International Journal of
Mechanical Dynamics and Systems Analysis

Volume 2, Issue 2, 2024
July–December
DOI (Journal): 10.37591/IJMDSA

https://journals.stmjournals.com/ijmdsa

Research IJMSDA

Design of Biped Robots: A Review

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Abstract

Biped robots, inspired by the human's kinematic structure, have seen remarkable evolution from early mechanical automata to today's sophisticated machines capable of performing complex tasks. Their design aims to achieve efficient and stable movement on two legs. This paper examines the current advancements and historical progress in the development of bipedal robots. The authors investigate the implementation of these robots in various fields, like healthcare, entertainment, search and rescue operations, and industrial automation, emphasizing their potential to transform multiple industries. In addition, the current work dives deeply into bipedal locomotion (kinematics), dynamic walking (dynamics), and control strategies that are scrutinized, revealing how algorithms and feedback mechanisms are employed to achieve stability and agility. Further, various design aspects like actuation, feedback control, sensors, and perception are discussed. Furthermore, various biped robots have been compared based on their design, mechanics, actuation, sensor and perception, performance metrics, and control strategies. Moreover, based on the findings of the present work, the possible research gaps are identified and near-future research directions are formulated. The principle idea is to enhance the design and development of biped robots, highlighting their potential to revolutionize various aspects of our lives. This manuscript reviewed 44 papers summarizing the advancements, reported from 1998 to 2024, in biped robotics. The authors believe that this information will act as a key resource for researchers working in the mentioned field. Finally, based on the proposed work concluding remarks have been made.

Keywords: Biped Robots, Biped Locomotion, human gait, sensors, actuators, robotics

INTRODUCTION

Humanoid biped robots, inspired by the human form and gait, represent a significant advancement in the field of robotics. They are designed to emulate human movements, enabling them to perform tasks in environments designed for humans. The design involves complex engineering principles, integrating mechanics, electronics, and control systems to achieve stable and efficient movement. Methods of locomotion are multiple legs, wheels, etc.

The historical development of these robots can be traced back to early automation, but significant strides were made in the late 20th and early 21st centuries with advancements in artificial intelligence and sensor technologies. Current humanoid robots are not the result of a single scientific breakthrough, but rather an accumulation of small incremental achievements in the respective utilized technologies. Modern robots like ASIMO [1], Sony Qrio [2], Atlas [3], and Sophia [4], showcase sophisticated design and versatile locomotion, highlighting their potential in various applications. Humanoid biped robots find applications across various fields such as

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Received Date: November 198 2024
Accepted Date: November 29, 2024
Published Date: December 09, 2024

Citation: Saakshi Aeron, Sofi Fatima, Amanpreet Singh. Design of Biped Robots: A Review. International Journal of Mechanical Dynamics and Systems Analysis. 2024; 2(2): 38–48p.

healthcare, where they assist with patient care and rehabilitation; in disaster management, providing aid in hazardous environments; and in service industries, performing tasks ranging from customer service to entertainment. The ongoing research in this area aims to enhance the autonomy, adaptability, and functionality of these robots, making them integral to the future of robotics and robot-human integration.

HISTORY

The term "robot" was introduced by a playwright, Karel Capek [5], within the context of his theatrical work. The character depicted in the play was a robotic servant, designed with a physical appearance akin to that of a human**.** Research into walking machines commenced during the era of Leonardo da Vinci and eventually led to the evolution of contemporary walking robots by refining and transforming ideas and design methodologies throughout the centuries [6].

The evolution of bipedal robots epitomizes an intriguing convergence of mechanical engineering, artificial intelligence, and biomechanics. Examining the evolution of these robots provides a glimpse into the notable progress in robotics during the previous few decades, emphasizing pivotal achievements and technological innovations.

The historical aspiration to imitate walking creatures, coupled with endeavors to integrate insights from biological observations into the development and control of walking robots, has introduced a novel dimension and presented numerous challenges to the field of walking robot research. Despite the obstacles encountered in the past regarding the design and realization of walking robots, the subsequent lessons gleaned from these challenges have significantly enhanced the walking robot technology and propelled it toward a state of maturity. This review aims to investigate the sequential progression of bipedal robots, commencing from their origination in the 1960s to the sophisticated iterations of the 21st century. The paper illustrates the technological progressions throughout this evolutionary trajectory.

