Modeling, Design and In-situ Demonstration of Bio-inspired Central Pattern Generator and Neuromorphic Computing Circuits for Complex Kinematic Control of Quadruped Robots

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Abstract

Quadruped robots have recently gained significant interest from rapidly growing applications such as search and rescue, inspection and maintenance, space exploration and personal companions. However, conventional solutions demand power-hungry processors with large battery sizes due to the complexity of control in a high degree of freedom (DoF) system. On the other hand, biological systems, e.g. vertebrate animals can achieve highly agile and efficient motion control through distributed central pattern generators (CPG) with neural oscillators, presenting promising resolutions to the challenges in robot control. This paper presents a cross-layer design methodology with bio-inspired CPG and neuromorphic control to address the hardware challenges of quadruped robots. In particular, to overcome the challenge of designing continuous-time differential equation based asynchronous autonomous CPG system, this work proposes a discretization and explicit pattern method (DEPM) to enable hardware based simulation and synthesis of the complicated CPG operation; In circuit realization, a novel bio-inspired mixed-signal CPG circuit is designed as a continuous-time CPG bio-emulator for solving differential neural dynamics, with 178X to 445X reduction of power compared with conventional solutions; Integrated with bio-inspired CPG circuit, a novel temporal-rated spiking neuromorphic computing circuit is also designed to deliver the required low-level kinematic control to the joint motors of quadruped robots rendering more than 10X power saving. A 65nm silicon test chip has been fabricated and integrated into a quadruped robot to demonstrate successful gait generation of the proposed design. Measurements show an overall 609X improvement in power efficiency along with a 10.9X reduction in latency over prior conventional digital motion controls. To the best of our knowledge, this is the first bio-inspired neuromorphic CPG system using a dedicated chip and being assembled into a real robot, demonstrating the significant benefits of bio-inspired robotic control.

CCS Concepts

• **Hardware → Analog and mixed-signal circuits**; • **Computer systems organization → Robotics**.

Keywords

Bio-inspired Design, Neuromorphic Computing, Spiking Neural Network, Quadruped Robots, Central Pattern Generator (CPG), Robotic Locomotion, Inverse Kinematics.

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1 Introduction

Legged robots such as Quadruped robots or Humanoid robots have recently observed rapid developments from industries and academia, with examples such as Go2 from Unitree [18] and Atlas from Boston Dynamics [3]. It is projected that the market of legged robots will explode with a CGRA of 52% in the next 5 years driven by the application of intelligent house-hold robots [10]. However, different from the widely demonstrated wheeled robot, e.g. mobile robot carts, legged robots are fundamentally much more challenging in terms of dynamic control of robot kinematics. Fig. 1 shows examples of various types of legged robots with high degree-of-freedom (DoF) controls and complex trigonometric functions for dynamic control of each joint of such robots. Conventional approaches for generating various gait patterns, such as trot, walk, and bound, rely on solving complex trigonometric functions for motor control. However, this incurs high computational costs and latency as the number of degrees of freedom (DoF) grows, e.g. from 3 ms to 75 ms on NVIDIA Jetson platform as shown in Fig. 1. This poses a significant challenge in meeting the real-time control requirement of a typical 20 ms motor update rate, especially when a

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high DoF is required. As a result, modern robotic hardware engages high-performance computing hardware with large power budget, e.g. 20W from the recent Nvidia's announcement [11], causing large battery size with higher body weight. It has been reported that the support of such computing has caused 155% increase of robot weight leading to vicious cycles of weight-power solving dilemmas [16]. Recently, bio-inspired solutions have drawn significant interest from research communities as alternative efficient methods for robot control. In the biological system, vertebrate animals, including human beings, can achieve highly agile and efficient locomotion without engaging complex mathematical computation processes. The process is known to be performed through so-called central pattern generators (CPG) which are neural networks producing coordinated patterns of rhythmic activity without relying on higher levels of centralized control, e.g. the brain. The CPG incorporates mutually coupled inhibitory and exhibitory neurons to generate self-sustained oscillation patterns which automatically deliver commands to motor neurons for the control of muscle activities. With feedback from sensory cells, CPGs can create seamless synchronization of body joints and smooth transitions of various gaits. More importantly, different from existing man-made robotic control, as shown in Fig. 1, CPGs follow a distributed computing principle, making the control highly scalable for high DoF and self-driven without an expensive central control unit, e.g. brain for commanding. For this reason, there has been significant interest from neuroscience and robotic community to study CPG based control for legged robots [2, 4, 21]. As will be demonstrated later in this paper, CPG-based control achieves exceptional efficiency, delivering over 10,000X power improvement with reduced latency compared to conventional robot control on GPUs while maintaining strong resilience to perturbations. However, as will be elaborated later, significant challenges are present when bio-inspired CPG and associated neuromorphic operations are applied into integrated circuits (IC) design for robotics: (1) CPG by nature is an asynchronous autonomous continuous system which is hard to be designed and simulated through existing digital design methodologies; (2) Complex coupling mechanisms of CPG require differential equation solvers to emulate the coupled oscillation behaviors which not only incur high computing costs but also does not comply with modern ASIC design flow; (3) Both implementing CPG operation on a silicon chip as well as engaging its operation with a spiking neuromorphic controller for bio-inspired robotic kinematic control have remained unaddressed to the VLSI design communities. As a result, all existing demonstrations for CPG based robotic control rely on general-purpose platforms, e.g. GPU or FPGA with tremendous power consumptions, failing to manifest the benefits of bio-inspired CPG control and to provide a practical design methodology for dedicated VLSI chips [1, 13].

