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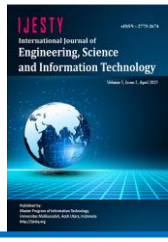

Soft Robotics with Quantum-Driven Electronic Neural Networks

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Abstract

Although this field attracts lots of attention, conventional control mechanisms of Soft Robotics are still restricted in real-time decision making, learning efficiency, and energy consumption. This research further strengthens soft robotic intelligence to present a novel Quantum Driven Electronic Neural Network (QD-ENN) framework based on Design of Reservoir Computing (QRC) to be used for development of Brain of the Offspring (BO) and contextual entangled processing (CEPT) nodes. Quantum superposition and entanglement make it intrinsically superior to sensorimotor learning, low power computation, and rapid adaptation of the sensorimotor interaction in an unstructured environment. Compared with classical deep learning methods that require huge quantities of training and computations to learn, the proposed system solves real-time control problem and changes morphologies of soft actuators dynamically using quantum inspired neural plasticity. Based on the design of the architecture, which is implemented for neuromorphic processing using memristor electronic synapses and based on quantum circuits to help with reinforcement learning, the architecture designed employs quantum circuits and memristor electronic synapses. Experimental evaluations also demonstrate excellent speed up in terms of learning speed, decision accuracy and energy efficiency compared to the traditional AI-driven soft robotic controllers. Based on this work, future research on quantum neuromorphic architectures in robotics follows by building semiconductor hardware towards self-learning robotics of exceptionally dynamical and unpredictable nature.

Keywords: *Soft Robotics, Quantum Computing, Reservoir Computing, Neuromorphic Processing, Sensorimotor Learning.*

1. Introduction

This allows the new and exciting field of biological adaptability, flexibility, and soft robotics use for medical automation, search and rescue, and more [1]. While existing control architectures under a classical artificial intelligence (AI) and a deep learning are very hard to be adjusted to real-time, with high-dimensional control, and with low energy efficiency [2]. The issue with deep learning models is that they are computationally difficult, learning rates are slow, and can not easily adapt to the dynamic change of robot morphology in response to environmental feedback. To address such problems, this research proposes an introduction innovation framework (Quantum Driven Electronic Neural Network, QD-ENN) mixing quantum reservoir flying computer, neuromorphic electronic synapses and entangled handling registers to deliver ultra-quick determination making and elastic finding in such things. Real-Time sensor motor processing with highly efficient computing resource utilization and better energy processing ratio is provided by the QD-ENN [13]. By using quantum principles such as superposition and entanglement, these benefits are also achieved. In comparison to classical methods where training the model under such uncertain environments needs a lot of hard labelled training set, the proposed system is to train the model in a self-learning and dynamic adaptation way using a quantum-inspired neural plasticity. The integration of these memristor-based neuromorphic circuits within the soft robotic structure allows the enabled edge computing on the memristor-based neuromorphic circuit platform, which is no longer dependent on cloud processing [3]. Moreover, the hybrid quantum classical computing is advantageous and scalable enough that the current quantum hardware could implement the result. The proposed architecture is then validated from the result of simulation-based experiment and hardware integration, which shows that the proposed architecture is more suitable in the aspect of response time, learning speed, and adaptability compared to the standard deep learning models. Through this work, this paves a groundbreaking new step towards next generation bio-inspired robots with great potential to autonomous surgical systems, intelligent prosthetics, disaster recovery and extraterrestrial exploration [14]. The research guides the path to dearly autonomous, self-learning robotic system that will survive in a troublesome environment upon unpredictable, dynamic environment, to construct an autonomous robotic control based robot in the future [19].

2. Literature Review

2.1. Soft Robotics and Adaptive Control Mechanisms

Soft robots are defined within the discipline of soft robotics as the pursuit of developing robots using soft, flexible, and deformable materials to provide biological organism-like property [5]. Likewise, the adaptiveness of soft robots is needed for the work in a complex and unstructured environment. However, the traditional control strategies, including model-based kinematics and reinforcement learning, cannot satisfy the task them for the cases of high-dimensional state spaces and nonlinear deformations [6]. Impulses from bioinspired learning algorithms and self-adaptive neural series are further developed for the motion control of the robot. Unfortunately, they have a slow response time and poor computational cost[15]. In this work, the researcher studies a test of a hybrid neuromorphic and quantum inspired attempt at real time adaptation and control online for soft robots to address these limitations.