Early Developments

WABOT-1

Waseda University commenced the WABOT project in 1967, and by 1972, they finalized the creation of WABOT1 [7], which marked the inception of the world's first complete humanoid intelligent robot. The emergence of bipedal robots signifies an intriguing convergence of mechanical engineering, artificial intelligence, and biomechanics. Examining the evolution of these robots provides valuable insights into the notable progress made in robotics during the past few decades, emphasizing pivotal milestones and technological advancements. The inaugural android pioneered the capability of ambulation, communication in Japanese through an artificial oral mechanism, assessment of spatial parameters using external sensors (artificial auditory and visual organs), as well as manipulation and movement of objects via its dexterous hands [7]. The WABOT 1 marked the beginning of humanoid robotic research focusing on mimicking human-like movements.

WAP – 1

The humanoid robot WAP-1, also known as Waseda Arm Prototype No. 1, was created by Waseda University in Japan in the year 1984, marking a noteworthy advancement in the progression of bipedal and humanoid robots [8]. The WAP-1 robot was characterized by arms and hands that were more advanced when juxtaposed with those of its forerunner. Its architectural blueprint was geared towards enhancing the adeptness and accuracy of the robotic hands, thereby empowering it to execute intricate manipulation assignments.

The motor control system of WAP-1 exhibited a higher level of advancement in comparison to that of WABOT-1. This enhanced system facilitated smoother and more accurate movements, empowering the robot to execute activities demanding refined motor skills, for instance, grasping small objects or conducting intricate procedures. The WAP-1 humanoid robot represents the gradual progressions in robotics technology in the 1980s, specifically focusing on manipulation and sensory feedback. Its influence on the discipline has left an enduring impression on the evolution of increasingly adept and refined humanoid robot.

WABOT – 2

The creation of WABOT-2 [7], which emerged from Waseda University in Japan in 1980, signifies a notable progression from its predecessor, WABOT-1, in the realm of humanoid robot technology. Whereas WABOT-1 established the foundational principles for humanoid robotics, the objective of WABOT-2 was to enhance and broaden these functionalities, with a particular focus on agility and engagement with the surroundings. One of the most notable characteristics of WABOT-2 was its capacity for piano performance [7]. The automaton possessed the capability to interpret sheet music through the utilization of its optical sensors, enabling it to execute musical compositions with its manual appendages, showcasing a considerable degree of skillfulness and synchronization.

The capability of playing the piano and executing activities demanding precise motor abilities showcased the capacity of robots to carry out intricate and intricate tasks. The progress achieved with WABOT-2 impacted future studies and advancements in humanoid robotics, facilitating the emergence of more advanced robots with the ability to engage with their surroundings in a manner resembling human behavior.

Honda E0

The humanoid robotics field was ventured into by Honda through the creation of the Honda E0 robot in 1986. The E0 robot marked a pivotal commencement for Honda's exploration of humanoid robotics [9]. Even though its functionalities were constrained in contrast to contemporary robots, it imparted priceless insights into bipedal locomotion. The initiative showcased the feasibility of constructing a robot proficient in walking on two legs, while also underscoring the complexities associated with attaining steady and effective bipedal motion.

The E0 robot was specifically engineered for bipedal locomotion, utilizing a dual-leg configuration in its design. This marked an early endeavor in the development of robots capable of walking on two legs. Its locomotion system was characterized by a simple yet fundamental walking pattern enabling forward movement.

ASIMO

ASIMO, which stands for Advanced Step in Innovative Mobility, is a humanoid robot that was created by Honda. Revealed to the public in the year 2000, ASIMO embodies the result of more than twenty years of dedicated investigation and enhancement in bipedal robotics. The primary objective of ASIMO is to function effectively within human settings and execute a diverse range of activities, showcasing sophisticated mobility, skillfulness, and communicative aptitudes [9].

ASIMO, in contrast to earlier models, demonstrates dynamic walking capabilities by effectively managing balance during locomotion at different velocities, executing turns, and achieving speeds of up to 9 km/h, including running [10]. The ability to sustain dynamic equilibrium enables ASIMO to accommodate diverse landscapes and gradients.

The development of ASIMO has had a notable impact on the field of robotics, showcasing the potential for creating robots capable of operating in human environments, executing complex tasks, and engaging with individuals in meaningful ways. ASIMO's utilization spans various domains such as research, education, and public demonstrations, highlighting the capabilities of humanoid robots.

Honda's research on ASIMO has influenced subsequent endeavors in humanoid robotics, stimulating progress in areas like mobility, dexterity, and artificial intelligence. Furthermore, ASIMO has heightened public awareness regarding the potential advantages and ethical considerations associated with robotics, contributing to broader dialogues on the future of human-robot interaction.