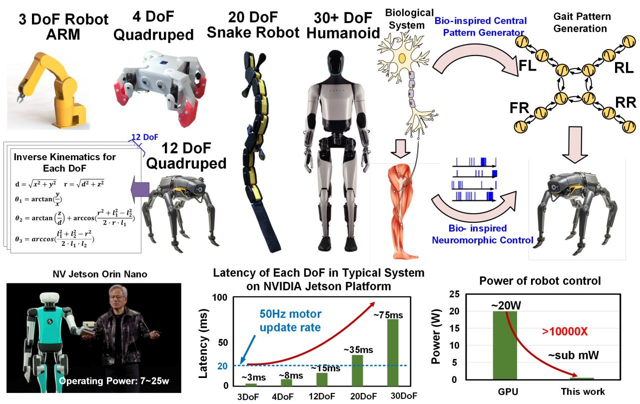


Figure 1: Power and latency comparison: Conventional control vs. bio-inspired control in legged robots.

In this work, for the first time, we deliver a comprehensive design framework for CPG based neuromorphic control of legged robots from modeling to circuit realization. A fabricated 65nm silicon test chip and in-situ real robotic demonstration with assembled quadruped robot is delivered to provide solid proof of the efficiency and efficacy of the proposed design methodology. Detailed contributions are summarized as follows: (1) A hardware-oriented modeling and synthesis technique is developed for efficient synthesis and verification of high DoF CPG system, addressing the challenge of non-conventional continuous differential solver based CPG modeling and related design complication; (2) As a circuit solution, a bio-inspired mixed-signal CPG circuit with configurable coupling matrix is designed as a continuous-time bio-emulator to realize the biological CPG for efficient gait generation; (3) Compatible with the proposed bio-inspired CPG circuit, a novel temporal-rated spiking neuromorphic computing circuit is also designed to deliver low-level kinematic generations for ultra-low power motor control; (4) As there is a lack of CPG-based silicon test chip, we have fabricated a 65nm test chip and assembled the test chip on a quadruped robot with an in-situ demonstration. The measurements showed a successful generation of various robots moving gaits and demonstrated major power saving compared with complex conventional trigonometric model based robotic control method. To the best of our knowledge, this is the first comprehensive bio-inspired CPG-based robotic control circuit demonstrating high efficiency over conventional control schemes.

2 Background of Biological Central Pattern Generator and Design Challenges

CPG is a distributed neural network located in the spinal cord of vertebrates and can generate rhythmic control patterns for biological motor control under the high-level simple tonic command signals issued from the brain. The mechanism behind CPG has been well studied both mathematically and experimentally [6, 15, 17]. In this work, we use the well-known CPG model based on Matsuoka oscillator for our implementation [7], while variants of such models such as Hopf Oscillator also exist [14]. Fig. 2 illustrates the biological CPG operation and a simplified system diagram for CPG based control. The CPG circuit consists of mutually inhibiting clusters of neurons, referred as "half-center oscillators" [15]. Each cluster of neurons has adaptable time constants and synaptic weights controlled by high-level modulation to establish a variety of rhythmic patterns through mutual coupling. Inside the neurons, two state variables u_i and v_i govern the dynamics of the neuron clusters. The state u_i is mainly affected by its own dynamics and mutually inhibiting connections from other neurons. State v_i has a decay function. The neuron's oscillation behaviors are influenced by the sensory input from sensory neurons c_i as well as descending tonic signal s_i from high-level control, e.g. brain. The output signal ai from CPG is sent to motor neurons for muscle control.

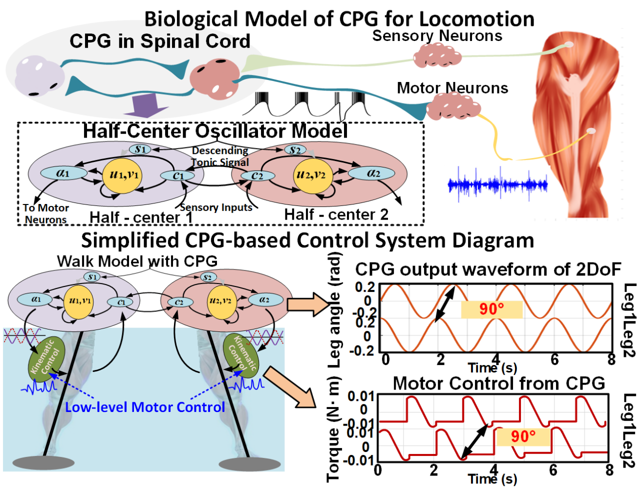


Figure 2: Biological model of CPG-based locomotion and simplified CPG-based control system.

