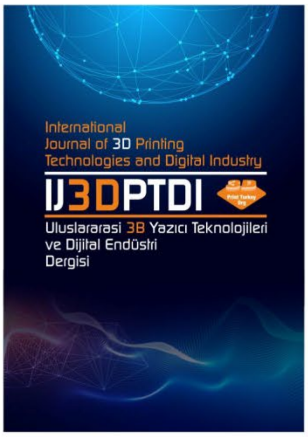

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INTERNATIONAL JOURNAL OF 3D PRINTING
TECHNOLOGIES AND DIGITAL INDUSTRY

ISSN:2602-3350 (Online)

URL: https://dergipark.org.tr/ij3dptdi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): *Uzun E., Tepe C., "Comparison of Mechanical Design and Flow Analysis of Quadruped Robots" Int. J. of 3D Printing Tech. Dig. Ind., 8(2): 162-172, (2024).*

DOI: 10.46519/ij3dptdi.1437626

Araştırma Makale/ Research Article

Erişim Linki: (To link to this article): https://dergipark.org.tr/en/pub/ij3dptdi/archive

COMPARISON OF MECHANICAL DESIGN AND FLOW ANALYSIS OF QUADRUPED ROBOTS

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(**Received:** 09.01.2024; **Revised:** 04.04.2024; **Accepted:** 16.04.2024)

ABSTRACT

In recent years, there has been a trend of developing innovative technologies inspired by living creatures in nature. Quadruped robots, in particular, have emerged as walking mobile systems with articulated leg structures that can skilfully perform dynamic movements that wheeled systems are limited to. These robots offer advantages in technical criteria such as manoeuvrability, cross-capability, controllability, terrain adaptability and stability. It is important to note that this evaluation is based on objective technical criteria rather than subjective opinions. This study compares the advantages and disadvantages of quadruped robots to wheeled systems. It highlights that quadruped robots outperform wheeled systems in manoeuvrability, obstacle overcoming, and speed, particularly in rough terrains. The study also suggests that designers of quadruped robots should consider aerodynamic factors, which are often overlooked. Flow analysis using the finite element method is crucial in robot design to enhance aerodynamic performance. This paper aims to comprehensively analyse the flow structure around quadruped robots using Computational Fluid Dynamics and investigate passive flow control methods to reduce the drag coefficient (Cd). The study examines four different robots, and the resulting Cd average percentage calculations are presented. The aerodynamic efficiency of Robot 4 compared to Robot 2 was found to be 95%. Similarly, the aerodynamic efficiency of Robot 3 was determined to be 28% compared to Robot 2. Additionally, it was determined that the aerodynamic efficiency of Robot 2 was 76% compared to Robot 1. These results provide an important comparison to understand the energy efficiency, differences in aerodynamic performance and relative effectiveness of quadruped robots.

Keywords: Aerodynamic, Computational Fluid Dynamics, Energy, Quadruped, Robot.

1. INTRODUCTION

Humanity has always strived to study living organisms in their natural habitats, generate novel ideas, and develop innovative technologies to enhance our daily lives. Such efforts are one of the most remarkable examples of recent years. A quadruped robot inspired by animals is capable of walking and performing dynamic movements [1]. Although wheeled vehicles have been in use for more than thousands of years, mountainous or desert terrain requires greater surface roughness than footed vehicles such as horses and mules. Over billions of years of evolution, the result of natural selection on the locomotion of land animals has fully demonstrated the adaptability, mobility and carrying capacity of four-legged mammals in rough terrain [2]. Wheeled robots move quickly but have poor manoeuvrability to navigate uneven ground or overcome obstacles such as stairs. Legged robots outperform wheeled robots in these terrain conditions [3]. Quadruped robots are walking locomotion systems with articulated leg structures and can also perform dynamic motions that are limited by wheeled systems. These robots are one of the most significant developments in the field of robotics [4]. Quadruped robot technology has developed rapidly since the 21st century. The robot's leg structure has been enhanced with bionic technology, improving its ability to adapt to various terrains. The manufacturing technology of power systems has led to the development of quadruped robots with integrated power sources [2]. Each system has its own advantages and disadvantages. A detailed comparison of the technical criteria of legged and wheeled robots is shown in Table 1. As can be seen in Table 1, the development of legged locomotion on land has grown continuously over the last decade due to the fact that legged robots offer more advantages than wheeled robotic vehicles. The advantages of legged locomotion depend on the posture, the number of legs and the functionality of the leg. Although wheeled and tracked robots can operate on flat terrain, their ability to operate in most rough and difficult terrain conditions is poor [5].

Table 1. Comparison between wheeled and legged robots [5].

