Proceedings of CONF-MLA 2025 Symposium: Intelligent Systems and Automation: AI Models, IoT, and Robotic Algorithms
DOI: 10.54254/2755-2721/2025.LD24812

Bioinspired Robotics: A Review of Four-Leg Movement, Sensor Integration, and Multimodal Learning

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Abstract. Bioinspired robotics is an advanced direction in the field of robotics. It has its own way to innovate robot technology through learning from evolutional accomplishments of biology system. As a kind of review type paper,this article has made a detailed summary on three important parts of quadrupedal gait motion,sensor integration and multiple-modal learning and analyzed its biomimetic theory,technological means and practical applications. A quadruped, it would let the thing do good everywhere, with senors they got a feeling from surroundings and also extra ways to get smarter. By thoroughly analyzing the technological evolution, application cases and difficulties in this area to discover its development tendency which can provide some references to promote the innovation and engineering application of robots theory..

Keywords: Bioinspired Robotics, Quadrupedal Movement, Sensor Integration, Multimodal Learning, Intelligent Decision-Making

1. Introduction

With the rapid iteration of AI and robotic technology, it has become more obvious that traditional robots are inadequate to operate in unstructured environments [1]. Organisms in nature developed for hundreds of millions of years and are endowed with excellent movements, advanced perceptions, and good learnings. Bioinspired Robotics is to deconstruct operation principle of living organisms and transforming them into engineering solution. Compared with conventional robots it has considerable advantage regarding mobility and environment fitting as well as wise decision making.

Among all kinds of bioinspired robot, quadrupeds get more notice because they can move over different grounds better and are more dynamic. Animals like dogs, cheetahs and goats have the ability to move around freely over rough ground, can get up after being disturbed and do quick tricks too. For example, a Spot robot made by Boston Dynamics, it’s inspired by quadruped’s way of walking. It can not only walk and turn freely on complicated grounds; also it could collect data about its surroundings right now by its own equipped instruments, then determine how to go on [2]. And it was also used for dangerous scenes like industrial inspection, disaster rescue, etc. This new way to mix up living things and today's tech is pushing robot technology into a fresh part of the game.

In this paper, we will give a summary of what has been done on the area of quadruped motion control, sensor integration technique and multimodal learning method on bioinspired robot. Examines the biological principles behind it, looks at representative technical implementation, and sees how they are used in different places. In this case it is then the key problems to find, like the real-time

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DOI: 10.54254/2755-2721/2025.LD24812

problem, how transferrable or robust a system would be. But as always also some trends that come soon.

By integrating thoughts coming from Biomechnaics as well as Sensoer fussion and inteligent learning i wish that by this study could help in the creation of a more innovative theorical bioinsipred robot systems aswell as make it easier to use in new and different fields sucha s disaster reeief, smat agriculture production, exploraing deep space to create a better human-machine ecoligcal circle.

2. Quadrupedal movement: biological principles and robot implementation

2.1. Biological foundations of quadrupedal locomotion

Main mechanical advantgage has already been taken advantage off on the way quadruped animal go about their gait. And taking equines locomotion as an example,the spring of hindlimb has some functions,it's like storing energy during the stance phase and then release to move. The forelimbs are stable and make a place for balance on the ground And this biomechanical model goes into designing robots, saying use bent joints, spread things around — important for getting energy-smart walking in your machines.

When the animals of Nervous System work together to Adapt on Terrain, Like this Robot Gives out Feedback The muscles/joints have their own versions of IMU's just like robotics but instead forces/torus are sensorized they tell where the muscle/joint is currently at and also modify which direction the limbs should take. From our Biololgical Close loop we paste back to robot using biomimic feedback and the Robot changes the step timings and joint angles just like if the Dog ran over some rocks.