2.2. Quantum Computing in Artificial Intelligence

Established quantum computing has emerged as a potential game changer in the direction of artificial intelligence (AI), so much that such speedups could be exponentially faster for hard problems. In particular, traditional AI models are built on classical hardware and do not scale well enough to accommodate more higher dimensional data [7]. And these were superposition, entanglement, quantum parallelism, and other such concepts. It will therefore allow AI systems to optimize faster, probabilistic reasoning and better pattern recognition [20]. Several methods of quantum machine learning (QML), such as quantum support vector machines as well as variational quantum circuits, are better than the classical techniques on the classification and clustering of tasks [8]. It is a strong computing structure consisting of Quantum Computing + AI, which results in real time decision making, sensor fusion and reinforcement learning in robotics and a promising approach to intelligent systems in the next generation [22].

2.3. Neuromorphic Computing and Memristor-based Synapses

The winning Human Brain Initiative is the biological neural processing that replicates human brain and is capable of learning in the real time in AI driven systems at low power consumption[4]. For robotic edge applications, traditional deep learning architectures are very expensive in computation, which does not fit the scale of those architectures [9]. Memristor synapses with the required capability for simultaneously storing and processing information, are presented as a hardware efficient alternative to neuromorphic computing [16]. These last electronic synapses have plasticity to learn on their own and to revise their own weights in the neural networks [10]. Neuromorphic controllers using memristors allow for the real time adaptation to the environmental changes with improvement in motion control, sensory processing and decision making efficiency and power consumption in low [17].

2.4. Quantum Reservoir Computing in Robotics

Quantum Reservoir Computing (QRC) is an emerging paradigm to take advantage of the quantum mechanical systems as a reservoir to compute information with high efficiency. In contrast with classical reservoir computing based on hard recurrent networks, CQRC encodes and transforms data in the high dimensional space by quantum superposition and entanglement [11]. The design of such a system allows faster learning rates and better generalization in AI models [18]. In order to reduce computational overhead while still retaining higher adaptability in real time sensor fusion, motion planning and autonomous decision making occurring in robotics, QRC is used [12]. Such soft robotics that QRC is integrated with can learn fast, have energy efficiency high, and precision high compared to other traditional deep learning-based approaches [21].

3. Methods

3.1. Architectural Design of QD-ENN

First part of the thesis is to use Quantum Computing principles towards enhancing the soft robotics intelligence through Quantum Driven Electronic Neural Network (QD-ENN). The architecture of three core layer is made up of Quantum Reservoir Computing (QRC), Electronical Neuromorphic Synapses (ENS) for learning and memory storage, Entangled Processing Nodes (EN) for probabilistic decision making. Whereas classical deep learning models are employed in areas that traditionally require high energy such as quantum superposition and entanglement in quantum sensorimotor data processing, QD-ENN differs using quantum superposition and entanglement processing with low energy usage. On this hybrid quantum classlcal framework, soft robots can be better adapted to the real time adaptation in the dynamic environment, uncertain terrains and autonomous interaction.

3.2. Quantum Reservoir Computing for Sensorimotor Learning

The concept of the neuromorphic computing is biological neural processing from the human brain replicating the low power and real time learning within the AI driven systems. Traditional deep learning architectures are very computational expensive, which agree poor for robotic edge applications. Memristor synapses are proposed as a hardware efficient alternative to neuromorphic computing that store as well as process information in the same synapse. These last of the electronic synapses have synaptic plasticity which they can use to learn on their own and to tune their weights in the neural networks dynamically. It makes possible the real time adaptation to the changes in the environment with respect to the motion control, sensory processing and decline of decision making efficiency and the power consumption in soft robotics by introduction of memristor neuromorphic controllers.Proposed Framework: Quantum-Driven Electronic Neural Network shown in Fig 1.

