Quadruped Robot Dog - LAIKA

1. Mesutcan ÖZKAN
Mechatronic Engineering
Marmara University
İstanbul, Turkey
mesutcanozkan.20@gmail.com

2. Mehmet Ekrem BEDİR
Mechatronic Engineering
Marmara University
İstanbul, Turkey
ekremmehmet499@gmail.com

Abstract—The rapid development of engineering technology has enabled the widespread use of autonomous robots that minimize workforce in various sectors. An example of this progress is the "LAİKA" autonomous dog project, initiated by two university students and encompassing a process from design to implementation. This autonomous dog aims to be used across a wide spectrum, especially in emergency situations, rescue operations, military use, education, and research. Such projects reflect the potential of technology to positively impact human safety, efficiency, and quality of life.

LAİKA is designed to move like an arthropod robot using 12 servo motors. These servo motors will perform desired rotational movements, directed by a special algorithm. Additionally, the robot will gain self-balancing capabilities thanks to an IMU (Inertial Measurement Unit) sensor on board. The kinematic equations of each leg will be derived to calculate the necessary angle values for the servo motors. These angle values obtained from the kinematic equations aim to enable the robot to both move and maintain balance.

Furthermore, cameras and sensors will be used for detection, object recognition, and tracking. Actions will be taken based on this data. In mechanical design, easy production, cost-effectiveness, and eco-friendly approaches are targeted. Therefore, PET-G, an advanced version of the polymer PET (polyethylene terephthalate) used in the production of plastic bottles, is preferred as the main material for production.

Keywords — Autonomous Robots; Quadruped Robot; Digital Twin; MATLAB; Arduino.

I. INTRODUCTION

A. Aims and Objectives

The aim is to initiate a domestic and national movement towards the robot sector, which is expected to be worth 500 billion US dollars by the year 2025. Within the framework of this general objective, the goals identified primarily involve reducing the costs of robot technologies in emergency situations, rescue operations, military use, education, and research, as well as minimizing work accidents. In addition, we aim to add new designs to the articulated leg robot category and become a leader in this field. Increasing the use of artificial intelligence in quadruped robots and leading in this area are also among the proposed goals. Lastly, we aim to make a difference in the industry by developing an original communication protocol with the high mobility and modular structure of our robot named LAİKA. With our planetary gear model design, which will provide a suitable production cost and high carrying capacity, we will have a structure that is both original and highly preferred. Additionally, by naming this project after Laika, the dog that freely roamed Moscow's Red Square and paid with her life for being the first dog sent into space in the technology wars, we also aim to create awareness

B. Intrinsic Value

Robots are rapidly gaining importance in a series of sectors. They are particularly preferred in fields like space sciences, biomedical, machinery industry, telecommunications, and communication. One of the primary reasons for this preference is the ability of robots to conduct preliminary exploration in dangerous and hard-to-reach areas, thus ensuring safety. Additionally, the decision-making capacity of artificial intelligence-supported machines provides a significant advantage in speeding up production processes and timely detecting and addressing potential problems, thereby increasing efficiency.

Looking at the magnitude of robotic technology, it is observed that the revenue of the industrial and non-industrial robotics market has increased between 2017 and 2025. By 2025, the global robotics market is expected to be worth approximately 500 billion US dollars. This growth will gain further momentum with the development of autonomous technologies such as personal assistant robots, customer service robots, autonomous vehicles, and unmanned aerial vehicles.

The most distinctive feature of our project in this market is its high mobility as an articulated leg robot. Articulated leg robots stand out with their ability to traverse irregular surfaces thanks to their flexibility and maneuverability. Their durability and resistance, which can be designed for use in challenging conditions, are noteworthy. Therefore, robots will find more interaction and use in many sectors in the future, contributing to the sustainable support of technological advancements.

II. Literature Review

The Turkish economy is stepping into a new phase with the transformation brought by Industry 4.0. In this change, local and national designs developed by Turkish engineers stand out. The 4-legged robot LAİKA stands out as an example of this innovative approach. Developed by Turkish engineers, LAİKA is compatible with Industry 4.0 and increases Turkey's global competitiveness with its versatile usage potential. This domestic design is not only a technological breakthrough, but also represents Turkey's cultural identity and innovation power. LAIKA stands out as an example that shapes Turkey's future and shows the power of local and national design.

In the article “Bio-inspired robotic dog paddling: kinematic and hydro-dynamic analysis” written by Yunquan Li et al. (2019), research on four-legged robots inspired by canids or felines has been widely reported and demonstrated. However, he states that none of these legged robots can cope with harsh environments containing water, such as small lakes, streams, rain, mud, and flooded lands. Our LAIKA robot dog will overcome this obstacle and be one step ahead of its other competitors in the market, thanks to its waterproof body.

According to the behavioral analysis made by Gail F. Melson et al. (2005) in their article titled "Robots as dogs: children's interactions with the robotic dog AIBO and a live Australian shepherd", children who normally spend more time with live dogs have SONY's Robot dog AIBO. They perceived him as a living dog and spent time interacting with him. Based on this article, our LAIKA robot dog will have the potential to appeal to children in terms of appearance and coloring.

In his article "Kicking a robot dog" published in (2016), Robert Sparrow comments on whether it is wrong to kick a robot dog after the video showing a man kicking the four-legged robot "Spot" published on the internet by Boston Dynamics in 2015. Based on this article, we are considering implementing a system that verbally warns people when they are in such a situation.

In their article titled "Demo: The Future of Dog Walking - Four-Legged Robots and Augmented Reality" published by Jannek Steinke et al. (2023), wireless control applications have become possible with the need to support use cases that demand low delays with high reliability from the communication network of 5G. states. We aim to use this innovative technology in our LAIKA robot dog and display the data we receive from the sensors on the HMI interface we have designed.

In Brian L. Due's article "Guide dog versus robot dog: assembling visually impaired people with non-human agents and achieving assisted mobility through distributed co-constructed perception" published in 2021, "Can a robot dog replace a guide dog?" and talks about the requirements for a robot dog to become a guide. We are advancing our work by taking these criteria into consideration in the design of the robot dog.

In his article “Arachnid-inspired Kinesthesia for Legged Robots” published in 2015, Nicholas Harvey explores the importance of limb position and movement in successful navigation for animals and robots. And as a result, he recommends using kinesthesia, also known as proprioception, to determine limb position. We aim to develop an algorithm in movement kinematics, taking animals as a reference.

In their article "Towards a biologically inspired small-scale water jumping robot" published by Bongsu Shin and his colleagues in 2008, they introduce a small-scale robotic system that imitates the ability of aquatic arthropods to jump on water. The robot in the study achieves a vertical jump by quickly releasing its bent legs to push the water surface. We will use the jumping technique in this study as a reference and use it in our own jumping technique.

In the article "A SURVEY OF LEGS OF INSECTS AND SPIDERS FROM A KINEMATIC PERSPECTIVE" written in 1988, Eugene F. Fichter emphasizes the limitations of arthropod robots and the need for more complex leg mechanics and control systems to work in complex environments. We optimized our design with the information we gained from this article.

In the article "Structure Design and Motion Planning of a Reconfigurable Robot with Flexible Waist" written by Yuntao Guan and his colleagues in 2023, the robot's flexible waist allows it to rotate its body, coordinate various actions and increase sports performance. Based on this article, we plan to make our LAIKA robot dog more flexible thanks to the servo motors in its legs.

In the article "Intelligent walking movements and control for a legged robot" written by B.L.Luk et al. in 1999, walking and climbing of a robot operated with pneumatic actuators are mentioned. Using this article as a reference, we determined the advantages and disadvantages between using a pneumatic actuator and a servo motor.

In the article "A BioInspired Neural Controller For a Mobile Robot" written by Michele Folgheraiter et al. in 2006, they focus on the role of biorobotics in the development of service robotic systems that can navigate in complex and dynamic environments and avoid obstacles. Based on this article, our LAİKA robot dog can be used in open fields just like a living dog. We aim to show movement.

In the study "Bio-Inspired Hexapedal Firefighting Robot" by Kirkland Boyd and his colleagues in 2022, they talk about the design and development of an autonomous legged robot designed to detect and extinguish candle flames. Based on this article, we plan to use our LAIKA robot dog in firefighting duties with the equipment we will place on it in the future.

In the article "Layout and Construction of a Hexapod Robot with Increased Mobility" written by Jan Paskarbeit and his friends in 2010, they talk about the advantages and disadvantages of two-legged and six-legged robots against each other. We determined our design requirements by evaluating the advantages and disadvantages in this article.

