance of exploring alternative designs to enhance mobility in harsh conditions. In the work by Fei Zhang and colleagues [7], the authors present a terrain-adaptive robot prototype explicitly designed for bumpy-surface exploration. They validate the robot's gaits through dynamic simulation and experiments on various deformable terrains. This research offers a practical example of a robot tailored for navigating challenging terrains and showcases the significance of rigorous validation processes for ensuring the effectiveness of robotic locomotion strategies. Their findings serve as an inspiring reference for our research into optimizing quadrupedal robot gaits for deformable terrain traversal.

To encapsulate, the project aims to address the pressing challenges of deformable terrain traversal by designing and constructing a quadrupedal robot that leverages optimal phase overlap or difference in its locomotion. Additionally, software techniques for kinematic measurements were leveraged to collect and analyze data related to the robot's performance. This paper will entail the design process, experimental methodology, and findings. The insights gained from this research endeavor are expected to contribute to the broader field of robotics and inspire further advancements in deformable terrain traversal and quadrupedal locomotion.

II. MATERIALS AND METHODS

A. Experimental Setup

The experimental setup, as shown in figure 2, consisted of a deformable (granular) terrain created using a homogeneous bed of 5mm diameter spherical pellets. The terrain was contained within a wooden frame, ensuring a consistent testing environment. The entire setup was crafted to rigorously assess the robot's gait adaptability and terrain negotiation abilities as it attempted to traverse the length of the pellet bed, with its performance meticulously documented for subsequent analysis.

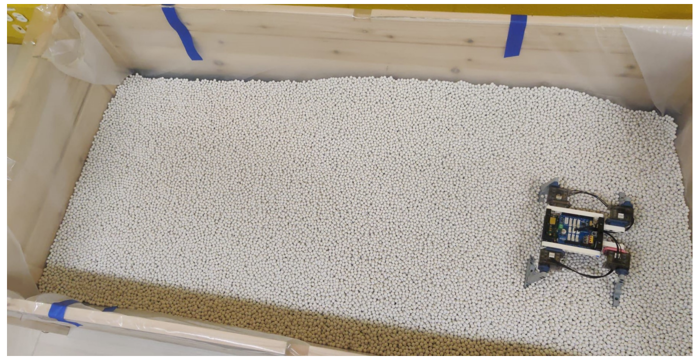

Fig. 2: Experimental Setup of the Deformable Terrain

B. Components and Design

The robot comprises a central body (Arduino Uno board with a Dynamixel Shield), four legs (Dynamixel XL-320 servo motors), and feet (Lego parts). It is evident from figure 3 that the legs are eleven centimeters apart. The leg is six centimeters long, and the foot is 5.5 centimeters long. Figure 3 shows the robot's assembly. The Arduino and the Dynamixel Shield are housed in a frame built using Lego parts. A rechargeable battery will power this robot, and the battery will be placed in an adapter. Initially, the robot is set to start with all the legs on the ground and the same velocity for all four legs with a fixed stride frequency. The legs start in the slow phase as more torque and less speed are required to propel the robot forward. The orientation of the slow phase (figure 4) is selected such that the robot generates the initial thrust, and later, the legs are in the fast phase to move the robot forward. The slow phase spans over 60^0 and is 40% of the total clock period. Subsequently, the phase difference and time periods are varied to finetune the optimal phase overlap of the bounding gait.

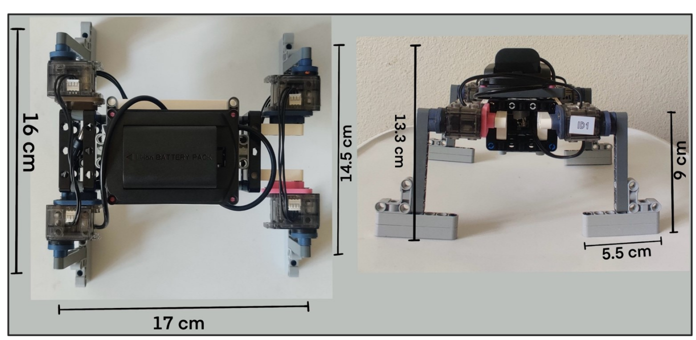

Fig. 3: Quadrupedal Robot Dimensions

The robot's leg length and foot length selection were driven by a series of considerations to optimize traversal performance over deformable terrain. The leg length of six centimeters was the optimal value as it allowed the robot to step over the irregularities of the spherical pellet bed without excessive energy expenditure or risk of entanglement. The foot length of 5.5 centimeters was chosen to maximize the contact area with the terrain. A larger foot size could distribute the robot's weight more effectively across the loose, granular material, preventing it from sinking into the deformable terrain and facilitating smoother propulsion. However, the feet mustn't be so large as to impede the robot's ability to lift and reposition its limbs swiftly.