2.2. Robotic implementation and technological advancement

2.2.1. Biomechanical design innovations

The current day machines like spot made by boston dynamics use biology to make it more mechanical. Joint wise, they have 3-DoF hips like a dog as well as 1-Knee like a canine to copy its agile motions. That's 40% more than the steel in carbon fibre composites would weigh, but that's fine; that can still carry load 2.5 times higher than its own robot weight -- important for getting around [3].

A distinguishing mark of good design is adaptable shape. Make robots able to use different ground by things like having extendable legs and change its body angle so it could move where ever is standing. Like on steep ascents, extra grabby parts based off how apes move their limbs pop out to get more purchase and there's about a third better at getting around bumpy terrain.

2.2.2. Evolution of control architectures

From Model-Based to Data-Driven Paradigms

Since we can not rely on the kinematics/dynamics model due to uncertain parameters and an unstructured environment. Contrary to this, for RL (robots would be allowed) they may allow themselves evolve with "try & reward". They learn the right motion strategy. Proper reward function that is stable(centerOfMassDeviation) and efficient(energyPerMeter), can let a policy learns much more better gait then human controller if there's no structure environment.

Case Study: Terrain-Adaptive Gait Learning

Using RL with deep nueral net on the spot like robot, it can walk stabley on 25° up ramp and unstaile slope of +/-10cm in 50 trail [4]. AlgORTHMs would tweak step LENGTHs, LEG STiFFness, TORSO ORiEntation – BEhaviOrS kind oF likE biologicAl REFLeXes jusT finE dOwn fOR

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mECaNICaL eFFICIeNcY. Compared to the PID Controller,it can save as much at 22%or even more energy. And it improves cross rate over obstacle between 65%-92%.

Hybrid Control Frameworks

And the blends have model stabiliser & planner who learn life is biology with machine's perfection. It's usually a pattern generating network (CPG) inspired by basic gait production in animals creating the fundamental cycle of gaits, with some kind of deep learning changing these things on the fly using data sensed. It produces massive synergism in terms of its stability and adaptiveness; it's speed matters (it could sprint up to 5m/s), also the turns need some degrees less than 1.5s for full circle.

2.3. Technological frontiers and challenges

Autonomy is what it right now; Morphological computation – the mechanical part creates simpler control problems. Robots also have complie robot tendon that can absorb shock similar to a mamines, so no needs very complex control but rather about 50% [5]. But in Bio-inspired sensorimotor integration of tactile, visual (and others) inertals are trying to copy how an animal's perceiving is solid even when they are 100% blind at beginning for the new place.

I am talking mainly about scalability of these ideas with low power cheaper techs since they currently all have really big batteries and expensive comp systems To get over them we need to advance mechanical miniaturization as well as our algorithms – it's the stuff biology gives us clues for advancement, like an impala's energy-efficient gait or a salamander's fault-tolerant move.

3. Sensor integration: empowering robots with perception capability

3.1. Collaborative work of multiple types of sensors

3.1.1. The key role of visual sensors

Visual Sensors are what makes a robot able to "see" its surrounding, and as such they have advanced mainly in two forms: A 2D Vision Sensor System or 3D Depth Sensing Technology.

The 2D visual sensing systems make use of CCD or CMOS imaging technology and can sense the digital imagery. Use CNN for doing the work of extracting some features from it like edge, texture pattern etc [6]. Combined with modern object detection algorithms like YOLO, these are very good at finding what an object is in a still picture, which could be helpful if you wanted to have machines automatically recognize objects sitting on factory conveyor belts.

The 3d depth sensing technologies make use of structure light, to enable the robots with perception of space is done by TOF cameras. In structured light sysems, depth is obtained from deformed patterns cast on objects and roundtrip times of lightsignals for TOF sensors are employed to get sub millemter measurements: It has become like dynamic measurement of obstacle distance just as in a busy warehoused for a robot, it's an absolute need.

