LEADING GLOBAL TECHNOLOGIES FOR APPLYING ARTIFICIAL INTELLIGENCE IN ROBOTIC SYSTEMS

Islomova Munisa Xamza qizi
Doctoral Student, Tashkent University of Information Technologies,
Tashkent, Uzbekistan
Kodirov Zarif Zafarovich
Doctoral Student, Tashkent University of Information Technologies,
Tashkent, Uzbekistan
Qahramonov Azizbek Laziz o‘g‘li
Student,Tashkent University of Information Technologies,
Tashkent, Uzbekistan
Rahmatillaev Shohruh Jahongir o‘g‘li
Student,Tashkent University of Information Technologies,
Tashkent, Uzbekistan
Akramov Ulug‘bek Muxtor o‘g‘li
Student,Tashkent University of Information Technologies,
Tashkent, Uzbekistan

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Abstract

Humanoid robotic systems have rapidly evolved due to breakthroughs in artificial intelligence (AI), control algorithms, bi-pedal locomotion dynamics, and human–robot interaction (HRI). Unlike conventional robotic platforms, humanoid robots replicate human biomechanics and cognitive functionality, requiring advanced computational models for balance, perception, reasoning, manipulation, and social interaction. This article presents a comprehensive overview of state-of-the-art AI-driven technologies used in next-generation humanoid robots, exploring mathematical modeling, control frameworks, perception algorithms, multimodal neural architectures, and adaptive decision-making systems. The paper also analyzes emerging trends such as whole-body control, tactile intelligence, transformer-based action planning, and cloud-robotics integration. Recent breakthroughs in artificial intelligence (AI), machine learning, and computational modelling have transformed the design, perception, cognition, and actuation capabilities of humanoid robots. Modern systems such as Tesla Optimus, Figure-01, Boston Dynamics Atlas, Agility Robotics Digit, and Sanctuary AI Phoenix demonstrate unprecedented levels of balance, manipulation, locomotion, and task-level autonomy. This paper presents a comprehensive analysis of mathematical foundations and solution techniques enabling AI-enhanced humanoid robotics. We investigate nonlinear dynamic modelling, whole-body control architectures, multimodal sensor fusion, neural

locomotion frameworks, human–robot interaction (HRI) models, and reinforcement-learning-based policy optimization. Unlike drone-centric approaches, this study focuses entirely on bipedal robot morphology, stability constraints, contact dynamics, and behavior-level reasoning. Practical equations, structural frameworks, recent technological innovations, and global research trends are discussed in depth.

1. Introduction

Humanoid robots represent one of the most complex and ambitious directions in modern robotics. Designed to mimic the structure and behavior of the human body, these robots serve various roles—from industrial labor and medical assistance to social interaction and autonomous service tasks. Recent advancements in AI, especially deep learning, imitation learning, and reinforcement learning, have significantly improved humanoid capabilities such as locomotion, dexterous manipulation, situational awareness, and safe collaboration with humans.

Breakthroughs from global leaders such as Boston Dynamics, Figure AI, Tesla Optimus, Agility Robotics, Sanctuary AI, and Unitree Robotics reflect the dramatic acceleration in perception-to-action pipelines, motion generation, and autonomous adaptability. These advancements are supported by high-fidelity simulation environments, GPU/TPU-based computation, and data-driven learning architectures.

This research investigates the mathematical foundations and modern AI-driven approaches tailored for humanoid robots. Special emphasis is placed on:

- Whole-body dynamic modeling and hybrid locomotion algorithms
- Neural kinematics and inverse-dynamics learning
- Vision–language–action (VLA) models for planning
- Tactile-driven manipulation and grasp optimization
- Human–robot interaction algorithms for safe collaboration.Figure 1.