Various mathematical models have been developed to describe CPGs, ranging from simplified coupled oscillators to more complex neural-network-based frameworks. In this work, we use the mathematical model based on Matsuoka oscillator [7] which is a biological plausible system model governed by coupled nonlinear differential equations:

$$\tau \frac{du_i}{dt} = -u_i + \sum_{j=1}^{n} w_{i,j} y_j - \beta v_i + s + \alpha f_i \tag{1}$$

$$\tau' \frac{dv_i}{dt} = -v_i + \max(0, u_i) \tag{2}$$

where u_i represents the internal state of the i^{th} neuron, while v_i is the self-inhibition effect of the i^{th} neuron. After applying a rectification function, the neuron produces an output y_i. The parameter $w_{i,j}$ denotes the weight of the inhibitory or excitatory connection and β is constant showing self-inhibition influence on the inner state. Other neural network-based models have also been previously developed. For instance, the Dynamic Recurrent Neural Network (DRNN) model provides a powerful framework for modeling CPGs and can capture temporal dependencies to adapt their oscillatory dynamics based on sensory feedback. A more advanced recent work based on Continuous-Time Recurrent Neural Network model (CTRNNs) [20] integrated with Reinforcement Learning (RL) is also proposed to autonomously learn optimal rhythmic patterns for complex motor tasks with more flexible and general neural dynamics. This work utilizes the widely used Matsuoka oscillator model as a baseline model with modeling results further verified by the more complex CTRNN model for biological CPG behavior.

Compared with conventional model based complex trigonometric control scheme, the benefits of such CPG based autonomous control schemes are (1) rooted from efficient biological operation, CPG system is a distributed control where each sub-module, e.g. pattern generation neurons for a single leg are self-controlled; This significantly reduces the dimensionality of the control scheme and makes the system much more scalable and computational efficient because the computing complexity grows linearly with DoF in CPG versus exponential growth in conventional centralized control system; (2) CPG design is highly noise resilient due to its self-driven nature leading to high rejection of noisy environmental impact compared with conventional model based execution; (3) CPG system can be trained or self-learned through various methods such as gradient descent, reinforcement learning, un-supervised learning [2, 9, 19], representing an intelligent evolutionary system compared with conventional hand-crafted control scheme. Hence as shown later, CPG is highly energy efficient and highly scalable by its principle. However, reproducing CPG based control in modern semiconductor IC chip is not trivial: First, CPG requires differential equation solver to fully emulate the CPG operations, which is not compatible with existing ASIC design methodology; Second, high computational costs for differential solver and intractable parameter solution space with large DoF make the synthesis of such system challenging from existing ASIC design methodology; Third, efficient silicon circuit realization of such models remain unknown currently. The following sections provide our proposed cross-layer solutions to address the above challenges.

3 Proposed DEPM Model and Synthesis of Solver-based Continuous CPG Dynamics

As shown in Fig. 3(a), the existing CPG models, e.g. the Matsuoka oscillator model [14] as a baseline in this work in equation (1) to (2), are continuous-time asynchronous system based on coupled differential equations. As a result, the models highly rely on numerically solving coupled differential equations to emulate the process of pattern generation and interactions among neurons. Unfortunately, the design flow of conventional integrated circuits does not support the key characteristics of the CPG operations, i.e. continuous system dynamics and ordinary differential equation (ODE) solvers-based solutions. As a result, CPG cannot be directly designed and verified in existing ASIC design flow. In addition, any ODE solver incurs high computation costs for both hardware implementation and system verification.

To address these challenges, as shown in Fig. 3(a), a discretization and explicit pattern method (DEPM) is developed to simplify CPG design within existing EDA flows as follows. (1) In the proposed DEPM approach, to remove the high cost of ODE solver, at the hardware implementation, neurons are represented by programmable oscillators with explicit pre-determined sinusoidal operation patterns, effectively removing the need for an ODE solver and minimizing computational overhead. The usage of pre-determined sinusoidal patterns is supported by numerous prior studies showing the accuracy of sinusoidal approximation of neuron kernels for robotic control, despite that scientifically, various waveforms may exist in a cross-coupled neural system [7][14]. In our implementation, the discretized oscillator is employed only for modeling, synthesis, and simulation purposes, while the proposed circuit implementation utilizes a continuous-time mixed-signal neural oscillator and CPG

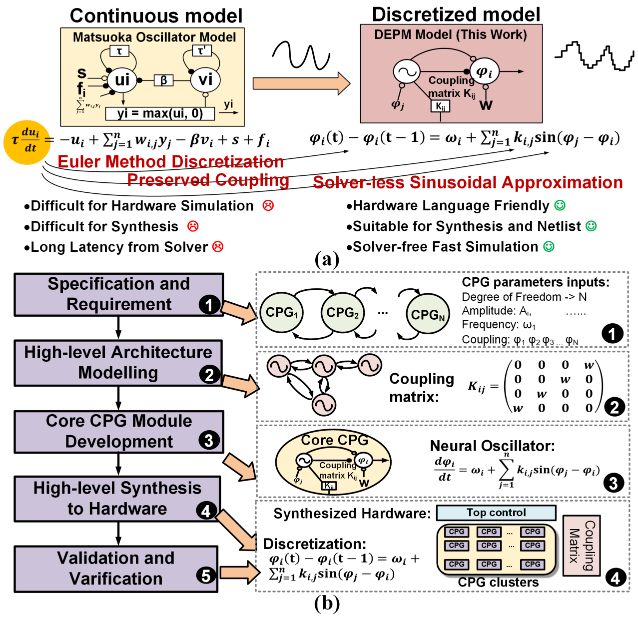


Figure 3: (a) Proposed DEPM method for hardware modeling; (b) Proposed design flow of CPG system.