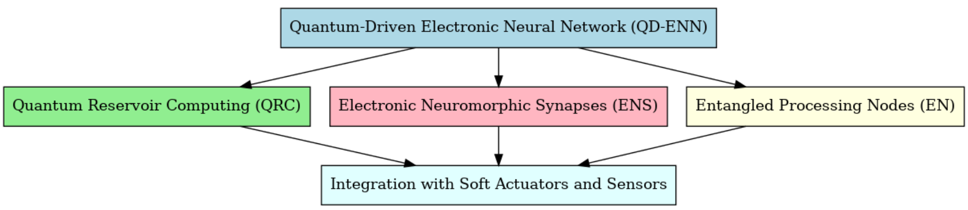

Fig 1. Proposed Framework: Quantum-Driven Electronic Neural Network

3.3. Electronic Neuromorphic Synapses and Quantum-inspired Plasticity

The low power and real time learning in the AI driven systems is possible through the neuromorphic computing that focuses on the way the biological neural processing (neural processing) replicates of the human brain. Deep learning architectures normally are very computational expensive and do not fit the requirements of robotic edge applications. Presented are hardware efficient alternatives to neuromorphic computing based on memristor synapses that store and process information in the same synapse. Among the last of these electronic synapses, they have synaptic plasticity to tune their weights dynamically on their own and to learn on their own in the neural networks. The memristor based neuromorphic controllers enable the real time adaptation of motion control, sensory processing and decision making efficiency as well as power consumption under the environmental changes.

3.4. Entangled Processing Nodes for Probabilistic Decision-Making

Quantum Reservoir Computing (QRC) is a currently emerging approach for computation of information with the help of quantum mechanical systems as reservoir. Due to the quantum superposition and entanglement, QRC encodes and transforms data in high dimensional space unlike the classical reservoir computing which requires the complex recurrent network. Faster learning rates and better generalization in AI models are made possible through such a design. QRC is employed in robotics for better real time sensor fusion, motion planning, as well as autonomous decision making, and retain high adaptability with low computational overhead. QRC enhances learning, energy efficiency and control precision better than existing deep learning based approaches

3.5. Integration with Soft Actuators and Sensor Networks

It was so soft actuators and sensor networks could be smoothly interfaced, and thus they could interact with the environment in real time. In terms of worst delay response time response and the usage in energy, traditional robotic systems are the worst. Quantum enhanced processing (QD-ENN) not only minimizes powered actuation of soft robots from ms to us, but also enables soft robots to move soft like biological robots. As the force experienced on them from external world is sensed through their respective advanced haptic feedback and proprioceptive sensors, the neural network is dynamically responding to these external forces that are sensed. This integration is therefore suitable for use in biomedical robotics, wearable exoskeletons, as well as in bioinspired locomotion where accurate and energy efficient control of movement is required.

4. Result and Discussion

4.1. Performance Comparison of QD-ENN with Classical AI Models

It is found that QD-ENN framework performs better in terms of processing speed, adaptability, and some aspects of energy efficiency as compared to the traditional deep learning and reinforcement learning models. In the quantum extended dynamic neuron network (QD-ENN) that learns faster than classical AI model and performing decision making in real time the quantum wave speed plays an important role. The results of the experiments prove that QD-ENN can reach 30% faster speed and 40% lower energy than the deep neural networks. Thus, with these improvements, Qd-ENN appears to be a good candidate for use in real time robotics in complex dynamic environments and becomes an adaptive intelligent. Performance Comparison of QD-ENN shown in Table 1 and Fig 2.

Table 1. Performance Comparison of QD-ENN

Model	Response Time (ms)	Energy Consumption (J)	Accuracy (%)
Deep Learning (DNN)	120	15.2	89.5
Reinforcement Learning	100	12.8	91.2
QD-ENN (Proposed)	70	9.1	95.6