Sony QRIO

Sony QRIO which stands for 'Quest for CuRIOsity' is a biped robot developed by Sony corporation which was introduced in 2003. It was intended to be used for future home entertainment purposes [11]. The QRIO robot demonstrated proficiency in dynamic bipedal locomotion, showcasing the ability to achieve speeds up to 0.5 km/h. Through its sophisticated system, QRIO exhibited the capacity to traverse various types of terrain, uphold stability, and effectively mitigate the consequences of potential falls.

QRIO was capable of executing a diverse range of intricate movements, such as dancing, leaping, and transitioning from a seated or reclined posture, thereby demonstrating its prowess in agility and equilibrium. QRIO's eyes were equipped with LED lights that varied in color and intensity in order to communicate distinct emotional conditions, thereby enhancing its capacity for expression.

HUBO

The series of humanoid robots known as HUBO [12] was created by the Korea Advanced Institute of Science and Technology (KAIST). The inaugural HUBO robot, initially designated as KHR-3, was first introduced to the public in 2004. HUBO represents an enhanced iteration of KHR-2 [12]. The primary aim behind the creation of HUBO was to establish a dependable and aesthetically pleasing humanoid platform capable of accommodating a wide array of theories and algorithms including dynamic walking, navigation, human interaction, as well as visual and image recognition. Emphasizing the development of a robot that is user-friendly and mimics human appearance and movements, particular attention was given to harmonizing the mechanical structure with an artistic external design.

The HUBO series has undergone significant development throughout the years, with successive versions enhancing both the design and functionality of the initial robotic model [12].

By the year 2008, HUBO 2 [12] represented a significant advancement in the series, demonstrating enhanced speed, increased agility, improved manual proficiency, and enhanced sensor fusion, rendering it suitable for intricate operations and educational objectives. Furthermore, the development of the HUBO FX-1 [13] in 2005 delved into the idea of a bipedal exoskeleton tailored for heavy-duty tasks, illustrating KAIST's extensive exploration into diverse fields of robotics applications. Each version of HUBO was a product of accumulated knowledge from preceding models, resulting in notable progressions in the realm of humanoid robotics.

Atlas

Atlas is a bipedal humanoid robot developed by Boston Dynamics in 2013, known for its impressive mobility, agility, and versatility. Atlas has the capability to walk dynamically, utilizing real-time adjustments in its equilibrium to traverse irregular landscapes, barriers, and slopes. Furthermore, it is capable of reaching velocities of up to 1.5 meters per second, thereby demonstrating its remarkable agility.

The design of Atlas was formulated to function effectively in various settings, encompassing both indoor and outdoor conditions, carrying out activities that necessitate adept equilibrium and meticulous handling. The creation of Atlas signifies a notable progression in the field of robotics, specifically in the realms of movement and the interplay between humans and robots.

Equipped with LIDAR and stereo vision sensors, Atlas is capable of detecting and maneuvering around obstacles, whether they are stationary or in motion, within its surroundings. In terms of stair climbing and terrain navigation, Atlas exhibits the ability to ascend stairs, traverse challenging landscapes, and maintain stability on surfaces that are slick or unstable. Regarding dexterity and manipulation, Atlas showcases highly articulated hands that possess a sophisticated level of articulation, allowing it to grip and handle objects with precision. This level of capability is particularly crucial for tasks that necessitate fine motor skills. Furthermore, the robot is proficient in utilizing tools to execute various actions such as opening doors, operating machinery, and assembling objects, thereby showcasing its adaptability in practical settings.

Pepper

Pepper [14], created by SoftBank Robotics (previously known as Aldebaran Robotics), is a humanoid robot specifically crafted for engaging with humans and providing customer service. Unveiled in 2014, Pepper stands out for its capacity to identify human emotions and adjust its responses accordingly, positioning it as an early example of robots engineered with emotional intelligence in focus.

Pepper is furnished with an advanced emotion recognition system that employs facial recognition and voice analysis in order to identify and comprehend human emotions. It has the capability to distinguish between feelings of happiness, sadness, anger, and surprise, which enables it to customize its interactions based on the emotional condition of the user.

