National University of Sciences and Technology

School of Mechanical and Manufacturing Engineering

MS Robotics and Intelligent Machine Engineering

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Writing a Report on a Mobile Robotics Related Paper (Module 1)

Paper Information:

Title	Design and Control of a Miniature Bipedal Robot with Proprioceptive Actuation for Dynamic Behaviors
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1 Abstract:

1.1 Research Problem:

This paper addresses the need for a cost-effective and accessible bipedal robot platform capable of exhibiting dynamic behaviors, aiming to overcome the limitations of existing humanoid robots in terms of cost, accessibility, and dynamic performance.

1.2 Key Methodologies:

The researchers designed and developed a miniature bipedal robot named BRUCE, incorporating a novel actuation scheme with cable-driven differential pulleys for hip joints and linkage mechanisms for ankles. They also proposed a convex formulation of Model Hierarchy Predictive Control (MHPC) for real-time control of complex motions.

1.3 Major Findings:

BRUCE demonstrated capabilities for dynamic behaviors such as walking, push recovery, and vertical jumping. The convex MHPC approach proved to be efficient and effective for real-time control, achieving a processing frequency of 250 Hz.

1.4 Significance and Implications:

This research presents a significant step towards making humanoid robots more accessible and capable of dynamic motions. The design principles and control methods implemented in BRUCE have the potential to influence future development of humanoid robots and facilitate research in dynamic locomotion.

2 Introduction

Humanoid robots, with their resemblance to the human form and potential for versatile movement, have long captivated the imagination of researchers and the public alike. These complex machines hold promise for applications ranging from disaster response and hazardous environment exploration to assistive technologies and personal service robots. However, despite significant advancements in the field, achieving truly dynamic behaviors like running, jumping, and agile maneuvering remains a significant challenge.

One of the primary hurdles in developing dynamic humanoid robots lies in the limitations of current actuation and control methodologies. Traditional servo motors, commonly used in robotics, often suffer from high gear ratios and limited force control bandwidth, hindering their ability to react quickly and smoothly to changing conditions. Series elastic actuators (SEAs), while offering improved compliance and impact mitigation, still face challenges in achieving high-bandwidth force control. The quest for more responsive and adaptable actuation has led to the exploration of novel approaches, including the use of proprioceptive actuators. These actuators, capable of sensing their own position and force, offer a promising avenue for achieving dynamic and compliant behaviors in humanoid robots.

Beyond actuation, the control of complex, multi-degree-of-freedom systems like humanoid robots presents a significant challenge. Model Predictive Control (MPC) has emerged as a powerful tool for planning and controlling robot motions. However, traditional MPC approaches often struggle with computational complexity and local minima issues, particularly when dealing with high-dimensional models and real-time constraints. Recent advancements such as Model Hierarchy Predictive Control (MHPC) offer potential solutions by combining the accuracy of full-body models with the efficiency of simplified models.

2.1 Accessibility and Affordability of bipeds:

Despite the remarkable achievements of cutting-edge humanoid robots like Boston Dynamics' Atlas and Agility Robotics' Digit, their high cost and limited accessibility pose a significant barrier for researchers and educators seeking to explore and advance the field. This lack of affordable and accessible platforms hinders the pace of innovation and limits the potential for wider exploration of dynamic humanoid locomotion.

2.2 Analysis of a Potential Solution:

This report delves into the research paper "Design and Control of a Miniature Bipedal Robot with Proprioceptive Actuation for Dynamic Behaviors" by Yeting Liu et al. (2022). This paper, published in the prestigious IEEE International Conference on Robotics and Automation (ICRA), presents a novel and promising approach to tackling the challenges outlined above.

The researchers introduce BRUCE, a miniature bipedal robot specifically designed for dynamic movements. BRUCE incorporates several key innovations, including a unique actuation scheme utilizing cable-driven differential pulleys for hip joints and linkage mechanisms for ankles, effectively reducing leg inertia and improving joint accuracy. Additionally, the robot leverages proprioceptive actuators for compliance and impact mitigation, further enhancing its dynamic capabilities. To address the control challenges, the researchers propose a novel convex formulation of MHPC, enabling efficient and real-time control of complex motions.