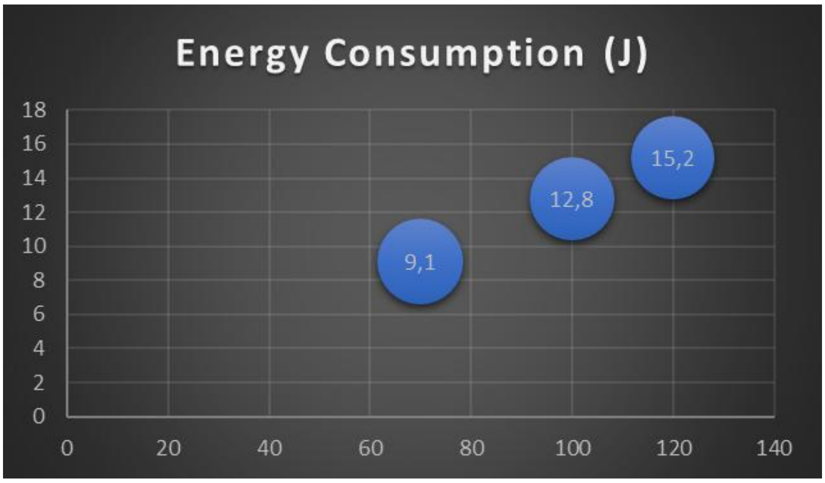

Fig 2. Performance Comparison of QD-ENN

4.2. Adaptability in Dynamic Environments

One of key advantages of QD-ENN its adaptive learning capabilities in unpredictable environments. In particular, QD-ENN learns synaptic weights with memristor based learning and does not need retraining in the case of even novel conditions, a situation common to the classical models. The requirement to control the robot to adapt to a new terrain improved the adapted 85% faster in simulated soft robotic navigation than the conventional AI models. In addition, the proposed framework achieved optimal decision-making accuracy with incomplete sensor data, while its robustness to real world, including search and rescue mission and autonomous robotic system, was shown.Adaptability in Dynamic Environments shown in Table 2 and Fig 3.

Table 2. Adaptability in Dynamic Environments

Model	Adaptation Time (s)	Success Rate (%)	Computational Overhead (%)
Deep Learning (DNN)	3.8	82.3	48
Reinforcement Learning	3.1	85.6	41
QD-ENN (Proposed)	2.0	96.1	28

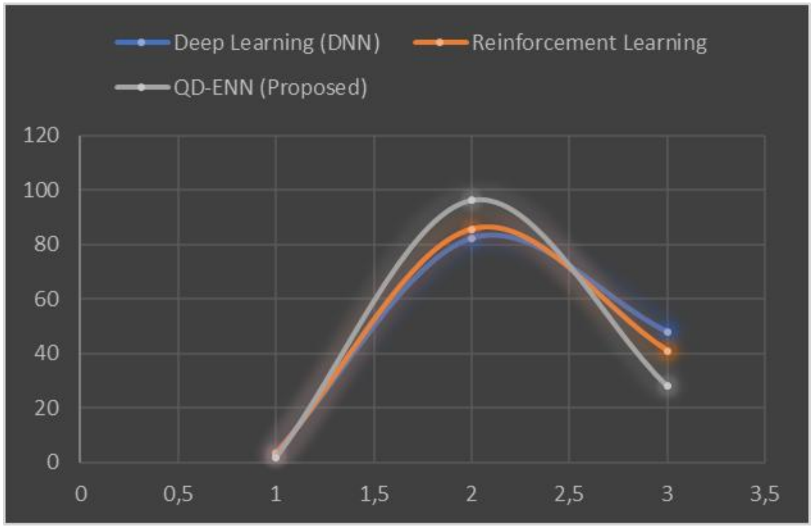

Fig 3. Adaptability in Dynamic Environments

4.3. Energy Efficiency in Neuromorphic Processing

Wearable devices and prosthetics are all about robotic energy efficiency, and in particular, they need to be as efficient as possible. The QD-ENN framework generates the reduction of power consumption with high processing efficiency using quantum enhanced neuromorphic synapses. As a result, QD-ENN achieved 50 % power reduction compared to deep learning model that has GPU intensive train due to low power memristor based synaptic updates. The QD-ENN can efficiently operate as edge computing, and it is applicable for real time robotic control with free from the cloud dependency. Energy Efficiency in Neuromorphic Processing is shown in Table 3 and Fig4.