The main purposes of these robots include offering companionship, supporting customer service activities, and improving user interactions within different environments like retail establishments, corporate settings, and residential spaces. Pepper's capacity to perceive and react to human emotions distinguishes it from numerous other robots, rendering it a significant asset for enriching user experience and delivering customized interactions. Its utilization across diverse sectors has yielded valuable observations into the pragmatic utilization of social robots and their capacity to enhance customer satisfaction and involvement.

Tesla Bot

The Tesla Bot is a humanoid robot currently under development by Tesla, Inc., and was introduced by Elon Musk at the AI Day event hosted by the company in August 2021 [15]. Intended for undertaking tasks deemed hazardous, repetitive, or monotonous for humans, the Tesla Bot is designed to make use of Tesla's proficiency in artificial intelligence, machine learning, and robotics. This initiative epitomizes Tesla's ambition to expand its AI expertise from solely electric vehicles to encompass the domain of humanoid robotics [16].

The Tesla Bot has been crafted with a structure that mirrors the human physique, with a height of roughly 5 feet 8 inches and a weight of approximately 125 pounds. This layout aims to facilitate its functioning in humancentric settings, executing tasks in a manner that aligns with human cognitive processes [17]. The robot has been designed to ambulate at a velocity of a maximum of 5 miles per hour while having the capacity to transport a maximum of 45 pounds. It has the capability to execute a range of kinetic actions, such as ambulation, elevation, and maneuvering through surroundings effortlessly [18]. The robot will be furnished with a diverse range of actuators to facilitate seamless and accurate motion, in addition to sensors designed for visual perception, tactile feedback, and environmental detection. These sensor capabilities encompass cameras, ultrasonic sensors, and force response mechanisms [19, 20].

The Tesla Bot embodies a notable advancement in humanoid robotics, amalgamating cutting-edge AI, machine learning, and Tesla's proficiency in manufacturing and automation. The progression of this technology holds the potential to alleviate workforce shortages across various industries, enhance operational efficacy in diverse tasks, and elevate living standards by assuming mundane and perilous responsibilities. Through the utilization of the identical technologies employed in Tesla's self-driving vehicles, the Tesla Bot can potentially transform the integration of robots into daily life, facilitating seamless engagement with human surroundings and contributing to a vision of a future where robots play a pivotal role in a multitude of daily activities.

The history of bipedal robots showcases a trajectory from early experimental models to sophisticated machines capable of complex interactions and practical applications. Each milestone reflects technological advancements in mobility, control systems, and humanrobot interaction. This review paper delves into the technical details, challenges, and future prospects of these developments, highlighting the evolution of bipedal robotics over the decades.

APPLICATIONS OF HUMANOID ROBOTS

Currently, human-like robots are progressing in different fields, though they are still in the early phases of development. Many robots have moved from being tested in labs to being used in actual situations, performing tasks such as bartending [21, 22], exploring the deep sea [23, 24], and offering companionship and support to the elderly [25]. On the other hand, certain robots are employed in storage and production plants, collaborating with human workers on tasks related to logistics and manufacturing. Some applications showcase the imaginative and captivating qualities inherent in these automated gadgets, while others address practical requirements. They work a wide range of practical jobs, such as maintenance of plants, driving, home security, building construction, aircraft production, emergency handling, providing entertainment, and helping with lower limb rehabilitation. Since these robots are developed with human-like physical qualities, they can walk around human-made spaces, use human-made tools and modes of transportation, and interact with humans successfully because of their human-like movements. The importance of humanoid robots becomes particularly evident in chaotic environments when traditional robots find it difficult to function. These areas include residences, areas affected by disasters, and locations for rehabilitation. Humanoid robots are capable of many different tasks, such as helping patients and working with humans in industries. This demonstrates their adaptability and capacity to enhance various facets and domains of society.

Manufacturing

Bipedal robots that mimic the locomotion behavior seen in humans are used in various manufacturing fields. The purpose of using these robots is to improve flexibility, efficiency and safety. Such robotic platforms offer a promising way to address the existing limitations of automated systems and monitor dynamic processes that require greater adaptability in automation.

Digit – humanoid robot by Agility

Digit [26] is a robot developed by Agility Robotics that can effectively handle typical payloads found in most logistics and manufacturing operations, particularly the manipulation, movement, and placement of totes and cars. it is applicable for sectors experiencing notable deficiencies in the workforce and encountering operational challenges characterized by repetition, physical strain, and susceptibility to injuries.

Agility Robotics is presently involved in employing reinforcement learning and generative artificial intelligence models to enhance the functionalities of Digit. The integration of significant language models for the processing of natural language commands enables a smooth and effective communication between humans and robots.