III. Design and Hardware

The LAIKA project, with its Quadruped structure and 12 servo motors, stands out for its impressive capabilities. The robot measures approximately 50 cm in length, 25 cm in width, 30 cm in height, and weighs 1 kg. It is designed to lift a load equal to its own weight. Additionally, LAIKA's ability to jump up to about 30 cm enhances its utility in various applications.

The Quadruped structure is expected to provide superior mobility, especially in rough terrain. This feature enables the robot to perform tasks such as field exploration and terrain mapping. The fast and agile movements provided by its 12 servo motors will allow it to make quicker turns compared to other Quadruped robots.

A specially designed algorithm for LAIKA's servo motors will use data from horse gait analyses to generate kinematic coordinates and servo angle values. This will enable the robot to perform actions such as walking, turning, bending, balancing, and jumping.

The camera and other sensors on the robot will enable it to perform tasks like object detection and Visual Odometry. LAIKA will use this information to determine its position and plan its movements accordingly.

The LAIKA project can be operated in two different modes: autonomous and manual. Furthermore, the robot can transmit data such as battery status and location to a cloud system, enabling remote access. This feature will provide users with real-time information about LAIKA's status.

A digital twin is a concept that involves creating a digital model of a real object, as in the LAIKA autonomous dog project, and performing design, testing, and simulation processes on this model. In this context, LAIKA's digital twin includes simulations of algorithms, sensors, and mechanical systems used from the beginning of the project design.

The importance of a digital twin lies in detecting potential errors and problems that might occur in the real world, optimizing the design, and improving performance through tests and simulations conducted in the early stages of the design process. Simulation tools like MATLAB are crucial helpers for engineers in identifying design flaws, optimizing algorithms, and evaluating system performance. Digital twins are used to identify design errors and deficiencies before producing a physical prototype. This reduces costs, accelerates the production process, and allows for the evaluation of important factors like energy efficiency in advance. Additionally, they enhance the reliability of the design by predicting problems that may arise during real-world testing. Therefore, digital twins are an essential tool contributing to the successful completion of complex projects.

A. *Servo Motor*

Servo motors play a crucial role in mechatronic projects like our robot dog. The most prominent feature of these motors is their ability to precisely hold a specific position with high accuracy. This allows for the legs or joints of our robot dog to be positioned accurately at desired angles. This precise control ensures that the movements of our robot dog are more natural and controlled. Moreover, the ability to precisely control the speed of the servo motors enriches our robot's mobility and allows for more realistic movements.

Another important feature of servo motors is their feedback mechanisms. These mechanisms enable real-time tracking of the motor's position, aiding in the efficient and accurate adjustment of the robot's movements.

Servo motors are also ideal in terms of ease of use. Generally user-friendly, these motors can be integrated into projects with simple connections, saving time and effort in mechatronic projects. The availability of servo motors in different sizes and power options offers the flexibility to choose according to the needs of the project. Selecting motors with different speed and torque combinations can enable our robot dog to move appropriately for various applications and terrains.

The rapid response times of servo motors are also important. This feature allows our robot dog to quickly adapt to sudden movements or changes. Additionally, the ability of servo motors to produce a consistent torque at a specific position offers a significant advantage in terms of energy efficiency. This enables the robot to operate for extended periods while conserving energy.

Depending on our project requirements and design goals, other types of motors or actuators might also be considered. The modular structure of our robot dog is designed to support leg designs with different speed and torque combinations, enhancing the flexibility and adaptability of our project. These features are fundamental for our robot dog to effectively work in various environments and conditions.

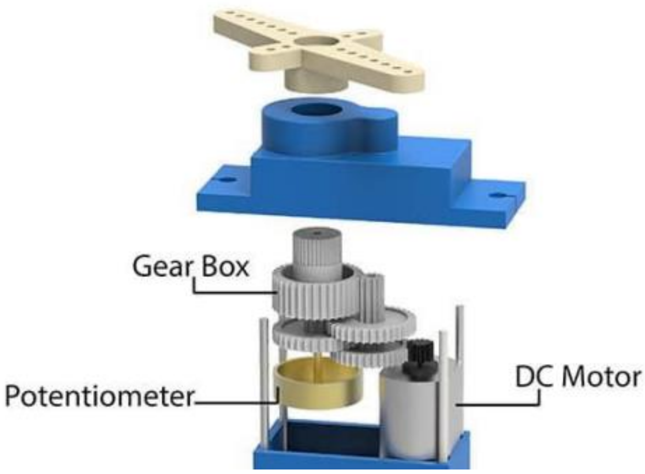

Figure 1 Servo Motor Internal Structure

B. *Modular Structure*

Our project is based on a modular robot dog design that adapts to the unique needs of users and environmental conditions. The main body of the robot offers an optimal structure in terms of robustness and functionality, while interchangeable legs enhance the diversity and flexibility of the project. This modular design gives users the opportunity to customize their robots for different terrain types, mobility capabilities, and tasks. For instance, legs designed for more challenging terrain conditions improve the robot's balance and mobility, whereas legs optimized for flatter surfaces offer advantages in speed and efficiency.

The primary focus of the project includes the robot's durability, adaptability, and user-friendly interface. The materials and design used in the robot's structure are chosen to provide a long-lasting and resilient usage. Adaptability allows the robot to easily conform to different scenarios; this requires a flexible platform in both software and hardware. The user-friendly interface simplifies the processes of setting up and programming the robot, facilitating user interaction with their robots. These features enable the robot to appeal to a wide range of users and be effectively used in various application areas.

The main goal of this project is to make robotic technology more accessible and applicable. The modular design broadens the robot's range of use, while allowing users to make customizations according to their own needs. This encourages innovation in the field of robotics and assists a broad spectrum of users to benefit from robot technology. Our project is designed to realize this vision and aims to be a significant step forward in this field.

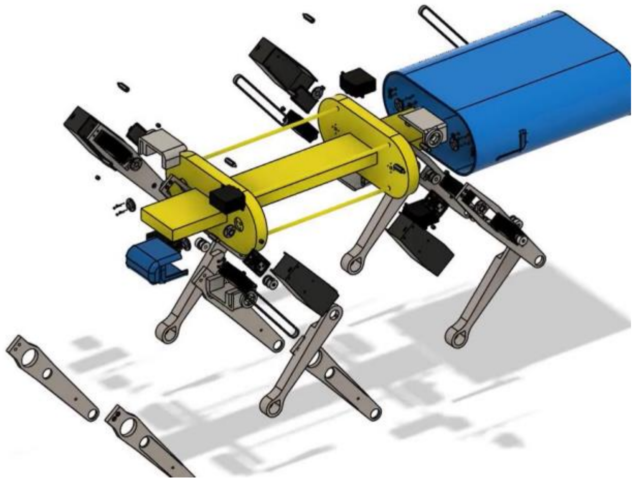

Figure 2 Modular Structure Demonstration

C. Body and Microcontrollers

The body serves as the central control unit of the robot and contains an Arduino UNO microcontroller platform for testing purposes, which will be followed using ESP-based microcontrollers in each leg. The Arduino UNO represents the brain functions of the robot and manages all movements, perceptions, and decision-making processes. The selection of this microcontroller platform is advantageous due to its reliability and the extensive user and developer community.

Another important role of the Arduino UNO in our project is its capability to communicate instantaneously with MATLAB software. MATLAB is a powerful software widely used in engineering and scientific calculations. This feature offers significant advantages in monitoring and analyzing our robot's performance, as well as in real-time control and adjustments. This communication allows for the optimization of our robot dog's movements and responses, and the implementation of more complex tasks and algorithms. Additionally, MATLAB's visual interface and analytical tools facilitate and accelerate the development process of our project.

The design of the body and the integration between Arduino UNO and MATLAB ensure efficient and effective operation of our robot dog. This integration enhances the robot's ability to collect, process, and respond to environmental data. Moreover, this structure enables the robot to quickly adapt to changing situations and needs, making it useful in various application areas. Overall, this integrated system plays a critical role in the development of our robot as an intelligent, flexible, and user-friendly platform.

D. Legs

Our robot's legs feature a special structure reminiscent of the wheel connections in Formula 1 cars. This design facilitates the easy and effective mounting of the legs to the robot's body. The connection made through screws ensures that the legs are securely attached and can be easily replaced when necessary. This modular approach allows the robot to be rapidly adapted to different conditions and needs.