circuit (Section 4) to allow high-quality silicon emulation of the biological differential neural dynamics. (2) To overcome the challenges of asynchronous continuous signal representation, we use a linear approximation of Euler equations to simulate the continuous dynamics of the CPG system as shown in Fig. 3(a) by discretizing the operation into discrete time steps, making it friendly for hardware programming language. (3) To preserve the behavior of neural coupling for mutual interactions among neurons without engaging complex ODE solvers, a coupling matrix is used to represent mutual feedback among neurons to establish the coupling among neurons for the emulation of the CPG system. Using the proposed DEPM method, the system can be implemented in a digital synthesis and simulation environment, while maintaining high accuracy of the dynamics of the original cross-coupled continuous system. The removal of ODE solvers dramatically reduces simulation complexity and enables the synthesis and simulation in existing EDA flow.

Fig. 3(b) shows the overall proposed design flow consisting of five steps: Step 1 defines the specification CPG network such as DoF, phase coupling patterns, dynamic properties, and environmental constraints. Step 2 elaborates the neuron unit coupling matrix from various gait patterns and neural architecture of CPG. Step 3 defines the basic neuron kernels which are circuit level emulation of the continuous-time neural oscillators. The neuron kernels, which are mixed-signal circuit design (Section 4) are inserted into the high-level netlist as library instances with pre-defined operation behavior in hardware language, e.g. Verilog. Step 4 performs discretization and synthesis to generate netlist for hardware design and simulation. Step 5 conducts simulation to verify the CPG behaviors in hardware language.

Examples of the proposed CPG network generation framework are shown with two high DoF case studies: a 12-DoF quadruped and a 20-DoF snake [2, 4]. In the 12-DoF quadruped as shown in Fig. 4(a), during walking, the joints of a single leg (RL) remain synchronized at 0 degrees, while a 90-degree phase difference is maintained between the front left (FL) and rear left (RL) legs. In the trot gait, to allow smooth joint movement, a 45-degree phase difference is preserved within each leg, while a 180-degree phase difference is applied across the legs. In both cases, the proposed CPG model aligns with conventional ideal solver-based CPG solutions. Fig. 4(b) shows a 20-DoF snake robot. Here, the coupling structure is designed not only for interconnections between body links but also for a hierarchical coupling between the front and rear tentacles, ensuring balance and smooth swimming motion. The waveform illustrates the coupling relationships between neurons 1 to 8 with a phase difference of 22.5 degree, as well as a smooth transition between two distinct swimming speed, 0.2m/s (0.26 body length/s) to 0.3m/s (0.39 body length/s), with preserved coupling relationship. Fig. 4(c) shows simulated evaluation on various DoF systems, ranging from 2 to 20 DoF evaluated on a i5-6500TE 2.3 GHz Quad-Core CPU. The proposed CPG modeling approach achieves a 5.3X to 33.5X reduction in computation time compared to the solver-based output with an accuracy loss of 0.5~1.5%, within the tolerable range for neuromorphic computing based robotic applications.

4 Proposed Bio-inspired Neural-Oscillator CPG for Emulating Differential Neural Dynamic

While there have been numerous studies on software-based CPG circuits implemented in a microprocessor, hardware CPG in silicon chip has not been demonstrated so far. Following our DEPM model in section 3, we designed a novel bio-inspired mixed-signal CPG circuits which emulate and solve the cross-coupled differential equations to establish on-chip CPG pattern generation for robot control. The circuit follows continuous-time neural dynamics of the neural oscillators and hence realizes the differential equation-based CPG operation in silicon with much lower power compared with a software or conventional digital implementation. Fig. 5(a) shows the proposed CPG circuit. Each neural oscillator in Matsuoka oscillator in Eq. (1) and (2) is realized by an autonomous ring oscillator forming a coupled neural network for the targeted 12-DoF quadruped robot. Four oscillators generate the foot-end pattern (4 DoF) for the robot's four legs, while a low-level kinematic control module expands this into the full joint pattern (12 DoF) using 3-output spiking neural networks. Additionally, a selection multiplexer (mux) samples the voltage from the CPG signal and converts it into time pulses via a Voltage-to-Time Converter (VTC) module for further processing. To realize the coupling matrix, all oscillator's internal phases are interconnected through a cross-bar programmable switch box which uses resistor switches to provide coupling mechanism for locking the oscillators and realizes all possible interconnect choices of the phases between two oscillators. A phase resolution of π/N (11.25 degree in this design, with N=16) can be created in this way. The realized coupling matrix allows phase locking of the individual free-running ring oscillators into synchronized wave generation emulating the biological CPG processes. By programming the crossbar switch boxes, different gait patterns with variable phase relationships from each oscillator can be generated. As simple inverter-based ring oscillator only generates square waves, another resistor combiner circuit is introduced to synthesize the phases into the sinusoidal waveforms by combining different phase outputs of the ring oscillator as shown in Fig. 5(a).