C. Methodology

To achieve the proposed understanding of the research hypothesis, the construction and testing of a quadrupedal robot designed to traverse deformable terrain will be studied in detail. The physical experiment must be conducted by subjecting the robot to traverse a simulated deformable terrain as shown in figure 2. The robot's gaits and timing parameters (ϕ_s, ϕ_o, and d_c) are programmed using Arduino. The optimal stride frequency, ω, was calculated through theoretical derivation.

$$\omega_{slow} = \frac{\phi_s}{t * d_c}$$

$$\omega_{fast} = \frac{360 - \phi_s}{t * (1 - d_c)}$$

In the above equations, t is the clock period, and d_c is the duty cycle.

The Buehler clock parameters (shown in figure 4) that were chosen are ϕ_s = 1.04 rad, ϕ_o = 3.66 rad, and d_c = 0.4. The duty cycle is the duration of the slow phase. ϕ_f is the fast phase, ϕ_s is the slow phase, and ϕ_o is the midpoint of the slow phase. The start and end times of the slow phase were calculated using the above parameters. These parameters are different from the conventional clock parameters for deformable terrain.

$$degreeSlowStart = \phi_o - \frac{\phi_s}{2}$$

$$degreeSlowEnd = \phi_o + \frac{\phi_s}{2}$$

$$timeSlowStart = \phi_o - \frac{\phi_s}{2 * \omega_{fast}}$$

$$timeSlowEnd = timeSlowStart + \frac{\phi_s}{\omega_{slow}}$$

In the above equations, ϕ_o, and ϕ_s were converted to degrees by multiplying it with $\frac{180}{\pi}$. degreeSlowStart was 180^0 and degreeSlowEnd was 240^0.

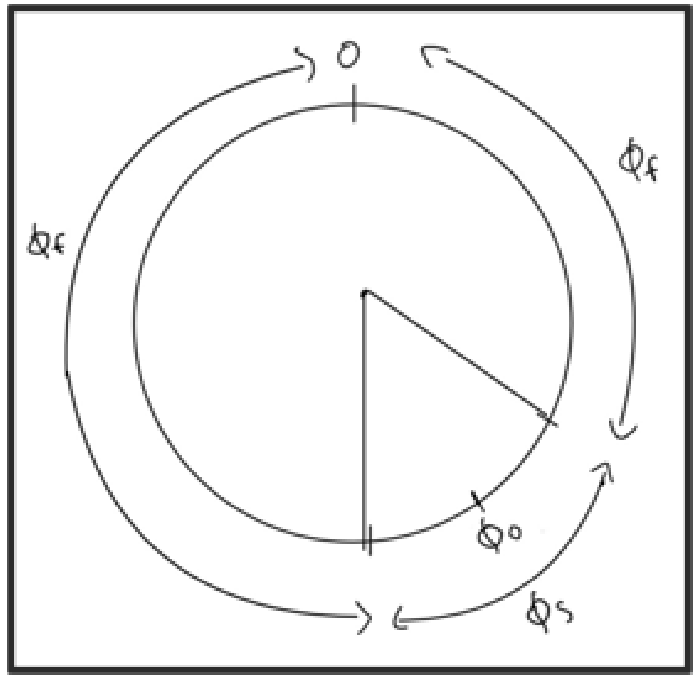

Fig. 4: Buehlar Clock Parameters

The selection of the Buehler clock parameters for the robotic setup was informed by experimental adaptation and trial-and-error, resulting in a configuration that yielded better performance on deformable terrain than conventional parameters. The duty cycle (d_c = 0.4) was a critical parameter that diverged from standard settings. By reducing the duration of the slow phase, the robot's feet spent less time in contact with the potentially unstable surface, decreasing the chance of sinking or creating significant disturbances in the pellet bed that could hinder movement. This approach was validated through empirical observations where the robot achieved faster traversal speeds, which, while unexpected, highlighted the benefits of a reduced-duty cycle in this context.