Technical Specifications	Wheeled robot	Legged Robot
Manoeuvrability	Poor	Good
Cross talent	Poor	Good
Controllability	Good	Poor
Terrain Compatibility	Poor	Good
Stability	Good	Poor
Cost-effective	Good	Poor
Navigating over obstacles	Poor	Good
Complexity	Poor	Good

Quadruped robot designs are widely used in various applications, from industrial to personal use. Their motion capabilities, adaptability, and capacity to perform a variety of tasks make them an ideal platform to increase the effectiveness of robotic systems. Robots are utilized in numerous manufacturing tasks, including painting, welding, assembly, soldering, handling, and conveying [1].

Mobile robots have a wide range of applications in various fields, including space exploration, military operations, and industrial use [5]. However, the design process of quadruped robots faces a fundamental problem in the form of aerodynamic factors, which are often overlooked. In particular, air resistance can pose a significant obstacle when these robots move at high speeds or operate in open spaces. Quadrupeds use a variety of gaits depending on their movement speed. At lower movement speeds, the robot uses a walking gait, which transitions to a sprint gait as the speed increases. At the highest range of movement speed, the robot uses a galloping gait [6]. To successfully design a legged robot, it is important to consider and optimize for aerodynamic challenges, as well as gait stability, robustness, speed, and practicality, including size, volume, weight, and energy efficiency [7]. Aerodynamic analyses are conducted using the finite element method to determine the optimal aerodynamic structure of robots. The finite element method simplifies complex engineering problems by dividing the solution domain into a large number of simple, interconnected sub-regions called finite elements. This means that it is possible to solve problems that are divided into parts connected by many nodes. The mesh method, which divides the surface into small parts and moves from the part to the whole, was used to perform airfoil flow analysis [8]. The aerodynamic performance of quadruped robots is often overlooked. This study aims to improve the aerodynamic performance of quadruped robot designs, increase their energy efficiency, and optimize their motion capabilities for industrial and research applications. To achieve this, a detailed analysis of the flow structure around the quadruped robots using Computational Fluid Dynamics (CFD) method will be conducted, and passive flow control methods for Cd reduction will be investigated.

2. MATERIAL AND METHOD

Modelling a quadruped robot requires creating an accurate representation of its physical properties and kinematics. Various methods for building such models have been studied in the literature.

Atique and Ahad [9] developed a quadruped robot controlled by the Android operating system. Inverse Kinematics Solutions and the Denavit Hartenberg rule were used to develop the structure. The movements were simulated using 3D software. An Android application was developed to control the robot via Bluetooth, allowing for six different movements. Yong et al. [10] investigated the optimisation of dynamic gait planning and stability control of quadruped robots under external disturbing forces. A quadruped walking robot platform with fourteen active degrees of freedom is designed. Subsequently, a forward kinematic joint model for quadruped robots is established based on the Denavit-Hartenberg (D-H) method. The inverse kinematic equations are solved to obtain joint values when the desired position and orientation are specified. Finally, a dynamic gait planning algorithm is proposed and tested on a quadruped robot. Xiong [11] designed a mobile quadruped robot based on the bionic and simplified octopus structure. The single leg kinematics of the robot were analysed using the Denavit-Hartenberg system, and the kinematic equation was obtained. The joint angles were then calculated by solving the inverse kinematics with the method of separate variables. The joint angles of the vertical oscillation stance phase and the oscillation phase of the robot's walking motion were calculated and analysed using MATLAB. The experimental results confirmed the universality of robot motion. These are two basic examples of the mathematical and kinematic approaches used to construct quadruped robot models. The study analyses four different robot models using the k-Omega SST turbulence model and CFD analyses, presented under subheadings.

2.1. Trial Analysis

The performance of the quadruped robot model will be tested in various environments, and its effectiveness in real-world conditions will be evaluated based on multiple criteria.

To analyze the flow around the quadruped robot design, we will use CFD analysis, which involves mathematical modeling of fluid dynamics and solving it through computer simulations. CFD is a comprehensive research tool that allows us to understand and optimize various parameters. The analysis includes the steps shown in Figure 1.