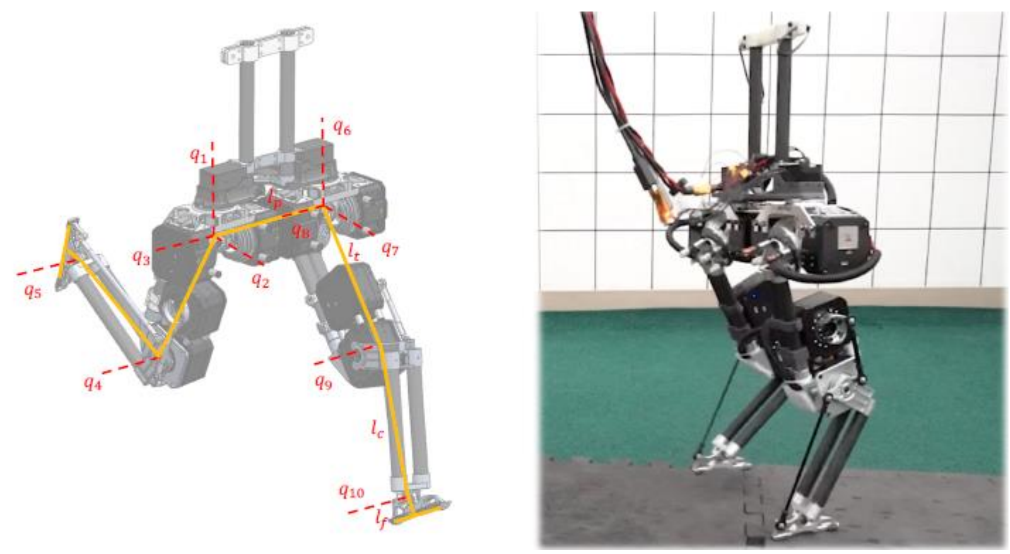

Figure 1 Bipedal Robot Unit with Compliance Enhanced (BRUCE)

This report aims to critically analyze and evaluate the design, control methods, and performance of BRUCE as presented in the research paper. It will assess the strengths and weaknesses of the proposed approach, discuss the implications for humanoid robotics research and education, and explore potential future directions for this promising platform. By examining the innovations presented in this work, we hope to gain a deeper understanding of the potential for accessible and capable humanoid robots to advance the field and inspire future research endeavors.

3 Summary of the Research Paper

The research paper delves into the design and control of BRUCE, a miniature bipedal robot specifically engineered for dynamic movements, aiming to address the limitations of cost, accessibility, and dynamic performance in existing humanoid robots. The authors propose a novel approach combining innovative mechanical design, proprioceptive actuation, and a convex Model Hierarchy Predictive Control (MHPC) framework to achieve this goal.

3.1 Key Design Features:

Low-Inertia Legs: BRUCE's legs are designed with a focus on minimizing inertia to facilitate agile and dynamic movements. Each leg possesses five degrees of freedom (DoFs) and incorporates a unique actuation scheme.

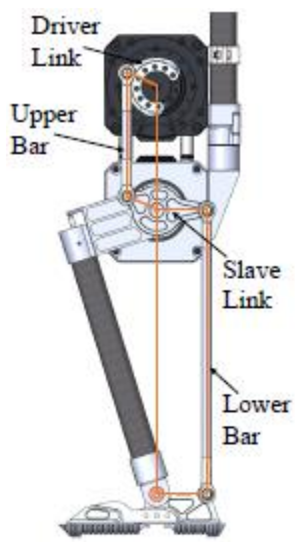

Figure 2 Leg Design of BRUCE

Cable-Driven Differential Pulleys: Replacing traditional bevel gears, a cable-driven differential pulley system is employed for the hip joints. This design choice offers advantages such as reduced backlash, improved joint accuracy, and increased available torque for powerful hip movements.