In terms of motorizing the legs, our project offers considerable flexibility. Different types of motors can be installed in the legs, enabling the robot to operate efficiently in environments with varying levels of difficulty. For instance, motors with higher torque capacities can be chosen for carrying heavy loads or operating in challenging terrain conditions. These types of motors allow the robot to perform more effectively in power-demanding situations.

On the other hand, more speed-focused motors can be used in situations where speed is crucial. These motors enable the robot to move faster and cover larger areas in a shorter time. This is particularly beneficial in time-critical scenarios such as search and rescue missions, where the robot's effectiveness is paramount.

This modular and flexible leg design allows our robot to adapt to a wide variety of application areas. Each motor type can be optimized for a specific task or environment, ensuring the robot performs at its best in every situation. Overall, this approach expands the usability of our robot and helps it deliver maximum efficiency and effectiveness in any circumstance.

Figure 3 Leg Design

E. Power Source

In our project, each leg of the robot dog receives its power needs from a central power connector located in the main body. This design eliminates the need to run separate power and data cables to each leg, thereby avoiding complex and cluttered cable connections. Thanks to this central connection point, both data transmission and power supply are managed from a single location, making the robot's design both aesthetically pleasing and practically tidy.

This approach has several advantages. Firstly, connecting and maintaining the legs becomes much simpler. Instead of dealing with numerous cables when changing or repairing the legs, you only need to disconnect from the central point. Secondly, this design enhances the overall reliability of the robot. Using fewer cables reduces the number of potential failure points and increases the system's durability.

Additionally, centralizing all power and data transmissions simplifies the management of the robot's electronic systems. This is particularly beneficial during programming and debugging, offering significant ease of use. For users, this translates to a more understandable and accessible robot.

In conclusion, this integrated power and data transmission system ensures our robot possesses a design that is superior both functionally and aesthetically. This not only allows the robot to operate more effectively and efficiently but also simplifies usage and maintenance processes.

F. Business Advantage

The various leg options we offer in our project have the potential to meet the needs and expectations of a broad customer base. These modular legs, with their easy and fast connection mechanism, allow users to effortlessly customize their robots without complex wiring procedures. This offers customers a flexible way to adapt their robots for different situations and tasks.

Users can customize their robots according to their specific needs, from terrain mobility to load-carrying capacity. For instance, legs designed for challenging terrain conditions enhance the robot's balance and navigation capabilities; whereas legs designed for flat and hard surfaces offer advantages in speed and efficiency. This flexibility enables users to employ their robots in various scenarios, such as search and rescue missions, warehouse management, or as personal assistants.

Another advantage of this modular design is economic efficiency. Users can update their robots without purchasing a new model, which is significant both in terms of cost-effectiveness and environmental sustainability. The modular structure of the robot offers long-term benefits of less waste and lower costs, with continuous improvement and adaptation.

In conclusion, this modular approach of our project makes our robot dogs suitable for different application areas while offering a user-friendly, flexible, and economical solution. These features make our project competitive and attractive in the market, creating a wide range of uses that meet various customer needs."

IV. REALIZATION AND MANUFACTURING

A. Business Plan

1) Literature Review

A literature review allows us to deeply understand the mathematical challenges our project may face and to determine the most suitable mathematical models and solution strategies to overcome these challenges. This process helps to strengthen the scientific validity of our project and solidify its mathematical foundations by examining similar studies. The key to success lies in correctly applying the knowledge found in the literature to our project, enhancing the system's performance with mathematical models, and bringing our project to a level comparable with other similar studies. This approach will ensure that our project is built on a strong foundation both scientifically and practically, contributing to achieving the targeted results.

2) Mechanical Design

The information obtained from the literature is of great importance in achieving a mechanical design that meets the specific requirements of our project. This process involves carefully analyzing the information in the literature and integrating it with the specific needs of our project, enabling us to create a design that is both functional and innovative. This approach will enhance the success of the project and allow the design to be tailored in a way that fully serves the objectives of the project. Consequently, combining the insights from the literature with the unique requirements of our project will contribute to making our design process more efficient and effective, and support the overall success of the Project.

3) Supply of Components

The procurement of mechanical and electronic components is critical for the successful completion of the project. The quality, durability, and precision of mechanical parts will have a direct impact on the robot's mobility and overall performance. Properly sourcing electronic components will determine the robot's sensing, control, and communication capabilities.

4) Digital Twin Design

The Digital Twin Design plays a vital role in the success of our project. From the onset of the project, simulations conducted through this design allow us to pre-evaluate the interactions between the servo motors, algorithms, and sensors that will be used. As a result, the digital twin provides engineers with a valuable tool in the early stages of the design process for identifying potential errors, optimizing and correcting these errors. The in-depth analysis and preliminary evaluation capabilities offered by the digital twin significantly contribute to the project's more effective and error-free progression, thus enhancing the efficiency of the design process and supporting the overall success of the Project.

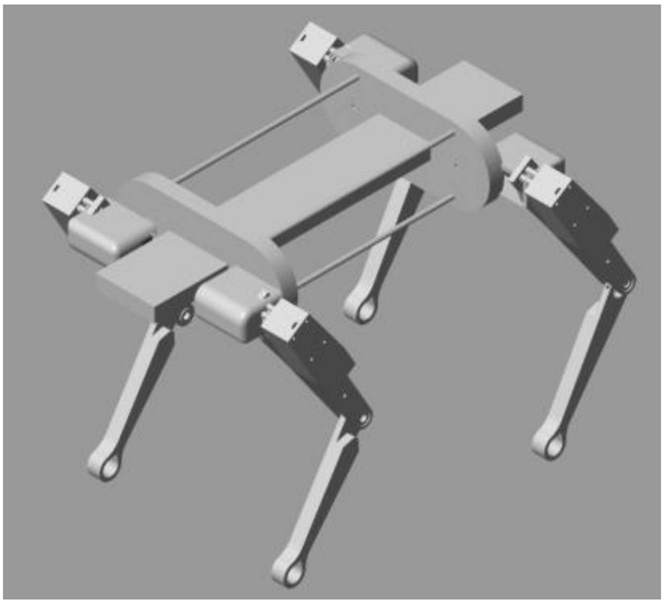

Figure 4 Digital Twin Image

5) Mechanical Analysis

The ability of the designed CAD parts to withstand stress without deforming and to be long-lasting defines the success criteria of the project. In this context, analyzing the stresses on CAD parts to ensure their mechanical strength and achieving a durable design are fundamental goals of the project. Meeting these criteria indicates the success of the design in terms of strength and durability. Furthermore, stress analysis in CAD parts is a crucial source of data for calculating and adjusting the robot's center of gravity, which is essential for ensuring the robot operates in a balanced and stable manner.

6) Analyzing Horse Walk

The established success criterion involves planning the robot's walking mechanism in accordance with the advantages and disadvantages of horse gaits. This indicates that information derived from horse gaits will be fundamental in determining the robot's walking strategy. In terms of contribution, it is considered that understanding different walking styles of various dog breeds presents a challenging information acquisition process. However, the analysis of horse gaits provides a more accessible accumulation of knowledge, enabling a more effective implementation of the robot's walking planning.

7) Designing a walking algorithm

The goal can be summarized as achieving the desired angle values for the servo motors. Using coordinate data obtained from gait analysis, we calculate the required degree of movement for each leg and, based on these calculations, provide the appropriate angle values to the servo motors.

8) Electronic design and electrical connections

Electronic design encompasses the control systems, sensors, and movement mechanisms of the project; the harmonious operation of these components is vital for the robot to perform the desired movements and functions. Additionally, establishing correct electrical connections ensures the device operates safely and enhances energy efficiency, thereby supporting the success of the project. Proper execution of the electronic design and electrical connections minimizes potential issues during the project process, increases the project's reliability, and ultimately enables LAIKA to successfully fulfill its intended tasks.

9) Performing general assembly and connection tests

These tests assess the practical suitability of the theoretical stages of the design process and provide an opportunity to identify and correct any assembly errors. They also ensure the integrity of the system by checking the healthy functioning of connections between different components. General assembly and connection tests are a fundamental assurance for the project to operate smoothly under real-world conditions and represent a crucial step in ensuring the hardware components work together harmoniously.

10) Test Track Design

The test course design holds critical importance in the LAIKA autonomous dog project. This design provides an environment to assess the robot's performance in real-world conditions and test its reliability. The test course is used to understand how the robot behaves in various scenarios, such as emergency situations, rescue operations, and military use. This allows for the pre-evaluation of the effectiveness of algorithms and sensors, and crucial features like mobility and balancing in real-world applications.