III. Results and Discussion

The quadrupedal robot was tested using a bounding gait with the following parameters: phase difference between the front two legs, phase difference between the rear two legs, and phase difference between the front and rear legs. Since the first two parameters remain the same for bounding gait, the third parameter varied, indicating the phase overlap. The experimental results align well with the hypothesis. As the phase overlap between pairs of legs increases, the robot's velocity initially increases and decreases after reaching a particular phase difference (0.4). This outcome corroborates the idea that there is an optimal phase overlap for leg coordination that maximizes the robot's velocity.

Figure 5 shows that the velocity begins to decline after reaching a peak with further increases in phase overlap. This decline beyond a certain point aligns with the hypothesis and

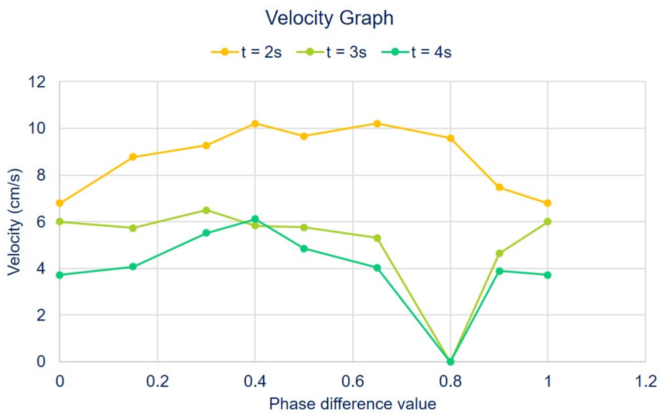

Fig. 5: Robot's Velocities for different Clock Periods

indicates that excessive synchronization between leg movements becomes counterproductive, possibly due to increased mechanical interference or inefficient gait cycles. The exact point at which the maximum velocity is achieved is crucial. It represents the optimal phase overlap for the most efficient locomotion. The rate of decline after the peak could provide insights into how sensitive the robot's movement is to changes in leg coordination. Experimental trials of different clock periods were performed, where in the case of a clock period of two seconds, the velocity peaked at 0.4 and 0.65 phase difference; for a clock period of three seconds, the velocity peaked at 0.3, whereas for a clock period of four seconds, velocity peaked again at 0.4. So, in conclusion, to these tests, the optimal phase overlap for leg coordination is 0.4, as a straight traversal of the robot was observed with the least number of deviations. The distance of the deformable surface was approximately 102 centimeters. The formula used to compute the velocities in figure 5:

$$\frac{Distance}{Time}$$

It was evident that the results proved the hypothesis. On the other hand, the robot toppled back when the phase difference was set to 0 or 1, i.e., when the front and rear legs were synchronized. This behavior was caused by the robot's center of mass toward its back end. Also, when the phase difference was set at 0.3, the robot exhibited a hopping-like movement (with every stride). Tables I, II and III represent the time the robot takes to traverse the deformable surface with different phase differences for clock periods t = 2s, t = 3s, and t = 4s, respectively.

The average velocities of various phase differences in time t = 2s was calculated. The velocity versus phase difference graph at t = 2s is plotted in figure 6.

Figure 7 depicts the phase overlap curve. The initial increase in velocity with increasing phase overlap between the legs indicates an optimal synchronization point. At this point, the leg movements are harmonized to complement each other, leading to a more efficient gait. This efficiency translates into faster movement as the robot can propel itself forward more effectively. The decrease in velocity after a particular phase overlap threshold is likely due to mechanical limitations and interference between legs. When the legs are too closely synchronized, they hinder each other's movement, leading to inefficiencies. This is due to physical collisions, timing disruptions, or the inability of the robot's control system to manage excessively synchronized movements.

Phase value	Time (s)	Velocity (cm / s)
0	15	6.8
0.15	11.63	8.77
0.3	11	9.27
0.4	10	10.2
0.5	10.55	9.66
0.65	10	10.2
0.8	10.65	9.57
0.9	13.65	7.47
1	15	6.8