Linkage Mechanisms for Ankles: To further reduce leg weight and complexity, the ankle joints are actuated using 4-bar linkage mechanisms instead of direct motor placement. This design necessitates careful consideration of link dimensions and buckling loads to ensure robust torque transmission.

Proprioceptive Actuation: BRUCE utilizes proprioceptive actuators for most joints, offering compliance and impact mitigation capabilities crucial for dynamic interactions with the environment. This choice deviates from traditional servo motors and SEAs, aiming for improved responsiveness and control.

Contact Sensing Feet: Lightweight contact sensing foot modules are implemented to provide feedback for state estimation during interactions with the ground, contributing to stable and controlled movements.

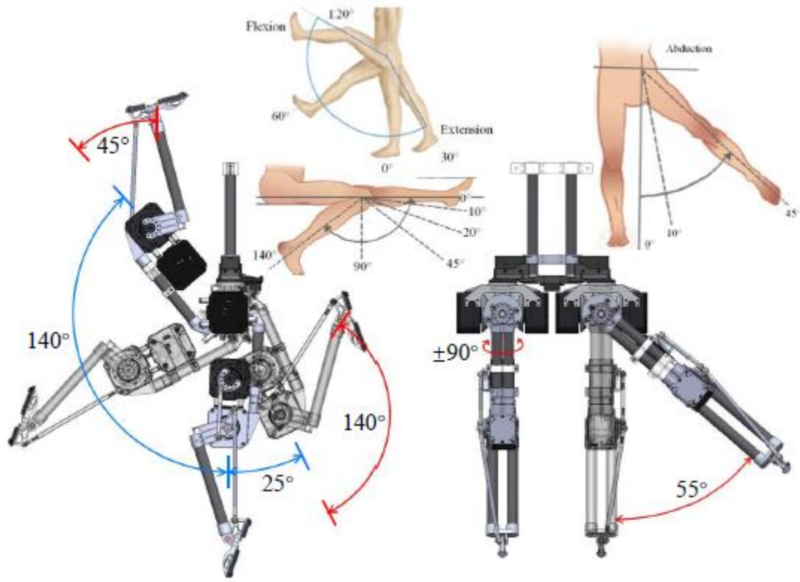

Figure 3 Lower body comparison of joint configuration and range of motion between BRUCE and human being

3.2 Control Framework - Convex MHPC:

To overcome the computational challenges of traditional whole-body MPC, the researchers propose a novel convex MHPC framework for real-time control of BRUCE. This framework leverages the accuracy of the full-body model for the immediate future and transitions to a simplified, linearized centroidal momentum model for longer-term planning. This approach balances computational efficiency with control accuracy, enabling real-time decision-making and dynamic motion planning.

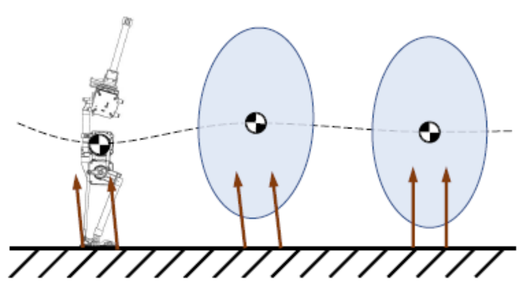

Figure 4 Illustration of the convex MHPC framework

3.3 Experimental Evaluation:

The research paper presents a series of experiments to evaluate the performance of BRUCE and validate the effectiveness of the proposed design and control methodologies. These experiments include:

Hip Joint Analysis: Comparing the cable-driven differential pulley system to traditional bevel gears, demonstrating reduced backlash and sufficient joint stiffness.

Kinematics Verification: A seesaw balancing test and preliminary walking experiments showcase the basic functionality and locomotion capabilities of BRUCE.