11) Basic Movement Test

Initially, a simple walk test is planned to evaluate the stages of the robot that have been completed so far. Subsequently, the robot is intended to successfully detect an obstacle it encounters and demonstrate an appropriate response, such as jumping over or climbing onto the obstacle. This process will provide an assessment to test the robot's overall performance and measure its ability to overcome obstacles in its path.

12) Basic motion optimization based on test data.

This optimization aims to ensure that the algorithms and servo motors operate in the most effective and efficient manner suitable for real-world conditions. Optimization based on test data will enable the dog to move quickly and accurately, maintain balance, and adapt to various environments. This enhances project success, maximizes energy efficiency, and allows the dog to perform its tasks more effectively.

13) Communication with cloud system

The cloud system enables the central storage, processing, and sharing of information gathered from the sensors and other data sources of the robot. As a result, LAIKA's digital twin is continuously updated and improved, design flaws are rapidly identified and corrected, and the project can be managed remotely by the team.

14) Object tracking with artificial intelligence.

This is the final stage of our project. If we have reached this stage carefully, our success can be definitively confirmed. We must be diligent to ensure there are no leaks in the hose connections. During aerial spraying, we need to monitor stability and be able to adapt the system immediately in case of any slippage. This final stage in achieving project success is of critical importance.

15) Outdoor Tests.

Outdoor field tests provide important insights into how the hardware and software respond under various challenging environmental factors. These tests also offer the opportunity to assess the accuracy of sensors, the practical effectiveness of algorithms, and the performance of the robot in real-world applications. The data obtained from outdoor field tests are used to improve project design and to identify potential issues in advance, thereby increasing the overall chances of the project's success.

B. Risk Management

1) Errors caused by servo motors.

Firstly, a detailed problem analysis should be conducted to identify the root causes of the errors. For fabrication errors, communication with the manufacturer is necessary. Software errors often stem from algorithmic issues or parameter settings; in such cases, reviewing the software and optimizing algorithms may be required. Additionally, using feedback systems (e.g., encoders) can enable more precise control of motor positioning. Regularly utilizing testing and simulation processes to better mimic real-world conditions and identify weaknesses in the design is also crucial.

2) Errors caused by IMU Sensor

It is essential to properly calibrate sensors and repeat this process regularly. Additionally, updating and improving the algorithms used to process and interpret sensor values is important. Employing filtering techniques and data processing algorithms can reduce noise and provide accurate data.

3) Problems caused by cost.

Modular design allows for each module to be optimized independently and for errors to be identified and corrected. This has been identified as the most important method for an economical solution. In this process, potential incompatibilities should be identified in advance through frequent testing and verification stages, and quick solutions should be found. Additionally, a proactive approach should be adopted by continuously updating and revising to maintain software-hardware compatibility.

V. Equations

A. Kinematic Equations

To enable our robot's mobility, its four legs, each housing three servo motors, need to step in a coordinated manner. This requires the simultaneous and precise control of a total of twelve servo motors. Kinematic equations, which take inputs in degrees and produce outputs, are crucial for the legs to reach the desired points effectively and accurately.

The following equation only involves two servo motors and is valid for two-dimensional (x and y axes) movements, but is not suitable for rotational movements.

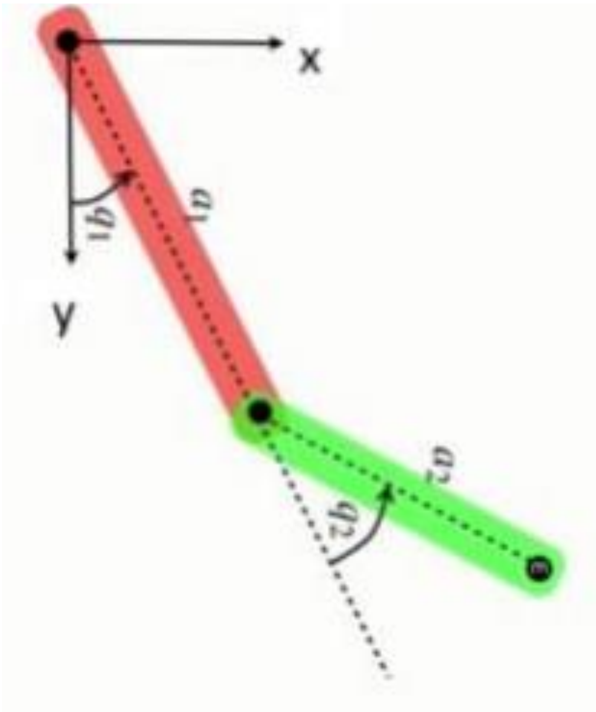

Figure 5 Dual Servo Kinematic Equation

$$\cos q_2 = \frac{y^2 + x^2 - a_1^2 - a_2^2}{2a_1 a_2}$$
$$q_2 = cos^{-1}(\frac{y^2 + x^2 - a_1^2 - a_2^2}{2a_1 a_2})$$
$$q_1 = tan^{-1}\frac{x}{y} - tan^{-1}\frac{a_2 \sin q_2}{a_1 + a_2 \cos q_2}$$

To enhance our robot's ability to perform rotation movements, quickly adjust its balance, and improve its overall mobility, we have added additional servo motors to the shoulder sections. These new servo motors enable the robot to perform more complex movements with ease. Additionally, we have updated our robot's kinematic equation to support three-dimensional movements (x, y, and z axes). This updated kinematic equation allows the robot to perform more precise and coordinated movements along each axis.

Thanks to these innovations, the movement capabilities of our robot have significantly improved. The three-dimensional kinematic equation assists the robot in effectively moving across more complex and varied surfaces, overcoming obstacles, and efficiently fulfilling its tasks. As a result, the robot's movement mechanism gains a more flexible and adaptive structure, allowing access to a wider range of motions.

$$q_3 = tan^{-1}(\frac{z}{y}) h = \sqrt{z^2 + y^2}$$
$$q_2 = cos^{-1}(\frac{h^2 + x^2 - a_1^2 - a_2^2}{2a_1 a_2})$$
$$q_1 = tan^{-1}\frac{x}{h} - tan^{-1}\frac{a_2 \sin q_2}{a_1 + a_2 \cos q_2}$$

B. Jump Scenario

To analyze the jumping capability of the robot, we first calculated the linear velocity of the legs based on the angular velocity and the length of the legs. The linear velocity was calculated using the given angular velocity in degrees per second for each leg of the robot and the lengths of the legs. The linear velocity is obtained by multiplying the angular velocity with the leg length.

Subsequently, based on this linear velocity, we calculated the kinetic energy generated in each leg. The kinetic energy provided by each leg depends on the dynamics of the movement and the mass of the leg. To find the total kinetic energy of the robot's four legs, we added up the kinetic energies of each leg. This total energy is the main factor determining the robot's jumping ability.

The total kinetic energy derived from all four legs of the robot has a significant impact on its mobility.

$v = r * \omega$ *(Generation of linear velocity of robot leg)*

$K = \frac{1}{2} m v^2$ *(Kinetic energy generated in one leg of the robot)*

$E = 4 * K$ *(kinetic energy generated in all legs)*

$h = \frac{E}{mg}$ *(height it can reach with the kinetic energy generated)*

Finally, we converted this total kinetic energy into height, considering the robot's mass and the acceleration due to gravity. The height is calculated by converting the total kinetic energy into gravitational potential energy. This calculation indicates how high the robot can theoretically jump and is a measure of the robot's jumping capability.

VI. Software

In our robot, the positions the legs need to reach (relative to the robot's center) are defined in matrix form in the software. Our software system performs operations on this position matrix, calculating the necessary angles for the legs to reach the desired positions. In this calculation, the lengths of the legs are considered to ensure the correct angles are determined. The code for this is provided in the Appendices Section under the title “DOF_3_Inverse Function”.

The angle values we obtain are subjected to a detailed observation process on our digital twin designed in the Simulink environment. At this stage, we conduct a comprehensive evaluation to understand the overall performance of the system by examining how each leg segment and joint movement is reflected in our digital twin. Additionally, we use the obtained angle values to simulate the behavior of the digital twin and observe how it reacts to possible scenarios. The Simulink Model we designed is provided in “Figure-6”.

Using the data obtained through the virtual sensors in our digital twin, we transfer the movements conducted in the Simulink environment to our real robot through an Arduino microcontroller. During this process, we monitor the internal state of the digital twin in real-time using the information provided by the virtual sensors and evaluate the control strategies we developed based on this data. The codes facilitating this entire process are provided in the Appendices Section under the title “MATLAB Code for Quadruped Robot”.