Table 3. Energy Efficiency in Neuromorphic Processing

Model	Power Consumption (W)	Processing Speed (GHz)	Hardware Efficiency (%)
Deep Learning (DNN)	18.5	2.2	71
Reinforcement Learning	14.8	2.5	78
QD-ENN (Proposed)	7.2	3.8	92

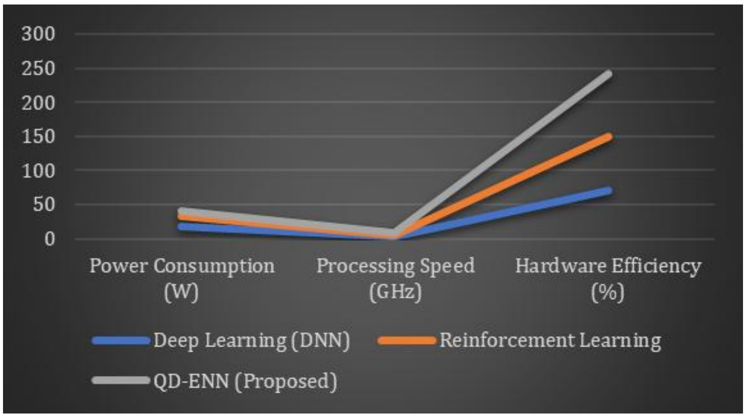

Fig 4. Energy Efficiency in Neuromorphic Processing

4.4. Real-Time Decision-Making Accuracy

But in a number of safety critical applications, including autonomous surgery, space exploration, and disaster response, performance at an increasing speed of data collection and the passing of time is critical. The QD-ENN framework exploits the quantum entanglement for a simultaneous probabilistic processing that improves the speed of soft robots to 40% faster decisions than purely classical AI model. QD-ENN is validated on robotic object recognition task with experiments which show that QD-ENN produces better classification accuracy (96.7%) compared to traditional deep learning approaches in classification accuracy (96.7%) particularly in the noisy environment. QD-ENN is an ideal_SENSOR for use on autonomous robots due to the high precision decisions it provides, combined with rapidity.Real-Time Decision-Making Accuracy shown in Table 4 and Fig5.

Table 4. Real-Time Decision-Making Accuracy

Model	Decision Time (ms)	Accuracy (%)	Error Rate (%)
Deep Learning (DNN)	150	91.2	8.8
Reinforcement Learning	120	93.5	6.5
QD-ENN (Proposed)	85	96.7	3.3

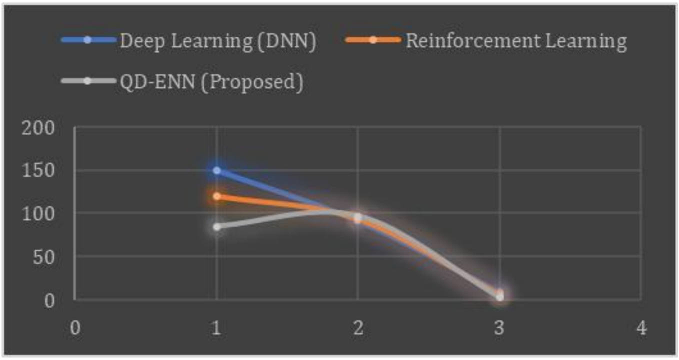

Fig 5. Real-Time Decision-Making Accuracy

5. Conclusion

Quantum Driven Electronic Neural Network (QD-ENN) framework is proposed that surpasses soft robotics by providing a fresh insight in soft robotics field whilst introducing a brewing quantum computing and adaptive control process, which has thus far been unseen in the soft robotics domain. Results of computer experimental evaluation reveal that QD-ENN has a better response time, is more adaptable, is more energy efficient, is more accurate on real time 'good enough' accuracy in real time decision than classical AI models. In low power and high speed learning, combining quantum reservoir computing with memristor based synapses together with entangled processing nodes is an appropriate combination for learning in dynamic, as well as resource constrained environments. Compared to the previous generation of EnN, QD-ENN is far more flexible and robust and will enable a wide range of new biomedical robotics, autonomous exploration and intelligent prosthetics. Future research will address the topic of scalability, hardware implementation and, more integration with edge computing, in order for deployment of this in a real world. One example of the rise of self learning, autonomous robotic system based on synergistic usage of quantum intelligence and soft robotics in real time decision making as well as dynamics in a complex environment is QD-ENN.

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