TABLE I: Traversal Times and Phase Differences for t = 2s

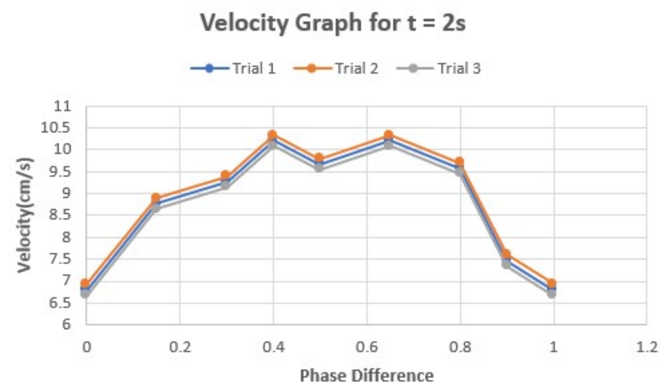

Fig. 6: Velocity for different Phase Difference at t = 2s

Fig. 7: Leg Position versus Time

The research question emphasized adaptive gait based on

Phase value	Time (s)	Velocity (cm / s)
0	17	6
0.15	17.8	5.73
0.3	15.7	6.49
0.4	17.5	5.82
0.5	17.7	5.76
0.65	19.2	5.31
0.8	0	0
0.9	22	4.63
1	17	6

TABLE II: Traversal Times and Phase Differences for t = 3s

Phase value	Time (s)	Velocity (cm / s)
0	27.4	3.72
0.15	25	4.08
0.3	18.5	5.51
0.4	16.7	6.10
0.5	21	4.85
0.65	25.3	4.03
0.8	0	0
0.9	26.2	3.89
1	27.4	3.72

TABLE III: Traversal Times and Phase Differences for t = 4s

phase overlap and stability of the robot on deformable terrain. The discovery of an optimal phase overlap in leg coordination directly speaks to the part of the research question concerning adaptive gait control. It was found that the robot's velocity increases with a certain level of phase overlap, demonstrating that adaptive gait control can significantly enhance traversal efficiency. This finding suggests that a carefully calibrated adaptive gait, which considers the optimal synchronization of leg movements, can lead to more efficient locomotion than a fixed gait pattern. The observation that velocity decreases after surpassing a specific phase overlap threshold is particularly relevant to the stability aspect of the research question. It implies that while adaptive control enhances efficiency up to a point, there is a trade-off with stability as legs become too synchronized. This finding is crucial for understanding how to balance efficiency and stability in deformable terrain traversal, which is a vital challenge for robots compared to those with rigid bodies and fixed gaits.

Finally, the discovery of a specific range of phase overlap that maximizes velocity is a significant contribution, as it informs the design and programming of robotic locomotion patterns for enhanced efficiency and speed. This study has substantial implications for deploying robots in challenging, deformable terrains such as disaster sites, extraterrestrial surfaces, or uneven natural landscapes. The ability to adaptively control gait for stability and efficiency could significantly enhance the performance of robots in search and rescue operations, environmental monitoring, and space exploration.

IV. CONCLUSION AND FUTURE SCOPE

In conclusion, the results of the experimental testing on the quadrupedal robot provide valuable insights into the optimal phase overlap for leg coordination during bounding gait. The findings confirm the initial hypothesis that an ideal synchronization point exists that maximizes the robot's velocity. The observed velocity pattern peaking at a phase difference of 0.4 and declining after that suggests a delicate balance in leg coordination, highlighting the importance of avoiding excessive synchronization.

The recorded instances of the robot toppling back when the front and rear legs were synchronized (phase difference of 0 or 1) and exhibiting a hopping-like movement at a phase difference of 0.3 underscore the significance of phase overlap in maintaining stability during locomotion. These outcomes contribute to understanding how adaptive gait control can enhance traversal efficiency while emphasizing the trade-off between efficiency and stability.

The detailed analysis of Buehler clock parameters and leg positions over time further supports the experimental results, providing a comprehensive view of the robot's movement dynamics. The empirical evidence for an optimal phase overlap in the gait of quadrupedal robots holds practical implications for the design and programming of robotic locomotion patterns, particularly in challenging terrains.

In the future, exploring rubber padding materials with enhanced friction characteristics could significantly improve a quadrupedal robot's grip on deformable surfaces, increasing its stability and traction. Additionally, integrating grooved or tread-like patterns into the robot's feet holds promise for achieving smoother and more controlled movement, reducing slippage, and enhancing performance on challenging terrains. The research outcomes have meaningful implications for deploying quadrupedal robots in real-world scenarios. The ability to adaptively control gait for both stability and efficiency positions these robots as promising assets in applications ranging from search and rescue operations to environmental monitoring and space exploration. Overall, this study contributes valuable knowledge to the field of robotics and lays the foundation for further advancements in developing agile and adaptive quadrupedal robots.

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