Convex MHPC Evaluation: Evaluating the control framework in dynamic scenarios including push recovery, center of mass (CoM) tracking, and vertical jumping, demonstrating the robot's ability to maintain balance, follow desired trajectories, and execute powerful jumps.

Overall, the research paper presents a compelling case for BRUCE as a viable and promising platform for exploring and advancing dynamic locomotion in humanoid robots.

3.4 Research Question:

The core research question addressed in this paper is:

Can a miniature bipedal robot with proprioceptive actuation and a novel convex MHPC control framework achieve dynamic behaviors such as walking, push recovery, and jumping?

This question encompasses several sub-questions related to the effectiveness of the specific design choices, the efficiency of the control framework, and the overall capabilities of the robot platform for dynamic movements.

3.5 Hypothesis:

The underlying hypothesis of the research is that the combination of BRUCE's design features, including low-inertia legs, proprioceptive actuation, and contact sensing feet, along with the proposed convex MHPC control framework, would enable the robot to exhibit dynamic behaviors effectively. This hypothesis is based on the expected benefits of each design choice and the capabilities of the control framework in handling complex motions and real-time constraints.

Methodology:

The research paper meticulously details the methodology behind the design, control, and evaluation of BRUCE, encompassing both the hardware and software aspects of the robot.

3.6 Design and Actuation

Joint Configuration: To strike a balance between achieving a human-like range of motion and maintaining a simple, lightweight design, each of BRUCE's legs features a 3-DoF configuration: a spherical hip joint, a single DoF knee joint, and a single DoF ankle joint. This configuration allows for versatile leg movement while keeping the overall complexity manageable.

Link Lengths: The proportions of BRUCE's body segments are scaled down from an average adult human to maintain a similar range of motion. The specific link lengths are chosen to achieve a total height of 660mm and prevent collisions between the hip actuators.

Hip Actuation - Cable-Driven Differential Pulley System: Instead of placing actuators directly at the hip joints, a 2-DoF cable-driven differential pulley system is employed. This design choice offers several advantages:

Reduced Leg Inertia: By placing the actuators closer to the torso, the inertia of the leg is significantly reduced, leading to more dynamic leg motions.

Increased Torque: The parallel actuation configuration allows both actuators to contribute to hip pitch movement, providing increased torque for powerful motions in the sagittal plane.

Zero Backlash: The cable-driven system eliminates backlash, a common issue with traditional gears, leading to improved joint accuracy and stability.

The system utilizes four cables in total, with two cables for each hip actuator, enabling independent control of hip pitch and roll through coordinated cable tensioning.

Ankle Actuation - Linkage Mechanism: To keep the tibia link as light as possible, the ankle actuators are housed within the femur link. Torque transmission to the ankle joint is achieved using two pairs of 4-bar linkage mechanisms in a parallelogram configuration. This choice offers high stiffness and eliminates the compliance issues associated with belt drives. The design necessitates careful consideration of link dimensions and material properties to prevent buckling under high torque conditions. The buckling load equation ensures the lower bar of the linkage mechanism can withstand the maximum torque:

$$F_{buckling} = \frac{\pi^2 E_l I}{L_l^2} \geq \frac{T_{max}}{l}$$

where:

$F_{buckling}$ is the buckling load.

E_l is the Young's Modulus of the lower bar material.

I is the moment of inertia of the lower bar's cross-section

L_l is the length of the lower bar.

T_{max} is the maximum actuator torque.

l is the moment arm of the slave link

Contact Sensing Foot: Each foot features a simple yet effective contact sensing mechanism. A layer of conductive copper foil is sandwiched between an aluminum base and a plastic contact layer. When the foot touches the ground, the plastic layer deforms, creating an electrical connection between the foil and the base, thereby detecting contact.

Control Framework: Convex MHPC for Real-Time Decision Making

Overall Software Architecture: The software framework operates in a multithreaded environment to ensure responsiveness and efficient resource utilization. Three main threads are implemented:

Motor Communication Thread: Handles low-level communication with the proprioceptive actuators and servo motors.