Complicated operating environment multispectral images with the ability to see difference between visible & ir wave get more system that leanin: So it can do live terrain classification and distinguish things like rocks from geological formations. Indoor,depth sensor most often goes together with SLAM algorithm that means Simultaneus Location and Mapping. A bit more specific is that RGB-D sensors use ORB-SLAM(ORB SIMULTANEOUS LOcAlization AND maPiNg) to make a perfect model in 3d Use both visual data streams and some sort of dynamic object detection to give me something that is cm accurate, ms obstacle avoidance [7].

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3.1.2. Auxiliary functions of other sensors

Multisense combination actually greatly increases the robot's senses, it's no more than that webcam. IMus with accelerometer+s and gyroscopes give us often enough samples for rate of turn & lin acceleration: Use the Internal Kalman Filter to merge data from everything on hand to reduce noise and give you that posture info in less than real time(ms) Dynamic balancing is very important in locomotion; like if a robot was going on rough terrain this would be needed.

Tactile sense contains the 3d forcetorque sensors. It is situated in the robot joint place; after this, we use multi-axis and also flexible and thin film pressure sensor arrays are attached on its sole [8]. It if for a sand substrate than the joint is having the force being put out from all 4 robotic leg and adapting to Point-SurFace Feline GAIT as they step off the Ground. When it comes to gravel surfaces, we make real - time joint torque adjustments just like dog so as to have a raise step like sole surface.

Combining lots of sensor types is really important for good robot operations. IMUdata helps stabilize poses when we do fast moves. It goes well with the eyes thathelp find places atthe sametime. And also fusing these two kinds of informations is good for navigation. The robot could also use visual to help it on routes and help with sense feel (touch) which would be used when its foot is touching the uneven or hard ground so but maybe faster but a safer way.

3.2. Breakthrough in sensor fusion technology

Sensor fusion tech is the main drive of biologically inspired robotics; it has an obvious developmental record which shows how smart systems have developed. In the beginning of technological development,the weighted average method is firstly used in the area of multi-source data fusion based on intuitive mathematical idea. In fact, it is to some extent heterogenous data fuse from different sources in predesigned weights. The advantage is it's much cheaper computationally, but the downside is that you have fixed weights allocated statically so we wouldn't be able to do very well in a complex environment.

The Kalman filter algorithm based on Bayesian is derived the deeper we go into theory, more and more. In order to solve the problem of how to accurately estimate in a noisily environment, it constructs state space models and observe models, and uses prediction updates that form a closed loop iteratively; KF is also used in SLAM which means Simultaneous Localization And Mapping for exact calculation of robot positions. It can be seen as one very important technical approach toward making automatic navigation possible:

The great leap made by the deep learning technology is also changing the concept of sensor fusion. Fusion approach based on Convolutional Neural Network(CNN)can automatically get the spatio-temporal information of heterogenous data like LiDAR, visuals, Inertial Measurement Unit (IMU) and so on by a multi-layers neuron network which is different from the traditional way depending on hand-crafted feature engineering [9]: Complicated terrains that needed traveling: CNN will thoroughly look over all kinds of properties concerning visual pictures and LiD A rray information: In comparison with the old ways, robots can have over 30 percent more correct feelings at very hard times like when obstacles move around and light changes quickly. And then it just appeared that the transformer model which had attention to globally represent different modals too is able for robots to be able make decision quickly in a unstructured setting. It can have an advantage.

In the logistics and warehouse, based on the information fusion of visual force sensor systems, we can realize the precise grasping of goods for objects with object surface texture characteristics by using force feedback. Ecological environment monitoring field can form a kind of multimodal recognition method, which will be able to obtain simultaneously the biological species information and the environmental physical parameter at once [10].

DOI: 10.54254/2755-2721/2025.LD24812

4. Multimodal learning

4.1. Theoretical basis of multimodal learning

4.1.1. Multi-sensory fusion learning imitates organisms

Organism have a good grasp about its surroundings via multisensory cooperation with very complicated perception. Take humans as an example, in the daily process of identifying objects, we get appearances of shapes, colors and textures from our visual system; we receive materials, temperature and hardness information about an object through the tactile system's touch; we also use our auditory systems to hear sounds caused by any movements or collisions with an object which helps determine its location and state. This kind of feeling goes through much computation and mixing among brains, so we can have whole knowledge of things.