A. Why MATLAB

MATLAB (Matrix Laboratory) is a high-level programming language used for a wide range of technical computing. It is especially important for matrix manipulations, numerical computations, data analysis, plotting graphs, modeling, and simulation. MATLAB is a preferred tool across various scientific disciplines, from engineering to physics and mathematics, and from computer science to biomedical engineering.

One of the major advantages of MATLAB is its effectiveness in rapid prototyping and algorithm development. Additionally, its ability to simulate complex physical systems allows researchers and engineers to test theoretical models in real-world scenarios. This feature is particularly revolutionary in fields like robotics and automation.

In our project, we converted the design files of our robot dog, which are in STL format, into a digital twin using MATLAB's Simscape Multibody Toolbox. This allowed us to closely observe our robot dog's digital twin through MATLAB's Model Explorer. This process played a critical role in understanding the robot's mobility and mechanical limitations.

Moreover, MATLAB’s powerful mathematical computing capabilities effectively run the robot's kinematic equations and control algorithms. During this process, MATLAB's user-friendly interface and comprehensive function library helped us to solve complex mathematical problems quickly and effectively.

Additionally, we visualized angular values obtained from the virtual sensors in our digital twin as graphs using MATLAB tools. These visualizations enabled us to better understand the robot's behavior and make necessary adjustments.

Using the MATLAB Support Package for Arduino Hardware, we controlled the Arduino UNO and its connected servo motors connected to the Serial port, based on the angular values obtained from our digital twin. This integration allowed us to establish a seamless connection between the digital and physical worlds, directly linking our theoretical models to real-world applications.

In conclusion, the extensive feature set of MATLAB provided significant advantages at every stage of our project. The flexibility and power offered by MATLAB were critical factors in the success of our project. Especially in rapidly evolving fields like robotics and automation, the use of a comprehensive and effective tool like MATLAB enables the development of innovative and effective solutions, making it an indispensable tool for such projects.

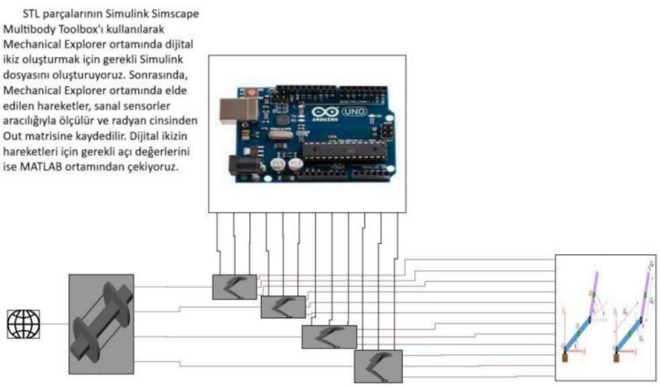

Figure 6 Simulink Design

VII. TESTING AND VERIFICATION

In our robot dog's digital twin created in the MATLAB environment, we determined specific position values in a matrix format to coordinate the movements of each leg. These values were designed to ensure that the robot's legs move simultaneously and efficiently. In our digital twin, these position values were sampled according to our chosen sampling frequency (20 Hz).

Subsequently, we applied these samples to the servo motors of our real robot through the Arduino microcontroller platform. This process was carried out to accurately reflect the movements in the digital twin on our real robot. The microcontroller implemented the position data from MATLAB in real-time by activating the robot's servo motors at appropriate intervals. Thus, the movements of our robot dog were harmonized with the movements designed and simulated in the digital twin.

We receive the angle values applied by the servo motors of our robot dog through the Arduino microcontroller, which communicates continuously with the MATLAB environment. These values are read and applied by the Arduino in real-time. We developed an interface to graphically display these servo angle values in the MATLAB environment. This allows us to monitor the movements and performance of the servo motors instantaneously.

Due to the quality of the servo motors, we used, the weights of our robot dog's legs, and the torques generated during movements, the motors sometimes cannot reach the desired angles precisely. These deviations can become more pronounced, especially in movements requiring high torque or when the center of gravity shifts. To resolve these issues, we thoroughly analyzed the response times and torque capacities of the servo motors in our system. Additionally, we optimized the structural design and weight distribution of the legs to reduce the load during movement.

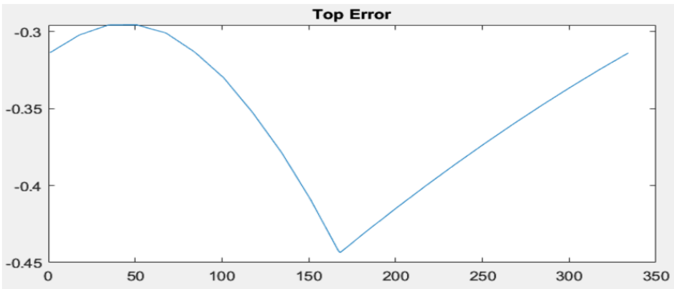

Figure 7 Angle Errors in a Servo

During the test process, we applied special processes to adapt the angle matrices generated by our digital twin in the MATLAB environment to the physical movement capabilities of our robot dog. During these processes, we used MATLAB's Arduino Toolbox feature. The Toolbox limits the angular movements of the servo motors to 180 degrees, which allows us to simulate the movement capabilities of real-world servo motors.

We adjusted the angle matrices according to the physical positions and movement limitations of the servo motors used in our real robot dog. These adjustments involved scaling and transforming the data from the digital twin to consider the physical constraints of the real world. For example, some angle values were not feasible due to the mechanical limits of the servo motors; hence, we adjusted these values to fit within the real movement ranges of the motors.

All these procedures were integrated as part of our software, so they could be automatically executed during each test and application. This integration allows us to control the movements of our real robot more accurately and effectively, achieving a high level of harmony between the digital twin and the physical robot.

In our system, the communication between MATLAB and Arduino and the low sampling frequency of the samples taken from the digital twin are among the primary reasons for movement issues in our real-time robot. The low sampling frequency leads to the robot's movements not being sufficiently precise in real-time, especially during complex or fast movements.

On the other hand, when we increase the sampling frequency, we encounter a new problem due to the limitations in the communication speed between MATLAB and Arduino. The higher sampling frequency means more angle values need to be calculated and transmitted. This situation results in the data transfer speed in MATLAB-Arduino communication being insufficient, leading to a slowdown in real-time movements, particularly problematic when the robot needs to respond quickly.

In our test scenario for the system, we made each leg move forward in a sinusoidal wave pattern and then retract back to the starting point along the horizontal axis. This scenario was designed to test the accuracy and fluidity of the movements of our robot dog's legs. The forward and backward movements of the legs were adjusted to create a natural and smooth walking rhythm, allowing us to closely examine the robot's balance and mobility.

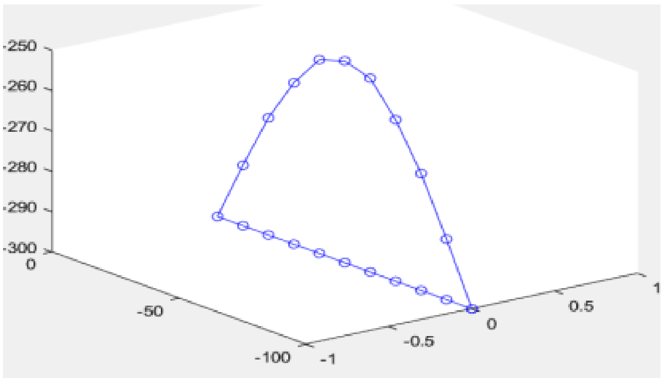

Figure 8 Test Case

To more comprehensively test the mobility of the shoulder servo motors and the 3-axis kinematic equations, we moved each leg to trace a square of 1 cm size on the X-Y plane. This test was crucial in verifying the precision of the robot's shoulder servos and the accuracy of our kinematic model. The square-shaped movement allowed us to assess the accuracy of the robot's leg movements, the angular control of the servo motors, and the overall mechanical structure.

During these complex movements, critical parameters such as the response time, torque capacity, and motion accuracy of each servo motor in our system were observed. Additionally, the dynamic loads and mechanical stresses generated during the robot's movements were analyzed. These tests enabled us to understand how the robot's kinematic model performed under real-world conditions and allowed us to make the necessary improvements.