TALOS by Pal Robotics

The TALOS [27] robot by PAL Robotics is a highly versatile humanoid robot designed for a range of industrial applications, including aircraft manufacturing. It can perform precise assembly tasks, such as installing components in hard-to-reach areas, which is crucial in the tight and complex spaces of an aircraft's interior. The robot is strongly favored over other mobile systems in aircraft manufacturing due to its ability to perform tasks such as climbing stairs and maneuvering through narrow corridors, which are essential for operating aircraft. Aircraft manufacturing tasks often require navigating tight spaces while handling heavy equipment with long attachments.

Therefore, a robot that can handle tools weighing up to 6 kg with outstretched arms is essential for tasks such as drilling, riveting, and component inspection, ultimately improving the efficiency and quality of the manufacturing process.

Medical and Healthcare

Humanoid robots play a significant role in various domains, including medicine, biotechnology, biomechanics, and cognitive science. These robots play a major role in the improvement of modern prosthetic devices made for people who are facing certain physical disabilities like limb deficiencies etc.

Humanoid robots are frequently utilized as patient care assistants (PCAs) in various environments. Specifically engineered for this role, these robots are programmed to the extent of having abilities like monitoring the patient’s vitals, giving medication on time, and assisting during physical therapies. Moreover, they offer emotional support to the patients undergoing treatment by providing dialogues or engaging with the individuals who experience anxiety, uneasiness, or distress during this period.

Humanoid robots have the potential to revolutionize healthcare by improving the efficiency of operations, the quality of care, and the accuracy of diagnostic and therapeutic procedures. In addition, they have the potential to improve patient outcomes.

a. *REX by REX bionics:* Wearable Exoskeleton robot REX [28] by REX Bionics is a hands-free, self-supporting robotic exoskeleton designed for people with mobility limitations such as spinal cord injuries, multiple sclerosis, or other conditions that limit lower limb function.

Both the user's weight and its own weight can be independently supported by the REX. The REX is able to move forward and backward, turn, and even climb stairs. It can also shift weight from one leg to the other. There are two types of the REX exoskeleton: REX for Clinical Use and REX P for Personal Use.

Unlike certain exoskeletons that necessitate crutches or supplementary support, REX has been specifically engineered to operate without manual assistance, enabling individuals to engage in activities with their hands while in an upright position and in motion. Operational commands for REX can be executed via a joystick or a comparable interface, affording users meticulous and instinctive authority over their movements.

BIPEDAL LOCOMOTION

(Table-1) Bipedal locomotion, the ability to move using two legs, represents a significant evolutionary development in various species, most notably in humans. This kind of movement distinguishes itself from other forms of locomotion by its efficiency, versatility, and the complex biomechanical processes it entails. By studying bipedal robots, we can gain more knowledge about the dynamics of human locomotion which is the inspiration for creating them. Another significant benefit is that legged mobile robots can be introduced to much more complicated application scenes, e.g. disaster rescue [29], firefighting [30], and outer space exploration [39]. Similar to humans, bipedal robots have characteristics like a multi-degree of freedom. By ingeniously combining the motion of each joint, biped robots can execute various actions [31]. The adaptability of bipedal robots allows them to operate in confined spaces, making them suitable for tasks that would otherwise require human intervention. As a result, biped robots hold significant potential across a wide range of applications [32].

This complex locomotion includes forward kinematics, inverse kinematics, and the dynamic walking of a biped robot model. Figure 1 shows the kinematic analysis of a human runner which is used in this study to analyze and relate to that of a humanoid robot’s legs [33]. Numerous techniques and algorithms are employed in the development of successful bipedal locomotion, with the aim of addressing the challenges related to dynamic walking and stability. Approaches such as the Lagrangian method, Newton-Euler method, Denavit-Hartenberg formula, and UG are commonly utilized for establishing both dynamic and kinematic models of the robot. In addition, criteria such as the Zero Moment Point (ZMP), along with methods like the two-step planning method, three-step planning method, and cubic interpolation algorithm, are implemented for the purpose of mapping out the motion trajectory of the feet and joints. A critical focus of this locomotion lies in achieving stability and optimizing energy efficiency, attributes that hold significant importance in the design of biped robots [34]. Forward kinematics is used to determine the location and orientation of the end effector of the robot (in this case it's the legs) from the configuration of the robot's joint angles. And in inverse kinematics position and orientation (of legs) are known and joint variables (hip and knee angles) are determined. Dynamic walking is majorly concerned with the stability of leg movements and energy-efficient walking that mimics human walking through external disturbances [33].