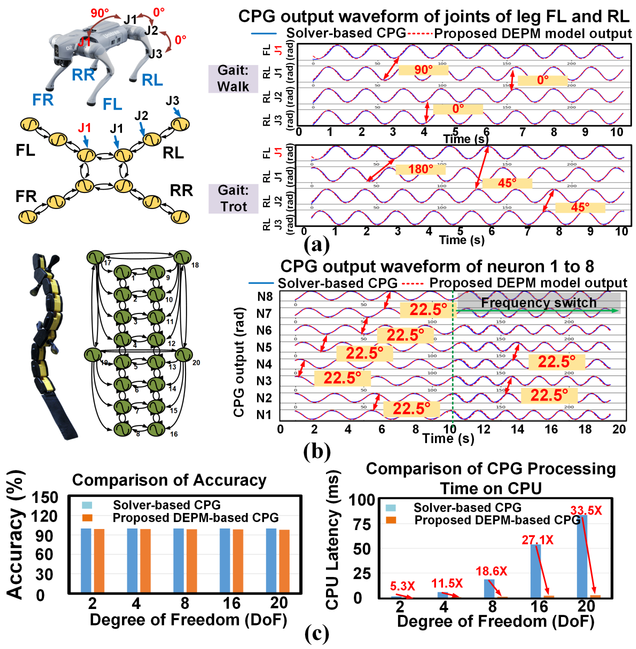


Figure 4: Case studies of proposed design. (a) A 12-DoF quadruped robot with waveforms for walk and trot gaits; (b) A 20-DoF snake robot with a smooth motion transition. (c) Comparison of accuracy and processing time between solver-based CPG and the proposed DEPM model.

To work with a neuromorphic controller (in Section 5), the synthesized sinusoidal waveforms are converted into time pulses using a voltage-time converter. As shown in Fig. 5(b), a phase counter sequentially turns on a phase selection multiplexer inside the VTC to sample the sinusoidal wave from the coupled oscillator at a specific time. The sampled voltage is stored in a capacitor. In the discharge phase, the stored voltage is linearly discharged through a current source until it crosses the reference voltage, generating a time pulse whose pulse width is linearly proportional to the voltage level. As a result, the VTC sends the temporal-rated spiking signals according to the desired CPG pattern to the next stage of neuromorphic controller. Compared with a previous FPGA implementation using a simplified Izhikevich model which requires solving nonlinear differential equations in real time with high computation cost [1], the proposed CPG circuits achieve a 178X reduction in power consumption for a single CPG and a 445X reduction for multi-CPG systems.

5 Low-level Neuromorphic Computing for Kinematics of Motor Control

For low-level motor control, we utilize bio-inspired neuromorphic computing, which naturally works with the mixed-signal CPG circuits described in Section 4. As depicted in Fig. 6(a), a quadruped

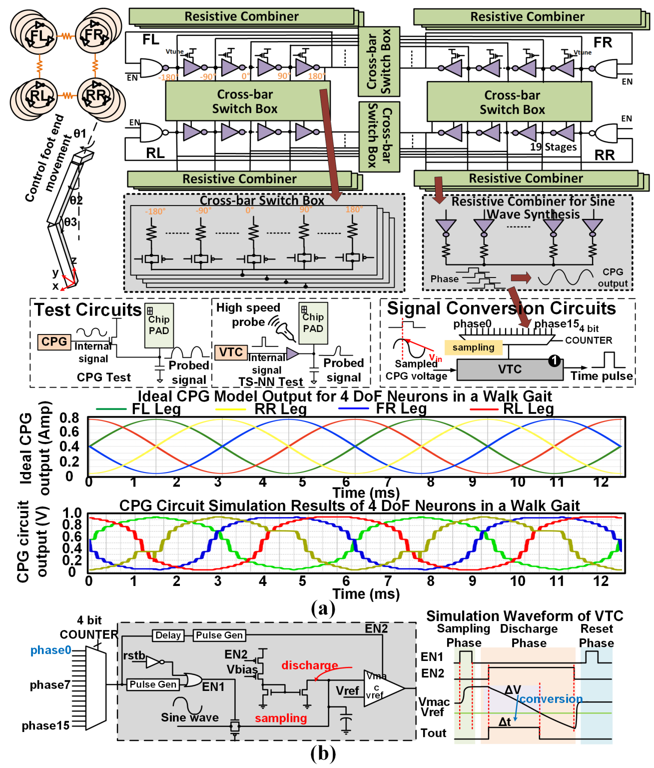


Figure 5: (a) Circuit design of bio-inspired mixed-signal CPG and comparison between the ideal CPG model and circuit output in a four-leg robot walk gait; (b) Circuit implementation of voltage-to-time converter.

robot must control each joint to realize the CPG pattern. However, the CPG pattern represents foot-end trajectories in Cartesian space (Xi,Yi,Zi), requiring inverse kinematics (IK) to convert these trajectories into joint space for direct motor control. The challenge of IK computation lies in its reliance on complex trigonometric functions which are computationally expensive [5]. This complexity increases significantly with higher degrees of freedom (DoF) in robotic systems. Spiking neural network based neuromorphic computing provides a low-cost computation solution to this challenge. As shown in Fig. 6(b), this work utilizes a spiking neural network to convert the CPG generated end-effector positions to joint angles in mixed-signal space, drawing inspiration from biological computation. The conversion function is implemented using a three-layer mixed-signal spiking neural network (SNN), consisting of three input nodes, 16 hidden-layer nodes, and three output nodes for each robot leg. Different from typical SNN implementation, we use temporal-rated spiking operation where the time-pulse's temporal duration represents the value of the neuron input and output. The temporal coding is more efficient than binary spike coding as it introduces less transitions to the logic circuitry. The mixed-signal temporal spiking neural network (TS-NN) engages a temporal spiking neuron (TS-Neuron) with a mixed-signal multiplication-accumulation (MAC). From the output of the VTC after the CPG pattern generator, the time-pulses are sent into a