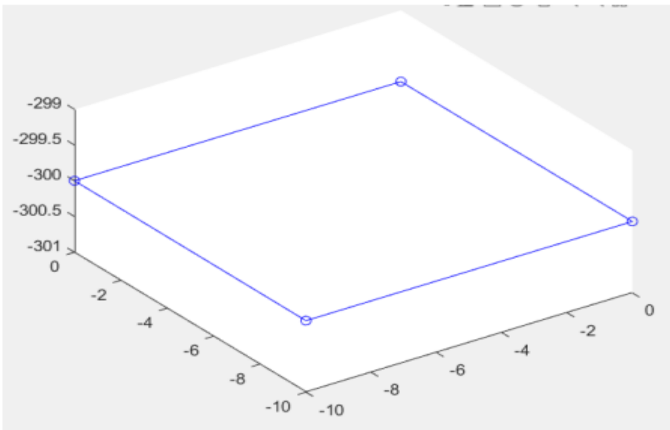

Figure 9 Shoulder Test Case

VIII. FUTURE STUDIES

Based on this project, we aim to conduct extensive academic research on the use of artificial intelligence in articulated leg robots and the development of autonomous driving algorithms in such robots. Our project is specifically designed for primary use in search and rescue, military, and logistics fields. We aim to equip our robot with the necessary hardware and software capabilities to operate effectively and reliably in challenging conditions in these areas. Additionally, we see significant potential in health and child development sectors; for example, in hospital medication distribution or interactive games to aid in children's motor skill development.

We plan to showcase our robot dog on various platforms to reach a wide audience, hoping to gather significant interest and demand. The diversity and innovative features of our project not only attract public attention but can also be seen as a significant leap in the field of robot technology. In this context, considering the modular structure and innovative features of our project, we aim to file relevant patents or utility model applications. This will protect our technological innovations and maximize their commercial potential.

We expect our project to lead new research topics in the future, such as robot kinematics, autonomous algorithms, kinematic and sensor technologies. Innovations in these areas will enable our robot to have more advanced capabilities and increase its applicability across a wide range of uses. In line with this, we will continue our work by closely following technological developments and constantly producing innovative solutions.

This broad vision of our project aims to create a significant impact both academically and industrially and strives to push the boundaries of robot technology.

IX. Results and Discussion

This work extensively examines the mechanical, software, and electronic designs of a four-legged robot named LAIKA, developed as part of a capstone project by students of the Mechatronics Engineering department at Marmara University. The development of LAIKA, the robot dog, aims to apply the fundamental principles of mechatronics engineering and offer an innovative robotic solution. The project's overall objectives and expected outcomes are set to follow and implement innovations in robotics and mechatronics.

In the literature review section, existing academic and industrial studies on quadruped robots and robotic dogs are thoroughly explored. This research focuses on the successes, challenges, and solutions of similar projects, thereby enabling the LAIKA project to be built on stronger foundations.

The mechanical design section deals with LAIKA's mechanical structure, materials used, mobility capabilities, and structural durability. The robot's movement mechanisms, challenges encountered during the design process, and methods for overcoming these challenges are detailed. The electronic hardware section reviews the robot's electronic components, control systems, and power management, providing in-depth information on the selection and integration of sensors, motors, and other electronic parts.

The manufacturing process section covers LAIKA's production stages, manufacturing techniques used, and assembly processes. The creation of the prototype and the challenges faced during production are addressed in detail. The software development section focuses on programming the robot, designing algorithms, and testing the software, discussing how software influences the robot's mobility and the challenges encountered in software development.

The test processes section includes tests conducted to assess LAIKA's performance, mobility, and durability, and the results of these tests. The data obtained from these tests are crucial for further improving the robot. The risk management section discusses the risks encountered throughout the project and how they were managed, focusing on risk mitigation strategies and project management techniques, contributing to the successful completion of the project.

In conclusion, the experiences gained from the design and development process of the LAIKA robot dog provide valuable insights and suggestions for future robotic projects. This study demonstrates the Mechatronics Engineering students' ability to translate theoretical knowledge into practice and develop innovative solutions.

The primary purpose of this study is to explore and advance the use of digital twin technology in the field of quadruped robots. A digital twin, through real-time data flow and simulations, creates a virtual copy of the physical robot, allowing for a more effective understanding and optimization of the robot's performance, behaviors, and potential issues. This approach enables better forecasting of scenarios the robot might encounter in real-world applications and improves decision-making processes.

Additionally, this project aims to develop a robot with high mobility capabilities. Mobility is crucial in terms of the robot's performance and adaptability in various ground conditions and when encountering obstacles. This goal is supported by the development of the robot's mechanical design, control algorithms, and sensor systems.

Finally, the project emphasizes a modular structure. Modular design facilitates the robot's adaptation to different tasks and environmental conditions. This allows for easy modification or upgrading of the robot's parts and functions, enhancing the robot's long-term use and flexibility. The development of a modular structure also simplifies maintenance and repair processes, thus increasing the robot's operational efficiency and reliability.

Each of these goals has been a priority in the capstone project of the students in the Mechatronics Engineering department at Marmara University, with extensive work conducted in these directions. The three primary objectives of the project have the potential to introduce significant innovations and advancements in the field of robotics and enable the students to reinforce their practical knowledge and skills in this area.

The design of the LAIKA robot dog is notable in terms of size and mobility. Measuring approximately 50 cm in length, 25 cm in width, and 30 cm in height, and weighing about 1 kg, it demonstrates a compact and lightweight structure. These dimensions allow the robot to move effectively in various environments, while its lightness contributes to energy efficiency and ease of movement.

The mobility of the robot is maximized using 12 servo motors. These motors endow LAIKA with agile and precise movements. Each servo motor controls the legs of the robot, enabling balanced and coordinated movements even in complex ground conditions. This mobility facilitates effective navigation in challenging terrain conditions and successful completion of various tasks.

Another significant aspect of the project is LAIKA's digital twin. This digital twin simulates the algorithms, sensors, and mechanical systems used from the project's inception. It provides valuable insights during the design and testing phases by modeling scenarios the robot may encounter in the real world. This accelerates the design process and allows for preemptive solutions to potential problems.

The kinematic design of the robot has also been meticulously addressed. The kinematic equations calculated for the three servo motors in each leg were initially designed for two servo motors and later developed to control the movements of three servo motors across three axes. This kinematic adjustment increases the robot's range of motion and flexibility, allowing for more complex movement scenarios.

These design features indicate that LAIKA is not just a technical achievement but also a significant innovation in the field of mechatronics engineering. The robot's compact size, advanced mobility, and use of a digital twin demonstrate how this project advances developments in the field of robotics.

REFERENCES

[1] *R. Liang et al., "A General Arthropod Joint Model and its Applications in Modeling Human Robotic Joints," in IEEE Access, vol. 9, pp. 7814-7822, 2021, doi: 10.1109/ACCESS.2021.3049469.*

[2] *R. Liang et al., "A General Arthropod Joint Model and its Applications in Modeling Human Robotic Joints," in IEEE Access, vol. 9, pp. 7814-7822, 2021, doi: 10.1109/ACCESS.2021.3049469.*

[3] *M. Folgheraiter, G. Gini, A. Nava and N. Mottola, "A BioInspired Neural Controller For a Mobile Robot," 2006 IEEE International Conference on Robotics and Biomimetics, Kunming, China, 2006, pp. 1646-1651, doi: 10.1109/ROBIO.2006.340191.*

[4] *E. F. Fitcher and B. L. Fichter, "A survey of legs of insects and spiders from a kinematic perspective," Proceedings. 1988 IEEE International Conference on Robotics and Automation, Philadelphia, PA, USA, 1988, pp. 984-986 vol.2, doi: 10.1109/ROBOT.1988.12188.*

[5] *N. Harvey and A. L. Nel, "Arachnid-inspired kinesthesia for legged robots," 2015 Pattern Recognition Association of South Africa and Robotics and Mechatronics International Conference (PRASA-RobMech), Port Elizabeth, South Africa, 2015, pp. 245-251, doi: 10.1109/RoboMech.2015.7359530.*

[6] *K. Boyd, "Bio-Inspired Hexapedal Firefighting Robot," 2020 IEEE MIT Undergraduate Research Technology Conference (URTC), Cambridge, MA, USA, 2020, pp. 1-4, doi: 10.1109/URTC51696.2020.9668907.*

[7] *A.G. Lamperski, O. Y. Loh, B. L. Kutscher and N. J. Cowan, "Dynamical Wall Following for a Wheeled Robot Using a Passive Tactile Sensor," Proceedings of the 2005 IEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005, pp. 3838-3843, doi: 10.1109/ROBOT.2005.1570706.*