Multimodal learning takes the cue from the biological sense of perception and processes multiple information sources like what robot sees, hears, touches etc. Tech used quite a lot trick, for example feature level fuse, trick at the decision level, further use deep learning models to make different model data come together The field of service robots uses the combination of cameras, microphone arrays and pressure sensors etc., to get users' expression, voice command, gesture action and other information in a short amount of time. Taking uncertain "voice" command issued by customers as an example: If there's such a sad look combined point at certain thing, it will activate some functions and then know what kind of service this person wants. And offer much more personal interactions. Multimodal learning is like it also helps our robot understand and make decisions if he/she sees lots of obstacles at one time as we roam freely over an area.

4.1.2. Classification and characteristics of multimodal learning algorithms

Concerning multimodal data processing, if we consider the way to use it as an feature fusion method by structure with the process of data from earlier stage for a good result and make full use of the powerful correlation among different modality’s clear. Based on the method based on decision fusion takes an independent analysis of all type modal data and does decisions level fusions. And also it can adapt for different types of many tasks. Strategy Model Fusions look through numerous various data modalities as well as analyze these with distinct personalized models in order to figure out how they work differently and make something much more complex model that will require very big computations for the system [11]. So in real engineering application, we must choose and improve the best kind of multimodal fusion approach by using systematic algorithm with constraints and performance criteria of different tasks.

4.2. Application cases of multimodal learning in robots

4.2.1. Autonomous navigation in complex environments

The urban street never stops moving so its robot has a computer vision module which targets it and does the semantics between the road signs and any humans walking around, also has a microphone array array doing sound waves and finding where that traffic noice came from, got an IMU to keep track of real time 3 dimension space postures. MultimodalData is used to be integrated with deep learningalgorithm which then uses it on a collaborativesystem and out of that, the system produces itsenvironment. Out ofThis generated Map The path can be generated aswell as made dynamic form trajectory planningUnder Constraint Safetyto occur If there are sudden blockades then the many sensor information Bayesian inferencing model initiates an emergency response stage. Then, based

DOI: 10.54254/2755-2721/2025.LD24812

on this info the motion planning re-optimization method is carried out by the robot so as for it to alter its own movement and path parameters for dynamic obstacle avoidance maneuvers [12].

4.2.2. Intelligent response in human-computer interaction

Educational robots depend on visual perception systems that capture the small expressions students have, they use speech recognition modules which help understand what kind of questions are asked and uses many methods for education. Specifically, when the conv net senses students being confused, it would immediately activate the teaching strategy changeover and go for an easier explanation of that particular piece of knowledge. By finding some certain problems using NLP, after we search the knowledge graph for exact solutions it greatly improves both the intelligence and usability of human computer interaction.

5. Challenges and future prospects

5.1. Technical bottlenecks and coping strategies

5.1.1. Energy efficiency bottleneck

Quadruped robots having high energy consumption is a major problem preventing them from being used in the industry. So to meet that challenge, we need some kind of “hardware +algorithm” two-pronged effort on saving energy. On the hardware side of things, we need to focus on R&D for better ways to store all that power—like more powerful batteries and those really quick-charging capacitors—in order to stay working longer than now. Meanwhile, algorithm improvements can realize intelligence of energy management by means of dynamic perception. One thing was found by the study performed in 2024 on UC Berkeley where they realized through adapting, samples from taking the sensors subsystem of navigating about stationary environments were reduced (still readable at 80%). Bringing everything total to only 25%. Apart from these the advancements in motion control can also be attributed towards the advances made by the gait planning algorithm, like passive dynamic gait from MIT, has shown a decrease of 18% motor energy cost on uneven ground as well and that also translates to lower system-level energy cost [13].