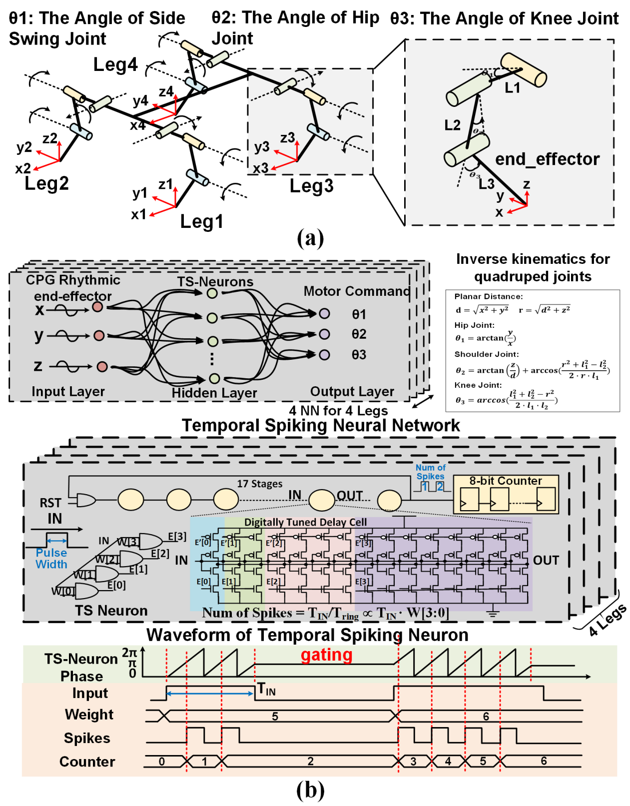


Figure 6: (a) Inverse kinematics of the quadruped robot; (b) Proposed neural network for inverse kinematic computation; hardware implementation and waveforms of the proposed temporal spiking neuromorphic computing for kinematics.

gated inverter-based oscillators whose propagation is enabled by the input pulse and the speed is proportionally programmed by the stored 4-bit digital weights. As a result, the numbers of output spikes are proportional to the accumulation across different inputs on the multiplication of the weights and the duration of the input pulses, realizing a multiplication-accumulation (MAC) operations in time domain. After MAC, the time-pulses are converted into digital counts with a simple counter and then pass through activation functions and scaling functions in the digital domain. The use of mixed-signal temporal spiking neural network for motor control brings benefits of compatibility with the proposed mixed-signal CPG as well as the significant power saving. Our evaluation shows that the proposed design achieves more than 10X power reductions compared with an ASIC implementation of conventional inverse kinematic computation. Since both the CPG and motor control circuits are designed using bio-inspired principles, our solution offers high efficiency and bio-plausibility for modeling and emulating real biological systems.

6 Test Chip and Full System Implementation

Fig. 7 illustrates our final chip-top architecture for a quadruped robot comprising (1) a central pattern generator for phase and gait

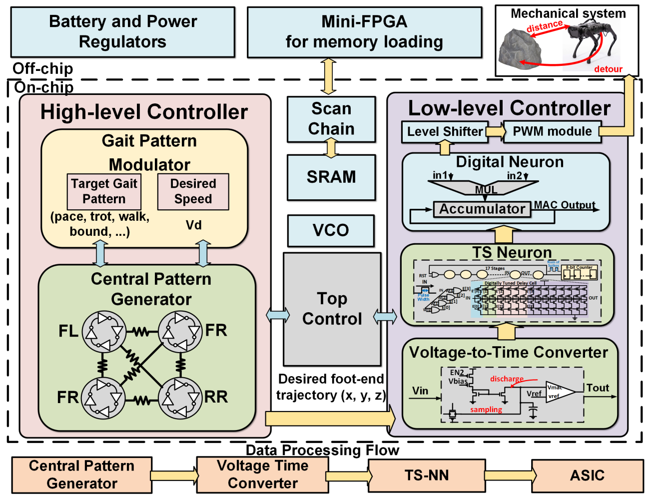
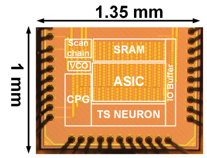


Figure 7: Test chip and system architecture.

generation, (2) neuromorphic computing neurons for lower-level motor control of the legs, (3) a top controller with a finite state machine and memory banks for data loading and chip configuration, and (4) a PWM module and level shifters for motor interfacing. We designed and fabricated the SoC test chip in TSMC 65nm, as shown in the chip die photograph and specifications in Fig. 8(a). The chip has an area of 1.35 mm² and operates with a supply voltage ranging from 0.7V to 1.0V, supporting frequencies from 10kHz to 1MHz with a power consumption of 232.7 μW and processing latency of 20μs for CPG and 5us for kinematics at 1V. Fig. 8(b) shows the chip test setup. To further evaluate our scheme at the system level, we built a complete robot system with a compact PCB mounted on the back of a quadruped robot. The PCB integrates our test chip, LDOs, a level shifter, and a mini-FPGA for chip programming.

