Association Journal of Interdisciplinary Technics in Engineering Mechanics, Vol. 3, No. 2, 2025
ISSN: 3049-0898

Design of a Bio-Inspired Legged Robot for Rough Terrain Locomotion

Peter Nabende[1]

[1]*Department of Electrical and Computer Engineering, College of Engineering, Design, Art, and Technology (CEDAT), Makerere University, Kampala, Uganda. E-mail: nabende.peter@cedat.mak.ac.ug*

Abstract--- This research presents a unique biologically motivated control technique for synchronizing the planning of a quadruped robot's gaits and foot Workspace Trajectory (WT), based on Central Pattern Generator (CPG) Neural Network (NN) WT (CPGNNWT). Initially, a foot workspace trajectory is designed using the Denavit-Hartenberg (D-H) nomenclature and inverse kinematics, offering benefits such as little mechanical shock, fluid motion, and streamlined trajectory. This work proposes an enhanced CPG using Hopf oscillators for seamless gait planning. A NN is ultimately developed and trained to transform the CPG output into the predetermined WT so that it can concurrently use the benefits of the CPG-based approach in gait prediction and the WT-based approach in foot trajectory preparation. Virtual prototype simulations and tests with actual quadruped robots are conducted to evaluate the efficacy of the suggested control technique. The findings indicate that the CPG effectively and efficiently regulates the quadruped robot's gait via internal variables. At the same time, the foot path aligns closely with the predetermined WT.

Keywords--- Bio-Inspiration, Legged Robot, Rough Terrain, Locomotion.

Received: 07 - 03 - 2025; Revised: 18 - 04 - 2025; Accepted: 29 - 05 - 2025; Published: 30 - 06 - 2025

I. Introduction

Legged robots are adept at traversing uneven terrain (Torres-Pardo et al., 2022). Despite their increased operational complexity compared to wheeled or tracked machines, innovative walking robots of all forms and sizes are being developed. With the augmentation of limbs, both the stability and the variety of gaits of the machine are enhanced. The most significant enhancement is seen between quadrupedal and hexapodal robots. Walking robotics exhibit static or dynamic stability and traverse environments by walking, running, leaping, or climbing (Stewart-Height et al., 2023). Hexapods are the most prevalent statically stable footed robotics. Possessing six limbs, they can use several gaits for movement. Numerous hexapods possess just three degrees of mobility per limb, limiting their ability to influence the location of the foot tip.

Four or more dimensions of mobility per leg augment the potential configurations of the robot's posture (Sihite et al., 2023). It has four degrees of freedom per leg, while Weaver, a proprioceptive-controlled hexapod, features five degrees of freedom per leg. In addition to the degrees of mobility of the limb, the configuration of each joint is crucial since it dictates the limb's range of motion. The coxa link in most enumerated robotics is the smallest limb segment. The femur and tibia connections must be of comparable size.

Conversely, the Crawler has a femoral connection that almost doubles the length of its tibia link, whilst the study has tibia links nearly double the length of their femur links (Llanes et al., 2025). Numerous researchers are endeavoring to replicate the framework or actions of insects to enhance the efficiency of legged machines, biologically inspired hexapod athletes featuring autonomous control and local leg reactions.

Notwithstanding the significant benefits of legged machines, their use in practical missions remains infrequent (Drew, 2021). Hexapod robots can traverse challenging terrain, with some capable of navigating sloped surfaces, but with reduced speed and increased energy expenditure. Utilizing a limb with a single controlled joint and a durable body design enhances the robot's durability and reduces energy consumption while mobility; this compromises the capacity to regulate the foot tip's location in challenging terrain precisely. An increased number of levels of mobility in the limb enhances the robot's maneuverability and that of its appendages (Rafeeq et al., 2021). An increased quantity of motors likewise elevates the robot's overall size and electrical consumption.

II. Proposed Bio-Inspired Legged Robot

This section introduces the Workspace Trajectory (WT), based on Central Pattern Generator (CPG) Neural Network (NN) WT (CPGNNWT) approach for controlling a quadruped machine using CPG- and WT-based methodologies. The detailed execution of the suggested CPGNNWT-based management approach is shown.

CPGNNWT Regulatory Framework

The core concept of the CPGNNWT control approach is to integrate the benefits of the CPG-based technique and the WT-based approach via a plastic intermediary layer, the NN, that transforms the CPG output into the predetermined WT. Their connection is shown in Figure 1.