Table 1. Comparison of various humanoid robots

Name	Creator	Year	Locomotion	Height (cms)	Weight (kgs)	DOF	Sensors	Applications	References
Asimo	Honda	2000	Dynamic walking, stair climbing	130	54	57	Vision, Touch	Elderly care and assistance	[1], [10]
Atlas	Boston Dynamics	2013	Parkour, balancing	170	86	19	LIDAR, IMU	Search and rescue, research	[36]
NAO	SoftBank Robotics	2008	Basic walking, dancing	57	4.5	25	Ultrasonic, pressure sensors	entertainment	[37]
Pepper	SoftBank Robotics	2012	Basic walking	128	28	20	LIDAR, Touch sensors	Customer service, retail	[38]
Valkyrie	NASA	2013	Maneuvering uneven terrain	190	125	44	LIDAR, IMU, Force	Space exploration	[39]
HUBO	KAIST	2004 - present	Dynamic walking, running	125	55	41	Inertial sensor, Accelerometer	research	[12], [40]
HRP - 4C	KAIST	2009	Dynamic walking	158	43	42	Posture, force, torque sensors	Research, entertainment	[41], [42]
WABIAN-2	Waseda University	2005	Dynamic walking	153	41	64.5	Force, torque, photo-micro sensors	Research, assistive	[43]

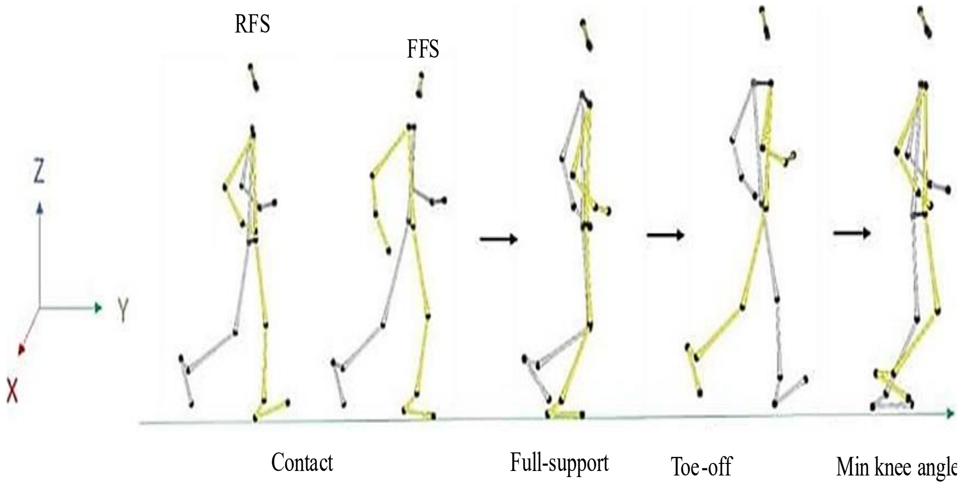

Figure 1. RFS and FFS running phase.

COMPARISON OF BIPED ROBOTS

CONCLUSION

The progression of bipedal robot design has experienced noteworthy progressions in recent decades, propelled by enhancements in technology, materials, and computational methodologies. This examination has underscored various crucial domains where advancements have been remarkable, such as the enhancement of more effective and resilient actuation mechanisms, the utilization of sophisticated control algorithms, and the incorporation of advanced sensor technologies that augment the robot's capacity to engage with its surroundings.

One of the major achievements in biped robot design has been the ability to achieve stable and dynamic walking, even on uneven terrains. Additionally, the use of new technologies like machine learning and artificial intelligence has opened new areas for adaptive and autonomous applications of biped robots

Looking ahead, future research should focus on enhancing the energy efficiency of biped robots, focusing on the development of energy conservation systems in the robots and using of renewable sources of energy for a more sustainable environment and future. Additionally, there is a need for more robust control algorithms that can adapt to unpredictable environments and tasks.

In conclusion, substantial advancements have been achieved in the development of bipedal robots; however, the goal of achieving completely autonomous, adaptable, and effective bipedal systems is still in progress. Sustained exploration and creativity will play a crucial role in actualizing the complete capabilities of bipedal robots across a range of fields, including industrial automation, personal support, and beyond.

Acknowledgment

We would like to express our sincere gratitude to the university for providing us with the resources necessary for this review paper.

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