State Estimation Thread: Combines sensor data from IMUs and the contact sensors with the robot model to estimate the current state of the robot.

Feedback Control Thread: Utilizes the proposed convex MHPC to compute optimal torque commands for the actuators in real time.

Convex Model Hierarchy Predictive Control (MHPC): This framework addresses the computational challenges of traditional MPC by employing a hierarchical approach:

Near Horizon - Full-Body Model: For the immediate future (first time step), the full-body dynamics of the robot are considered to generate accurate control actions. The dynamics are formulated as:

$$H\ddot{q} + C\dot{q} + G = S_a^T a\tau + \sum_{i=1}^{N_c} J_{ci}^T F_i$$

where:

$\ddot{q}$ represents the generalized coordinates

H is the inertia matrix

$C\dot{q}$ represents Coriolis and centrifugal forces

G is the gravity force vector

S is the actuation selection matrix

τ is the actuation torque vector

J_{ci} and F_i are the Jacobian and contact force for the i-th contact

N_c is the total number of contact points

Long Horizon Model: To reduce computational complexity for future time steps, a simplified and linearized centroidal momentum model is used. This model focuses on the linear and angular momentum of the robot, disregarding detailed joint movements. The model is represented as:

$$\dot{l} = m\ddot{p} = mg + \sum_{i=1}^{N_c} f_i$$

$$\dot{k} = \sum_{i=1}^{N_c} r_i \times f_i$$

where:

l and k are the linear and angular momentum

m is the robot's mass

p is the CoM position

g is the gravity vector

f_i and r_i are the contact force and position vector for the i-th contact

Model Transition: To ensure consistency between the two models, the centroidal momentum matrix is used to relate the full-body model's generalized acceleration to the rate of change of centroidal momentum.

Optimization Problem: The control problem is formulated as a Quadratic Program (QP) with the objective of minimizing the tracking error and control effort while satisfying various constraints related to joint torque limits, contact forces, and friction cones. This QP is solved in real-time at 250Hz, providing optimal torque commands for the actuators.

Evaluation: The researchers conducted several experiments to evaluate the performance of BRUCE and validate the effectiveness of the proposed methodology:

Hip Joint Backlash and Stiffness: Comparing the cable-driven system to traditional bevel gears, demonstrating reduced backlash and sufficient joint stiffness for reliable operation.

Kinematics Verification: A seesaw balancing test and preliminary walking experiments demonstrated the basic functionality and locomotion capabilities of BRUCE.

Convex MHPC Evaluation: Testing the control framework in dynamic scenarios including push recovery, CoM tracking, and vertical jumping, showcasing the robot's ability to maintain balance, follow desired trajectories, and execute powerful jumps.

The results of these experiments demonstrate the successful implementation of the proposed design and control methodologies, highlighting the potential of BRUCE as a valuable platform for research and education in dynamic humanoid robotics.

4 Critical Analysis:

4.1 Strengths:

Innovative and Effective Design: The use of cable-driven differential pulleys and linkage mechanisms for actuation offers a novel approach to reducing leg inertia and increasing joint accuracy, contributing significantly to BRUCE's dynamic capabilities. This design choice demonstrates a clear understanding of the challenges in humanoid robot design and presents an effective solution for achieving agility and responsiveness.

Proprioceptive Actuation for Compliance and Control: Employing proprioceptive actuators provides several benefits, including inherent compliance, impact mitigation, and high-bandwidth force control. This choice aligns with the growing trend of utilizing proprioceptive actuation in dynamic robots and contributes to BRUCE's ability to interact safely and effectively with the environment.

Efficient and Real-Time Control Framework: The proposed convex MHPC framework effectively addresses the computational challenges of traditional whole-body MPC while maintaining control accuracy. By combining full-body and simplified models, the framework achieves a balance between performance and efficiency, enabling real-time control of complex motions.