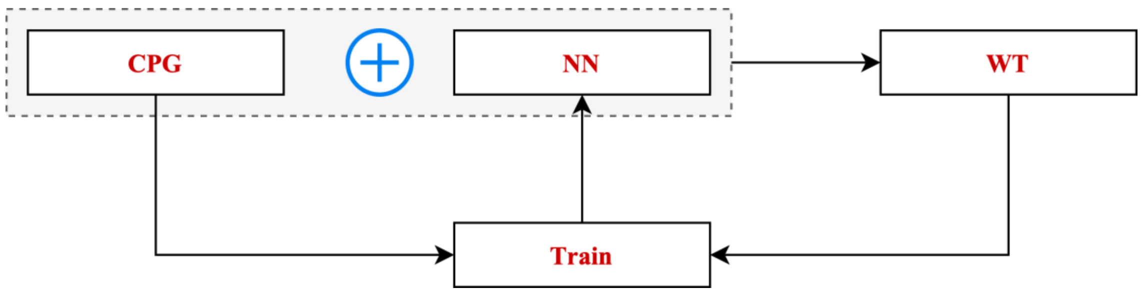

Figure 1: Control model of the proposed system

The NN is derived by training on sample pairs consisting of the central pattern generator output and the predetermined waveform template. Thus, the prearranged WT is reinstated using the CPGNNWT control paradigm.

This research identifies the uppermost circular ran box as the CPG stage and the center circular dashed box as the learned NN layer, where a, b, c, and d represent four the same NNs that transform the CPG results into organized control messages for multiple joints within a leg, the NN transforms the command indicate from CPG unit 1 into synchronized control signals for joints /1, /2, ... /n of the left front leg), given that the NN possesses multi-input and multi-output capabilities. The significance lies in the fact that as the number of components in a leg requiring coordination increases, the benefits of this control paradigm become more apparent. The research designates the suffix n = 2, since the quadruped robot type discussed in this study has just a hip joint and a knee joint per leg.

Implementation of the CPGNNWT Management System

Following the introduction of the scheduled WT and CPG, the CPGNNWT-based management approach will be implemented in the following phases.

Phase 1: Selection of the NN and determination of its inputs and outputs

This research selects the NN with Radial Basis Function (RBF) (Ding et al., 2021, Sohrabi et al., 2023) for a pair of factors: It is a regional approximation network that trains rapidly and avoids convergence to local minima. It is a three-layer feed-forward system including a solitary hidden layer, capable of approximating all continuous functions with arbitrary accuracy.

Considering the efficiency, structural dimensions of the NN, and computing expenses, the NN is delineated as follows: A single input generates the CPG output, producing two synchronized impulses to regulate the hip and knee ligaments of a leg concurrently. The CPG production remains within the (-1,1) range for both the swinging and stance periods. The input of the NN is overlapping. While the NN can autonomously distinguish whether the leg should be in the swinging or stance position based on the central pattern generator outputs, it comparatively increases the structural size. Each CPG oscillation unit has two results, maintaining a precise connection between them regardless of its state, where i = 1.

Phase 2: NN Construction and Training

The critical aspect of RBF architecture is the hidden layer's vertices, which influence network performance and computational difficulty. This study utilizes the synchronized control impulses of both knees and hips as the result, with the main result x of the CPG unit, having a duty coefficient B = 0.5 throughout a gait phase, serving as the input for training the RBFNN. The overall count of training samples is 2000, with 1000 pairings allocated to the swinging phase and 1000 to the positional stage. The distribution frequency of the RBF is 0.35

for the swinging phase NN (Nswing) and 0.8 for the position phase NN (Nstance). The MATLAB NN toolkit is employed to examine the number of vertices in the hidden layer and other characteristics of the RBF alongside its training efficacy.

Phase 3: The result of the CPGNNWT Management System

The result of the CPGNNWT control system fundamentally comprises the output of the CPG combined with that of the NN. The walking and trotting motions are the predominant gaits of the quadruped robots. The CPGNNWT results curves for these gaits and their shifts are shown, with A = 0.4, and duty factors of B = 0.65 for walking and p = 0.45 for trotting.

The first row of contours represents the CPG results. In contrast, rows 2-5 depict the CPG + NN results, specifically the CPGNNWT results, which concurrently regulate the joints of the hips and knees of a leg to modify foot locations according to the predetermined WT. Regardless of the walking or the methods of gait change the robot undergoes, the output forms of the CPGNNWT align with the predetermined foot WT, and the resulting lines are ongoing, effortless, and devoid of abrupt points.

III. Results and Discussions

A virtual model simulator with Webots and tests with actual quadruped robots are conducted accordingly to verify the accuracy and legitimacy of the proposed CPGNNWT-based control approach.

Simulation of Virtual Models

It is an advanced platform for modeling, programming, and simulating autonomous vehicles. A quadruped robotic virtual prototype is developed in the Webots modeling environment with elements and settings to enhance the monitoring of locomotion efficiency and the foot path of the machine, CPS detectors, utilized to acquire the position of Global Positioning System (GPS) points inside the global coordinate framework of the simulated structure, are included at its geometric centre and foot point, accordingly (Table 1). Touch detectors were included at its base to quantify the downward torque exerted by the foot.