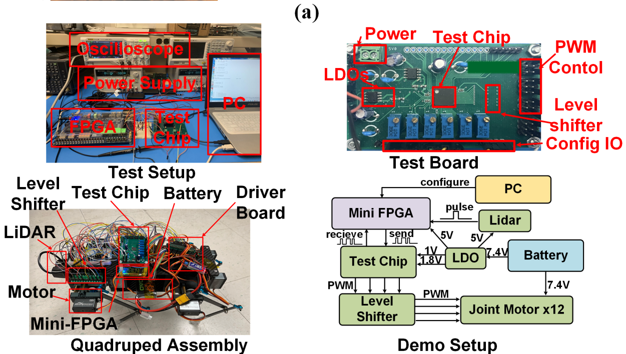
7 Test Results and In-situ Demonstration

To measure the internal circuit's behavior without interfering with the oscillator's operations, as shown in Fig. 5(a), a source-follower circuit with limited output range (clipped lower voltage) is used to capture the CPG's voltage while a high-speed probe is used to capture the waveforms of the internal time-domain spiking signals. The measured voltage/time-domain signals are correlated with simulations for validation of the chips. As shown in Fig. 9(a), the CPG circuit exhibits a coupled pattern between output neurons, with voltage output converted into the time domain (Section 4). It achieves locked phase shifts of 90° and 180° with correctly generated sinusoidal waveforms. Fig. 9(b) shows the voltage-to-time converter (VTC) with an Integrated Nonlinearity (INL) of less than 2 LSB. The proposed CPG circuits reduce power consumption by 178X to 445X compared to FPGA implementation [1]. To validate the functionality of the proposed neuromorphic controller for low-level control, Fig. 10(a) presents an example of conversion between Cartesian space and joint space, demonstrating that the neuron output closely aligns with the ideal inverse kinematic values, with an MSE of less than 0.001 radian. The overall accuracy of the neuromorphic controller is further evaluated in Fig. 10(b),



Technology	65nm CMOS
Active Area	1.35 mm²
Power	232.7uW @1V
Frequency	10KHz - 1MHz
Supply Vdd	0.7 - 1.0V
SRAM	12 KB

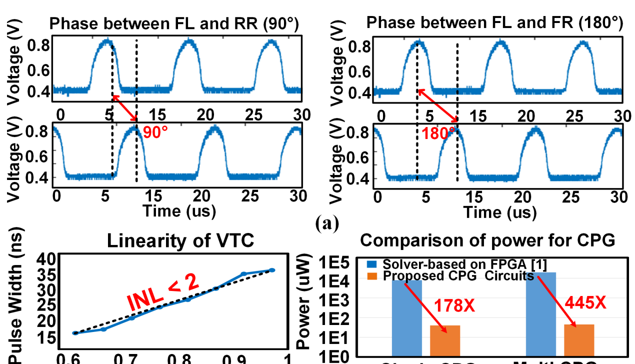
(a)



(b)

Figure 8: (a) Fabricated die micrograph and chip specification; (b) Chip test setup and robot assembly for demonstration.

covering a range of inputs and quadruped gaits, including walk, trot, bound and pace. The measured linearity of the spiking neural MAC achieves an INL of less than 2LSB. The neural network is offline trained based on ideal inverse kinematics and quantized into 4 bits. In our evaluation, the 4-bit quantized neural networks incur 1.2% accuracy loss while the mixed-signal circuit introduces an additional 0.9% loss, compared with ideal inverse kinematics in motor angle generation. The accuracy loss is insignificant in terms of the gait control as demonstrated later in the system test. The proposed neuromorphic controller with TS-NN achieves a power efficiency of 7.8 9.5 TOPS/W for neural network operation at a supply voltage of 0.7V to 1V.



(b)

Figure 9: (a) Measured CPG waveforms in a walking gait for the quadruped robot showcasing the leg coupling; (b)VTC linearity, and the power saving of the CPG.

To evaluate the overall proposed framework and data flow in real system, a 12DoF quadruped robot was assembled with our test chip controlling the robot's 12 joint motors. Fig. 11(a) shows detailed continuous snapshots of the robot's leg during real-time walking of the robot following CPG patterns. Fig. 11(b) shows that leg coupling is established by the programmed coupling matrix with four different gaits, i.e. walk, trot, bound and pace, demonstrating that the output pulse width accurately reflects the CPG phases' response to the designated coupling relationship. For example, the walking gait maintains a 90-degree phase difference between the Rear Right leg and the Front Right leg, as captured in high-speed camera snapshots. At timesteps t1, the two legs exhibit a 90-degree phase difference, which is preserved at timesteps t2, indicating that the CPG pattern remains locked with the proposed CPG generator. Additional gait patterns, with leg coupling relationships ranging from 0 to 180 degrees, are illustrated in Fig. 11(b).