[8] *B Kwak, D. Lee and J. Bae, "Flexural Joints for Improved Linear Motion of a Marangoni Propulsion Robot: Design and Experiment," 2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob), Enschede, Netherlands, 2018, pp. 1321-1326, doi: 10.1109/BIOROB.2018.8488118.*

[9] *B.L. Luk, S. Galt, D. S. Cooke and N. O. Hewer, "Intelligent walking motions and control for a legged robot," 1999 European Control Conference (ECC), Karlsruhe, Germany, 1999, pp. 4756-4761, doi: 10.23919/ECC.1999.7100087.*

[10] *J. Paskarbeit, J. Schmitz, M. Schilling and A. Schneider, "Layout and construction of a hexapod robot with increased mobility," 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, Tokyo, Japan, 2010, pp. 621-625, doi: 10.1109/BIOROB.2010.5626605.*

[11] *Y. Guan et al., "Structure Design and Motion Planning of a Reconfigurable Robot with Flexible Waist," 2023 9th International Conference on Electrical Engineering, Control and Robotics (EECR), Wuhan, China, 2023, pp. 1-4, doi: 10.1109/EECR56827.2023.10150029.*

[12] *B. He, Z. Wang, M. Li, K. Wang, R. Shen and S. Hu, "Wet Adhesion Inspired Bionic Climbing Robot," in IEEE/ASME Transactions on Mechatronics, vol. 19, no. 1, pp. 312-320, Feb. 2014, doi: 10.1109/TMECH.2012.2234473.*

[13] *B. Ma, Z. Liu, C. Peng and X. Li, "Trotting gait control of quadruped robot based on Trajectory Planning," 2021 4th World Conference on Mechanical Engineering and Intelligent Manufacturing (WCMEIM), Shanghai, China, 2021, pp. 105-108, doi: 10.1109/WCMEIM54377.2021.00031.*

[14] *Biswal, P., & Mohanty, P.K. (2020). Development of quadruped walking robots: A review. Ain Shams Engineering Journal.*

[15] *Raibert, Marc H., Kevin Blankespoor, Gabriel M. Nelson and Robert Playter. "BigDog, the Rough-Terrain Quadruped Robot." IFAC Proceedings Volumes 41 (2008): 10822-10825.*

[16] *Li, Yang, et al. "Towards object tracking for quadruped robots." Journal of Visual Communication and Image Representation 97 (2023): 103958.*

[17] *Qi, J., Gao, H., Su, H., Han, L., Su, B., Huo, M., ... & Deng, Z. (2023). Reinforcement Learning-Based Stable Jump Control Method for Asteroid-Exploration Quadruped Robots. Aerospace Science and Technology, 108689.*

[18] *TAHERI, Hamid; MOZAYANI, Nasser. A study on quadruped mobile robots. Mechanism and Machine Theory, 2023, 190: 105448.*

[19] *JIANG, Han, et al. Stable skill improvement of quadruped robot based on privileged information and curriculum guidance. Robotics and Autonomous Systems, 2023, 170: 104550.*

[20] *FANG, Lizhou, et al. Open-source lower controller for twelve degrees of freedom hydraulic quadruped robot with distributed control scheme. HardwareX, 2023, 13: e00393.*

[21] *QI, Ji, et al. Integrated attitude and landing control for quadruped robots in asteroid landing mission scenarios using reinforcement learning. Acta Astronautica, 2023, 204: 599-610.*

[22] *PARK, Sangyoon, et al. BIM-based scan planning for scanning with a quadruped walking robot. Automation in Construction, 2023, 152: 104911.*

[23] *HALDER, Srijeet, et al. Construction inspection & monitoring with quadruped robots in future human-robot teaming: A preliminary study. Journal of Building Engineering, 2023, 65: 105814.*

[24] *ZHANG, Yanbin, et al. Hybrid learning mechanisms under a neural control network for various walking speed generation of a quadruped robot. Neural Networks, 2023, 167: 292-308.*

[25] *YAO, Qingfeng, et al. Adaptive legged manipulation: Versatile disturbance predictive control for quadruped robots with robotic arms. Robotics and Autonomous Systems, 2023, 104468.*

[26] *CHEN, Zhijun, et al. Fault-tolerant gait design for quadruped robots with one locked leg using the GF set theory. Mechanism and Machine Theory, 2022, 178: 105069.*

[27] *LUO, Jianwen, et al. Prismatic Quasi-Direct-Drives for dynamic quadruped locomotion with high payload capacity. International Journal of Mechanical Sciences, 2022, 235: 107698.*

[28] *CHAI, Hui, et al. A survey of the development of quadruped robots: Joint configuration, dynamic locomotion control method and mobile manipulation approach. Biomimetic Intelligence and Robotics, 2022, 2.1: 100029.*

[29] *JI, Qinglei, et al. Synthesizing the optimal gait of a quadruped robot with soft actuators using deep reinforcement learning. Robotics and Computer-Integrated Manufacturing, 2022, 78: 102382.*

[30] *MISHRA, Krishna Anurag, et al. Fuzzy logic controlled autonomous quadruped robot. Materials Today: Proceedings, 2022, 63: 49-55.*

[31] *CUI, Junxiao, et al. Design and experiments of a novel quadruped robot with tensegrity legs. Mechanism and Machine Theory, 2022, 171: 104781.*

[32] *CHEN, Xin, et al. Realization of indoor and outdoor localization and navigation for quadruped robots. Procedia Computer Science, 2022, 209: 84-92.*

[33] *CHEN, Jiawei; XU, Kun; DING, Xilun. Adaptive gait planning for quadruped robot based on center of inertia over rough terrain. Biomimetic Intelligence and Robotics, 2022, 2.1: 100031.*

[34] *WANG, Kexin, et al. Vision-based Moving Target Tracking of Certain Target for Quadruped Robots. Procedia Computer Science, 2022, 209: 23-30.*

[35] *LIU, Jinhao, et al. A person-following method based on monocular camera for quadruped robots. Biomimetic Intelligence and Robotics, 2022, 2.3: 100058.*

[36] *LI, Jing, et al. Development of a miniature quadrupedal piezoelectric robot combining fast speed and nano-resolution. International Journal of Mechanical Sciences, 2023, 250: 108276.*

[37] *LUO, Bende; LUO, Yinlin. A balanced jumping control algorithm for quadruped robots. Robotics and Autonomous Systems, 2022, 158: 104278.*

[38] *KROLICKI, Alexander, et al. Modeling Quadruped Leg Dynamics on Deformable Terrains using Data-driven Koopman Operators. IFAC-PapersOnLine, 2022, 55.37: 420-425.*

[39] *MANU, Amritanshu; GUPTA, Shakti S.; KOTHARI, Mangal. Path Tracking Strategy for Quadruped Robots Using a Hierarchical Framework. IFAC-PapersOnLine, 2022, 55.1: 192-197.*

[40] *CHEN, Chin-Tai; LIAO, Po-Sheng. Additive design and manufacturing of a quadruped robot actuated by electrothermal effect of shape memory polymer. Sensors and Actuators A: Physical, 2023, 357: 114401.*

[41] *MOYER, Virginia; FICHTER, Eugene; FICHTER, Becky. Analyzing dynamics of arthropod walking. In: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, 1988. p. 710-711.*

[42] *KIM, Juhyeon, et al. Deep learning-based 3D reconstruction of scaffolds using a robot dog. Automation in Construction, 2022, 134: 104092.*

[43] *WANG, Ke, et al. A unified model with inertia shaping for highly dynamic jumps of legged robots. Mechatronics, 2023, 95: 103040.*

[44] *PONCE, Hiram, et al. Modeling and simulation for designing a line walking chameleon-like legged robot. Simulation Modelling Practice and Theory, 2022, 121: 102648.*

[45] *YU, Haoyang, et al. Hierarchical jumping optimization for hydraulic biped wheel-legged robots. Control Engineering Practice, 2023, 141: 105721.*

[46] *KOVAL, Anton; KANELLAKIS, Christoforos; NIKOLAKOPOULOS, George. Evaluation of Lidar-based 3D SLAM algorithms in SubT environment. IFAC-PapersOnLine, 2022, 55.38: 126-131.*

[47] *LINDQVIST, Björn, et al. Multimodality robotic systems: Integrated combined legged-aerial mobility for subterranean search-and-rescue. Robotics and Autonomous Systems, 2022, 154: 104134.*

[48] *WANG, Jiankun, et al. A survey of the development of biomimetic intelligence and robotics. Biomimetic Intelligence and Robotics, 2021, 1: 100001.*