Accessibility and Open-Source Potential: The researchers' intention to make BRUCE an affordable and open-source platform is commendable and holds significant implications for the field of humanoid robotics. This move has the potential to democratize access to advanced robotics research and education, fostering innovation and collaboration within the community.

4.2 Weaknesses:

Limited Degrees of Freedom (DoFs): Compared to some advanced humanoid robots, BRUCE possesses a limited number of DoFs, particularly in the ankle joints. This design choice, while simplifying control and reducing weight, may restrict the robot's capabilities for tasks requiring complex foot movements or manipulation.

Incomplete Upper Body Development: The current prototype lacks a fully developed upper body, limiting its functionality and potentially affecting its performance in tasks like jumping and balancing. The absence of an upper body also restricts research into full-body coordination and manipulation tasks.

Limited Experimental Validation: While the presented experiments showcase the basic capabilities of BRUCE, more extensive testing and evaluation in diverse and challenging environments would provide a more comprehensive understanding of the robot's performance and robustness.

4.3 Implications:

The research presented in this paper holds several significant implications for the field of humanoid robotics:

Advancement of Humanoid Robot Design: The design principles and actuation strategies employed in BRUCE can inspire and inform the development of future humanoid robots, leading to more affordable, accessible, and capable platforms.

Exploration of Dynamic Locomotion: BRUCE provides a valuable tool for researchers to explore and study dynamic locomotion behaviors such as running, jumping, and navigating complex terrains. This research can contribute to the development of more robust and adaptable control algorithms for legged robots.

Educational Value and Community Engagement: By making BRUCE an open-source platform, the researchers pave the way for wider accessibility and utilization in education and research. This move can foster community engagement, collaboration, and knowledge sharing within the field of humanoid robotics.

5 Discussion:

The development of BRUCE, as presented in this research paper, represents a significant step forward in the pursuit of affordable and capable humanoid robots. The innovative design choices, efficient control framework, and focus on accessibility offer valuable insights and potential solutions to long-standing challenges within the field.

The utilization of cable-driven differential pulleys and linkage mechanisms for actuation effectively addresses the issue of leg inertia, a critical factor in achieving dynamic movements. This design choice, coupled with the implementation of proprioceptive actuators, showcases a clear understanding of the requirements for building robots capable of agile and compliant interactions with the environment. The success of BRUCE in performing dynamic tasks such as push recovery, CoM tracking, and jumping validates the effectiveness of these design choices and highlights their potential for future humanoid robot development.

The proposed convex MHPC framework offers a promising solution to the computational challenges associated with traditional whole-body MPC methods. By employing a hierarchical approach that balances model accuracy with computational efficiency, the researchers demonstrate the feasibility of real-time control for complex and dynamic motions. This advancement paves the way for more sophisticated control strategies in future humanoid robots, enabling them to execute increasingly complex tasks in dynamic environments.

The researchers' commitment to making BRUCE an open-source platform with an affordable cost holds immense potential for democratizing access to humanoid robotics research and education. This move can empower a wider community of researchers, educators, and students to engage with this technology, fostering collaboration, innovation, and accelerated progress in the field. The accessibility of the platform also opens doors for exploring applications in various domains, including education, research, and potentially even personal assistance.

However, it is essential to acknowledge the limitations of the current prototype. The limited degrees of freedom, particularly in the ankles, may restrict the robot's capabilities for certain tasks. Additionally, the absence of a fully developed upper body limits the research possibilities for full-body coordination and manipulation. Further development and refinement of the platform are necessary to address these limitations and expand the range of potential applications.

6 Conclusion:

This research makes significant contributions to the field of humanoid robotics by introducing BRUCE, a miniature bipedal robot capable of dynamic behaviors. The innovative design, efficient control framework, and commitment to open-source development showcase a promising path towards creating more accessible and capable humanoid robots. With further development and community engagement, BRUCE holds the potential to inspire and accelerate advancements in humanoid robotics research and education, paving the way for a future where these versatile machines can play a significant role in various aspects of our lives.