Table 1: Virtual results

Variables	**Value**
L * W * H (cm)	50 * 20 * 40.5
Weight (kg)	5
Length -1 (cm)	15
Length-2 (cm)	15
Hip joining length	(-π,π)
Knee joining length	(-π,π)

Conduct an Experiment with an Actual Quadruped Robotic

After the virtual model simulations, the CPGNNWT control approach, using identical variables, is implemented on an actual prototype, with the basic variables shown in Table 2. A speedometer is included at the center of gravity of the body to monitor surges along three axes: the x-axis (longitudinal), the y-axis (vertical), and the z-axis (side).

Table 2: Experimental results

Variables	**Value**
L * W * H (cm)	40 * 22 * 42.
Weight (kg)	4.2
Length -1 (cm)	15
Length-2 (cm)	15
Hip joining length	(-π,π)
Knee joining length	(-π,π)

To verify the proposed control approach, the experimental findings of the trot and walk gaits, together with their transitions, are examined. The robot's real walking distance S is around 0.2 m, and the gait time T is roughly 1 s. The most excellent leg lift height H is approximately 0.03 m, which aligns well with the variables established in CPGNNWT and the prepared foot WT. The average movement velocity during 10 seconds is around 0.4 m/s. The maximum lateral displacement is 0.1 m, equating to roughly 0.5 seconds.

The robot's accelerating curves during movement are shown. In the vertical direction (y-axis), the velocity remains constant at approximately 9.8 m/s^2 (gravitational velocity), indicating that the predesigned WT mitigates mechanical stress. Along the longitudinal axis (x-axis), the variation in velocity is greater during trotting and lesser during walking, attributable to the enhanced stability of the walking gait compared to trotting. The speed range is minimal in the lateral position (z-axis) except during the gait transition phase.

In summary, from the perspective of the whole movement procedure, the movement of the material prototype is smooth, and the body oscillations are within a suitable range. The foot path remains consistent with the scheduled WT according to the hip articulation position structure, confirming the accuracy and efficacy of the proposed control approach.

IV. Conclusion

The final comments are summarized as follows.

An enhanced foot WT using a synthetic cycloid is proposed, including benefits such as little physical impact, fluid motion, and an elegant trajectory.

This work presents an enhanced CPG using Hopf oscillators that successfully achieves smooth gait planning via adjusting its internal variables.

A biologically motivated control technique using CPGNNWT is proposed for the locomotion management of a quadruped robot, successfully merging the benefits of CPG-based and WT-based methods. The proposed control technique effectively facilitates multi-joint coordinated control inside a leg, since the NN has multi-input and multi-output capabilities. In theory, the CPGNNWT control model can produce any specified periodic WT, contingent only upon the difficulty of the NN.

The study investigates adaptive fluid locomotion on uneven terrains by incorporating input and referencing the brain systems of legged livestock, using responses and online training of NN.

References

[1] Torres-Pardo, A., Pinto-Fernández, D., Garabini, M., Angelini, F., Rodriguez-Cianca, D., Massardi, S., ... & Torricelli, D. (2022). Legged locomotion over irregular terrains: State of the art of human and robot performance. *Bioinspiration & Biomimetics*, *17*(6), 061002.

[2] Stewart-Height, A., Koditschek, D. E., & Johnson, M. J. (2023). Reimagining robotic walkers for real-world outdoor play environments with insights from legged robots: a scoping review. *Disability and Rehabilitation: Assistive Technology*, *18*(6), 798-818.

[3] Sihite, E., Kalantari, A., Nemovi, R., Ramezani, A., & Gharib, M. (2023). Multi-Modal Mobility Morphobot (M4) with appendage repurposing for locomotion plasticity enhancement. *Nature communications*, *14*(1), 3323.

[4] Llanes, A. C., Venard, E., Youn, S., Van Tassel, D., Goncalves, L. F., & Belthur, M. V. (2025). The Significance and Limitations of Pre-and Postnatal Imaging in the Diagnosis and Management of Proximal Focal Femoral Deficiency. *Diagnostics*, *15*(11), 1302.

[5] Drew, D. S. (2021). Multi-agent systems for search and rescue applications. *Current Robotics Reports*, *2*(2), 189-200.

[6] Rafeeq, M., Toha, S. F., Ahmad, S., & Razib, M. A. (2021). Locomotion strategies for amphibious robots-a review. *IEEE Access*, *9*, 26323-26342.

[7] Ding, X., Liu, J., Yang, F., & Cao, J. (2021). Random radial basis function kernel-based support vector machine. *Journal of the Franklin Institute*, *358*(18), 10121-10140.

[8] Sohrabi, P., Jodeiri Shokri, B., & Dehghani, H. (2023). Predicting coal price using time series methods and combination of radial basis function (RBF) neural network with time series. *Mineral Economics*, *36*(2), 207-216.