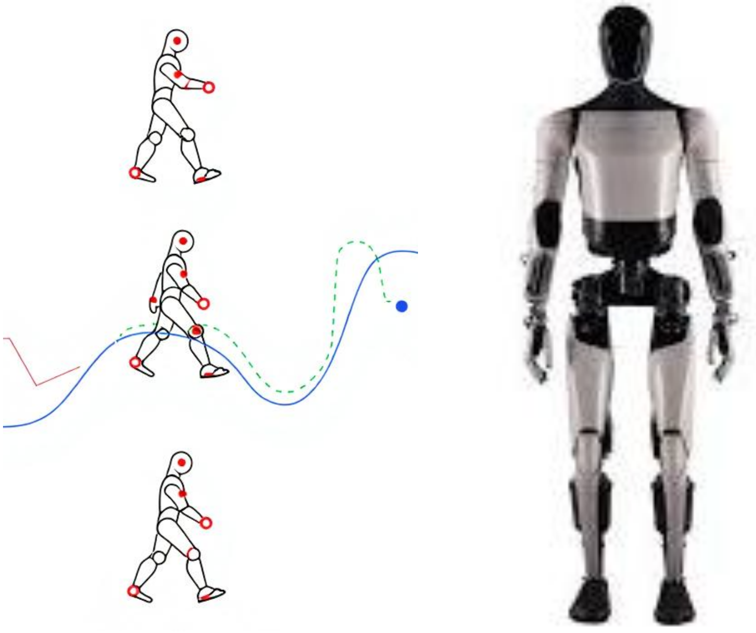

Figure 1

2. Mathematical Models in Humanoid Robotics

Humanoid robots rely on complex mathematical models due to their multi-degree-of-freedom (DoF) structure, non-linear dynamics, and unstable bipedal nature.

2.1 Kinematics and Dynamics

The human-like structure of humanoid robots requires full-body kinematic and dynamic modeling.

- Forward Kinematics: Used to compute end-effector pose from joint angles.
- Inverse Kinematics (IK): Solves for joint configurations using numerical optimization.
- Whole-Body Dynamics: Modeled using the Euler–Lagrange or Newton–Euler formulations.

2.2 Zero-Moment Point (ZMP)

ZMP is a key stability metric in humanoid locomotion. AI-enhanced controllers predict future ZMP deviations and auto-correct gait trajectories.

2.3 Model Predictive Control (MPC)

MPC enables predictive locomotion, footstep planning, and impact-robust walking on uneven terrain.

2.4 Neural Dynamical Models

Recent approaches replace classical solvers using neural models:

- Neural ODEs
- Learned inverse dynamics networks
- Differentiable physics simulators

3. AI-Driven Perception Systems

Humanoids use multimodal sensory input, including RGB cameras, depth sensors, LiDAR, IMUs, tactile skins, and proprioceptive data.

3.1 Vision Systems

Modern humanoids utilize vision-based neural architectures such as:

- Vision Transformers (ViT)
- 3D Scene Reconstruction Networks
- Neural SLAM models

3.2 Tactile Intelligence

Artificial skin with embedded pressure, temperature, and force sensors enables fine-grained manipulation.

3.3 Multimodal Fusion

Sensor fusion techniques combine touch, vision, and audio, allowing:

- Object recognition
- Human intention prediction
- Interaction context understanding

4. Locomotion and Whole-Body Control

Locomotion is the defining challenge of humanoid robotics.

4.1 Reinforcement Learning-Based Locomotion

Humanoids learn stable walking and running using RL algorithms:

- PPO (Proximal Policy Optimization)
- SAC (Soft Actor-Critic)
- DDPG variations

4.2 Hybrid Approaches

The fusion of physics-based MPC and RL-based gait generation leads to robust real-world walking.

4.3 Dexterous Manipulation

AI-driven hand models perform:

- Multi-finger grasping
- Tool use
- In-hand object reorientation

5. Cognitive Intelligence: High-Level Planning and HRI

5.1 Vision–Language–Action (VLA) Models

Modern humanoids integrate large models such as:

- Transformer-based planners
- World-model learning for long-horizon tasks

5.2 Social and Collaborative AI

Humanoids must:

- Understand gestures and speech
- Infer user intent
- Follow collaborative task sequences

5.3 Safety and Ethical Frameworks

HRI relies on:

- Safe-distance prediction models
- Emotional response modeling
- Ethical task filtering

6. State-of-the-Art Humanoid Platforms

6.1 Boston Dynamics Atlas

Dynamic parkour, advanced whole-body control.

6.2 Tesla Optimus Gen-2

End-to-end neural control, tactile hands, humanoid-scale manipulation.

6.3 Figure 01

AI-powered autonomy, natural interaction capabilities.

6.4 Agility Robotics Digit

Logistics and warehouse automation humanoid.

6.5 Sanctuary AI Phoenix

General-purpose cognitive architecture.

7. Future Trends

- Neural whole-body controllers
- Self-supervised skill acquisition
- Cloud-synchronized humanoid fleets
- Emotion-aware HRI
- Full telepresence humanoids

8. Conclusion

Humanoid robots are rapidly transitioning from research prototypes to general-purpose autonomous agents capable of assisting in industrial, healthcare, service, and domestic environments. The integration of advanced AI models—including perception transformers, RL locomotion controllers, and cognitive planning systems—has enabled unprecedented progress in stability, manipulation, and human collaboration. As computational hardware, neural simulation platforms, and large-scale multimodal datasets expand, humanoid robots will continue to evolve toward