5.1.2. Computational resource constraints

So as for how we're goingto integratemulti—mode perceptionsystemanddeeplear-ning system, it’s gonna begreatly constrained computing deviceson managing edge. In order to solve them, we need a combination of software innovation and hardware innovation. Hardware wise, if you build your own special ai speeding up chip, use different heterogenous computing platform, it will also increase your calculation density a lot. And one of many is the Nvidia Jetson Orin nano board made specifically for robotics on the edge. And can have max throughput of 40TOPS and can take about 12+ sensor data on the fly, yet only draw a mere 10W. As for software, techniques like model quantization, knowledge distillation, etc., can be used to cut down on the parameter space of algorithms. Recently, a research group at Stanford used the Neuro-architecture search to reduce vision-based obstacle avoidance algorithm by roughly 80 % in terms of parameters count, but there is no increase more than 1.5 percent on accuracy. When you make this better, now the graph runs super fast, and it can do complicated decisions right away at the edge.

DOI: 10.54254/2755-2721/2025.LD24812

5.2. Future development trends

5.2.1. Interdisciplinary integration

Bioinspired Robotics is rapidly approaching the point where it becomes fully interwoven with fields like neurology, material sciences, biomechanics. At the vanguard of technology, people are taking advantage of knowledge about biological neural networks to create new controls that can learn on their own. For 2025 we are going to be doing a paper out of the Max Planck institute for Intelligent Systems where they'll actually be recreating some spinal cord reflexes on an wallaby like apparatus. Could do this in real time by acting like it's got a bad leg; changes its gait again in under.5s, and is still dashing about 85% quicker [14]: At the same time, with the advancement in materials science, there are intelligent material which can heal themselves like a biological tissue regeneration. The Harvard University's Wix Institute have made a Poly-Urethan Based Robotic Actuator that can still have 90% of it's mechanical strength once they are hurt. By embedding tiny veins which releases the medicine to cure once structural damage has been detected and it improves how long a robot can live in different locations on earth but very hot or full of harmful chemicals.

5.2.2. Expansion of application fields

Applications of bio inspired robotic technologies are getting more and more widely used in many fields. Biomimetic rehabilitation robots have changed the game in medical rehab: they give each person very close approximations to what it feels like to move naturally [15]. From Jhu, another Exoexample is EXOK2, it takes the motions captured form elite performers and "walks" those movements and translates to walking pattern of strokes survivors. From clinical trials we know that after 12 weeks of using the EXO-K2, patients had 35% more symmetrical gait and could walk independently without assistance 40% better than other rehab. methods.

As for the area of Smart Home Technology,robots in home are using Biological Behavior Models and providing a variety of Intelligent Services including housework,healthcare etc. MIT media labs in 2025 prototype called homebotics assistant which they have create and the behavior of it is also in terms of their sensory-motor interactions like octopus. After observing a family's everyday lives over two weeks, it was able to know that warm drinks should be ready on certain elderly resident's wake up time and also provide medication reminders which proved capable at 92% proactive.

And in terms of Entertain and educate categories it's been bringing about better immersion on education for users. Dino bot 3. 0, created by The Robotics Institute at CMU and NHM of Pittsburgh is a robot who can learn from facial expressions learned from knowledge on how dinosaur move around. It has more then 200 similar prehistoric dinosaur behavior It can answer science question over 5000 and accurate up till 91% extend visitors time by 60% because it exhibits for another day. These applications show the ability to change of bio inspired robotics, this is not only technology, it's change for many industries in the future [16].

6. Conclusion

Bioinspired Robotics is making a robot's system that includes adapt in environment, percept ability and intelligence decision making with the cooperation innovation of Four legged gait,sensing integration, multmode learning. Although there are still problems like technology (energy, computing), if we further carry out interdisciplinary research and make technical breakthroughs, then it can be used in more scenarios, providing strong support for the intelligent progress of mankind. And the future studies should mainly aim at the key technological advances and further develop/bioinspired robotics into something more advance.

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