[49] *SHAHABPOOR, E.; PAVIC, A. Human-structure dynamic interactions: Identification of two-degrees-of-freedom walking human model. Journal of Sound and Vibration, 2024, 569: 117974.*

[50] *MORADI, Vahideh; SANJARI, Mohammad Ali; STERGIOU, Nick. Single subject analysis of individual responses to prosthetic modifications based on passive dynamic walking model. Clinical Biomechanics, 2022, 100: 105815.*

[51] *HE, JingYe, et al. Survey of quadruped robots coping strategies in complex situations. Electronics, 2019, 8.12: 1414.*

[52] *LI, Xiaoqi; WANG, Wei; YI, Jianqiang. Foot contact force of walk gait for a quadruped robot. In: 2016 IEEE International Conference on Mechatronics and Automation. IEEE, 2016. p. 659-664.*

[53] *ZHANG, Dong, et al. Design of an Unconventional Bionic Quadruped Robot with Low-degree-freedom of Movement. In: 2021 6th International Conference on Control and Robotics Engineering (ICCRE). IEEE, 2021. p. 55-60.*

[54] *NANDHINI, M.; KRITHIKA, V.; CHITTAL, K. Design of four pedal quadruped robot. In: 2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI). IEEE, 2017. p. 2548-2552.*

[55] *BHATTI, Asad, et al. A Purposed model for Quadruped footprint generation. In: 2020 3rd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET). IEEE, 2020. p. 1-5.*

[56] *KASHIRI, Navvab, et al. Evaluation of Hip Kinematics Influence on the Performance of a Quadrupedal Robot Leg. In: ICINCO (1). 2016. p. 205-212.*

[57] *HUNT, Alexander; SZCZECINSKI, Nicholas; QUINN, Roger. Development and training of a neural controller for hind leg walking in a dog robot. Frontiers in neurorobotics, 2017, 11: 18.*

[58] *PETRESCU, Relly Victoria, et al. Inverse kinematics at the anthropomorphic robots, by a trigonometric method. American Journal of Engineering and Applied Sciences, 2017, 10.2: 394-411.*

[59] *ZHANG, Jinrong; WANG, Chenxi; ZHANG, Jianhua. The kinematics analysis and configuration optimize of quadruped robot. The Open Automation and Control Systems Journal, 2014, 6.1.*

[60] *LI, Zhaolu, et al. Motion Control Method of Bionic Robot Dog Based on Vision and Navigation Information. Applied Sciences, 2023, 13.6: 3664.*

[61] *IIDA, Fumiya; GÓMEZ, Gabriel; PFEIFER, Rolf. Exploiting body dynamics for controlling a running quadruped robot. In: ICAR'05. Proceedings., 12th International Conference on Advanced Robotics, 2005. IEEE, 2005. p. 229-235.*

[62] *LI, Xin, et al. Mechanical design of the legs of hydraulically actuated quadruped bionic robot. In: 2013 ICME International Conference on Complex Medical Engineering. IEEE, 2013. p. 626-632.*

[63] *BIN, Li; XUEWEN, Rong; YIBIN, Li. Review and analysis of quadruped robots with articulated spine. In: The 26th Chinese Control and Decision Conference (2014 CCDC). IEEE, 2014. p. 5074-5079.*

[64] *BOAVENTURA, Thiago, et al. Stability and performance of the compliance controller of the quadruped robot HyQ. In: 2013 IEEE/RSJ international conference on intelligent robots and systems. IEEE, 2013. p. 1458-1464.*

[65] *LI, Qi, et al. Towards Generation and Transition of Diverse Gaits for Quadrupedal Robots Based on Trajectory Optimization and Whole-Body Impedance Control. IEEE Robotics and Automation Letters, 2023, 8.4: 2389-2396.*

[66] *REBULA, John R., et al. A controller for the littledog quadruped walking on rough terrain. In: Proceedings 2007 IEEE International Conference on Robotics and Automation. IEEE, 2007. p. 1467-1473.*

[67] *ARIKAWA, Keisuke; HIROSE, Shigeo. Development of quadruped walking robot TITAN-VIII. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS'96. IEEE, 1996. p. 208-214.*

[68] *SAKAKIBARA, Yoshihiro, et al. Foot trajectory for a quadruped walking machine. In: EEE International Workshop on Intelligent Robots and Systems, Towards a New Frontier of Applications. IEEE, 1990. p. 315-322.*

[69] *HIROSE, Shigeo; KATO, Keisuke. Study on quadruped walking robot in Tokyo Institute of Technology-past, present and future. In: Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065). IEEE, 2000. p. 414-419.*

[70] *PONGAS, Dimitris; MISTRY, Michael; SCHAAL, Stefan. A robust quadruped walking gait for traversing rough terrain. In: Proceedings 2007 IEEE International Conference on Robotics and Automation. IEEE, 2007. p. 1474-1479.*

[71] *HIROSE, Shigeo, et al. Quadruped walking robot centered demining system-development of titan-ix and its operation. In: Proceedings of the 2005 IEEE international conference on robotics and automation. IEEE, 2005. p. 1284-1290.*

[72] *ZIMMERMANN, Simon; PORANNE, Roi; COROS, Stelian. Go fetch!-dynamic grasps using boston dynamics spot with external robotic arm. In: 2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2021. p. 4488-4494.*

[73] *KUMAR, PALIVELA ARUN; NARAYAN, YEOLE SHIVRAJ. Design of a quadruped robot and its inverse kinematics. International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), 2017, 7.4: 241-252.*

[74] *Sun, Wenkai, Xiaojie Tian, Yong Song, Bao Pang, Xianfeng Yuan, and Qingyang Xu. 2022. "Balance Control of a Quadruped Robot Based on Foot Fall Adjustment" Applied Sciences 12, no. 5: 2521. https://doi.org/10.3390/app12052521*

[75] *Li, Y., Fish, F., Chen, Y., Ren, T., & Zhou, J. (2019). Bio-inspired robotic dog paddling: kinematic and hydro-dynamic analysis. Bioinspiration & biomimetics, 14(6), 066008.*

[76] *Melson, G. F., Kahn Jr, P. H., Beck, A. M., Friedman, B., Roberts, T., & Garrett, E. (2005, April). Robots as dogs? Children's interactions with the robotic dog AIBO and a live Australian shepherd. In CHI'05 extended abstracts on Human factors in computing systems (pp. 1649-1652).*

[77] *Sparrow, R. (2016, March). Kicking a robot dog. In 2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI) (pp. 229-229). IEEE.*

[78] *Steinke, J., Rischke, J., Sossalla, P., Hofer, J., Vielhaus, C. L., Vom Hofe, N., & Fitzek, H. F. (2023, June). The Future of Dog Walking–Four-Legged Robots and Augmented Reality. In 2023 IEEE 24th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM) (pp. 352-354). IEEE.*

[79] *Due, B. L. (2023). Guide dog versus robot dog: assembling visually impaired people with non-human agents and achieving assisted mobility through distributed co-constructed perception. Mobilities, 18(1), 148-166.*

[80] *Guan, Yuntao, et al. "Structure Design and Motion Planning of a Reconfigurable Robot with Flexible Waist." 2023 9th International Conference on Electrical Engineering, Control and Robotics (EECR). IEEE, 2023.*

[81] *Li, Yunquan, et al. "Bio-inspired robotic dog paddling: kinematic and hydro-dynamic analysis." Bioinspiration & biomimetics 14.6 (2019): 066008.*

[82] *Harvey, Nicholas, and André Leon Nel. "Arachnid-inspired kinesthesia for legged robots." 2015 Pattern Recognition Association of South Africa and Robotics and Mechatronics International Conference (PRASA-RobMech). IEEE, 2015.*

[83] *Shin, Bongsu, Ho-Young Kim, and Kyu-Jin Cho. "Towards a biologically inspired small-scale water jumping robot." 2008 2nd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics. IEEE, 2008.*

[84] *Fitcher, Eugene F., and Becky L. Fichter. "A survey of legs of insects and spiders from a kinematic perspective." Proceedings. 1988 IEEE International Conference on Robotics and Automation. IEEE, 1988.*

[85] *Luk, Bing Lam, et al. "Intelligent walking motions and control for a legged robot." 1999 European Control Conference (ECC). IEEE, 1999.*

[86] *https://robotacademy.net.au/lesson/inverse-kinematics-for-a-2-joint-robot-arm-using-geometry/*

[87] *https://www.mathworks.com/help/supportpkg/arduinoio/ug/control-servo-motors.html*