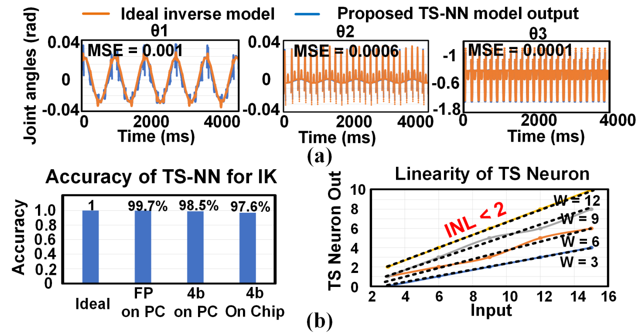
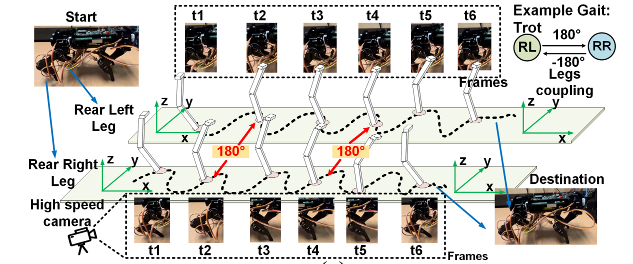


Figure 10: (a) Measurement results on accuracy of temporal spiking neural network for inverse kinematics; (b) linearity of the TS Neuron.

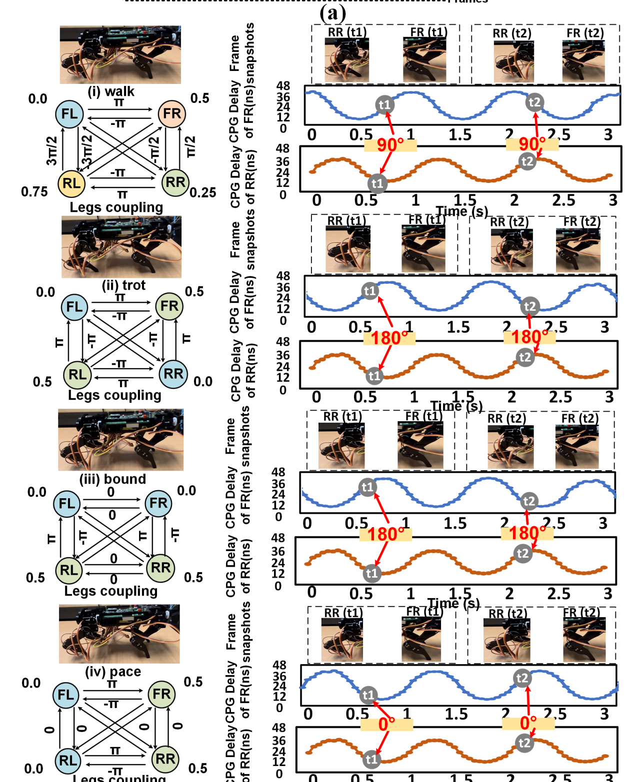
Fig. 11(c) presents a comparison table with existing robot control platforms and previously published test chips. The proposed design enables a bio-plausible, universal CPG-based motion control system that supports high degrees of freedom. Leveraging a low-power mixed-signal implementation, the bio-inspired system achieves a 609X power reduction compared to a prior digital SoC for motion control [8], 4081X over a hybrid synergistic chip used in an unmanned bicycle system [12], and a 920,000X improvement over a widely used general-purpose GPU platform [13]. In terms of kinematic computation, the proposed system achieves a 10.9X speedup over GPU-based kinematic computation [13], owing to the novel bio-inspired TS-NN architecture. This work presents the first demonstration of a bio-plausible, mixed-signal CPG-based neuromorphic test chip for real-world robotic locomotion, highlighting the promising potential of bio-inspired robot control.

8 Conclusion

This work proposes a cross-layer design methodology from system design to circuit realization on bio-inspired CPG control system using the proposed DEPM method for quadruped robots. A highly efficient robotic CMOS chip with only 232.7μW power is designed and fabricated in a 65nm technology and assembled onto a real quadruped robot to demonstrate the efficiency of the solution. By leveraging novel bio-inspired mixed-signal circuits, the proposed design achieves an overall power saving of 609X and a latency



(a)



(b)

	IEEE RAL'21 [13]	Front. Neurosci. '13 [1]	Nature'19 [12]	ISSCC'23 [8]	This work
Platform	GPU	FPGA	ASIC	ASIC	Mixed-signal
Application	Rigid Body Dynamics	CPG	Unmanned Bicycle	Autonomous Mobile Robots	Quadruped Motion Control
Feature	Digital	Digital	Neuromorphic	Digital	Bio-inspired
Technology	-	45nm	28nm	28nm	65nm
Total area (mm²)	-	-	14.44	4.39	1.35
Frequency	1.7GHz	100MHz	300MHz	200MHz	1MHz
Power	215 W	20mW	950mW	142mW	232.7uW
Latency: For CPG	-	50us	-	-	20us
Latency: For kinematics	54.4us	-	-	-	5us
Energy Efficiency for NN	-	-	1.28 TOPS/W	-	7.8~9.5 TOPS/W

(c)

Figure 11: (a) Details of quadruped testing; (b) Camera shots of different gaits of the quadruped robot of walk, trot, bound, pace, (c) Comparison table with existing works.

reduction of 10.9X. The bio-emulating CPG circuits achieve a 178 to 445X power improvement over conventional solver-based designs, while the neuromorphic controller demonstrates more than an order of magnitude power reduction compared with an ASIC implementation of conventional inverse kinematic computation with less than 1% accuracy loss from the mixed-signal circuits. The adoption of distributed CPG operation and spiking neuromorphic architecture enables real-time gait control for robot locomotion over complex terrain with high efficiency. This is the first time a dedicated ASIC chip is used to demonstrate the potential of bio-inspired CPG design for efficient robotic operations.

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