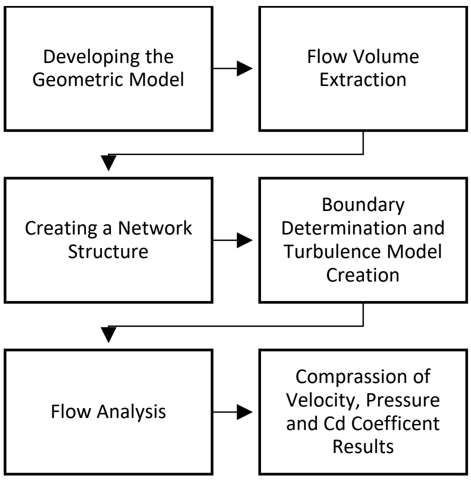


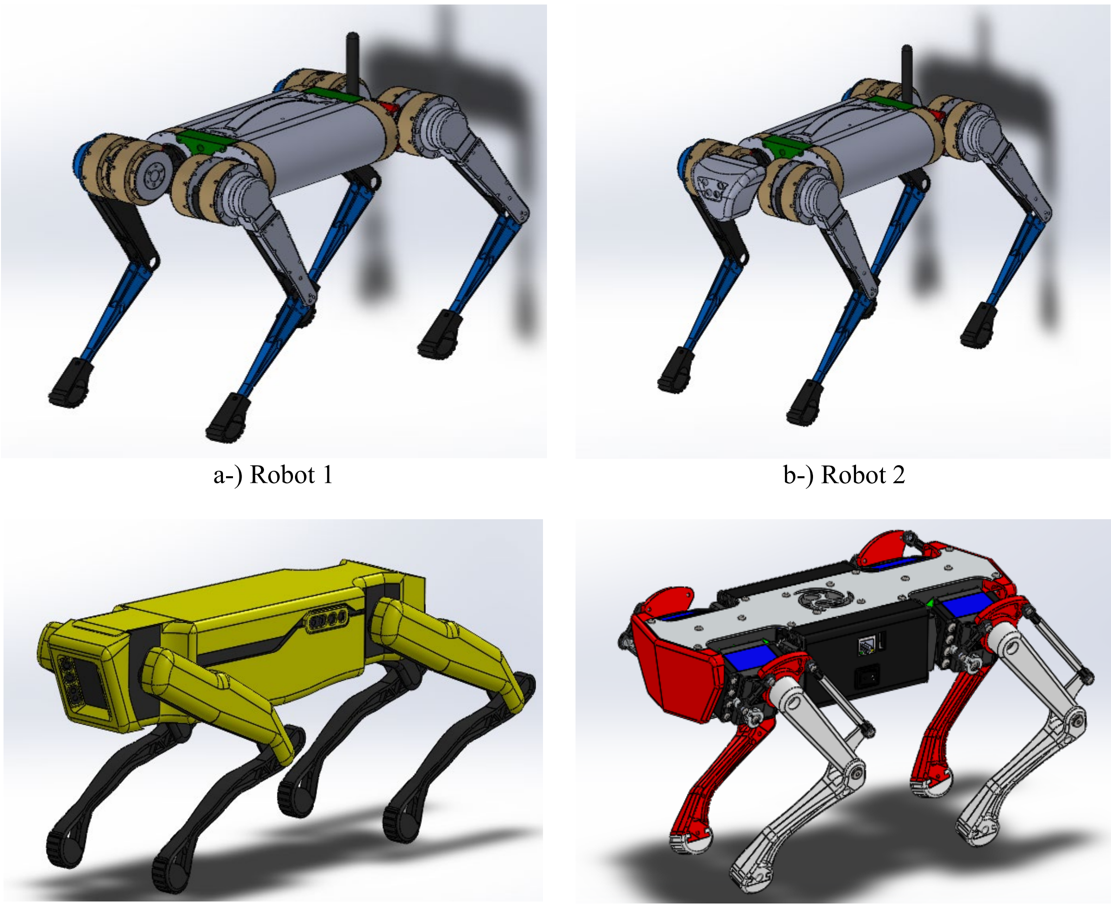
Figure 1. CFD analysis steps.

The study employed geometric modelling as the method for quadruped robot modelling. Other modelling methods include kinetic modelling, dynamic modelling, artificial neural networks, machine learning models, system identification methods, and simulation-based modelling.

2.1.1. Geometry Modelling

The task involves creating a detailed digital representation of the physical geometry of the quadruped robot in a computer environment.

Nowadays, mass production methods have evolved into mass-customised production, which requires the production of small quantities of similar but geometrically different parts. Therefore, it is necessary to rapidly design similar parts. The need for effective definition of design parameters has led to the development of design methods. Computer Aided Design (CAD) is a widely used method in all engineering fields. CAD refers to the computerised drawing of a part, a building or a map according to certain rules. In Mechanical Engineering, CAD is specifically used for part and mould design. Computer-aided systems are extensively used in design and manufacturing processes today. Worldwide, there are many CIS and Computer-Aided Manufacturing (CAD) programs with different features developed for this purpose [13]. These design techniques, known as parametric design, play a crucial role in fast and flexible design processes. Additionally, since a new construction involves design and stress calculations, designs are subject to frequent changes. They may require rapid reshaping of an existing product and design changes based on engineering analysis results. CIS systems are essential tools that aid engineers in the forming, detailing, fabrication, and assembly phases of design. Just as computers are crucial in the design phase of engineering systems, the use of CIS software is an inevitable necessity. The CIS system is designed to aid engineers in the design, detailing, manufacturing, and assembly phases. While computers are crucial in technical system design, the use of CIS software is also significant [12]. Figure 2 provides isometric views of the robots to be analyzed by CFD.



a-) Robot 1 b-) Robot 2 c-) Robot 3 d-) Robot 4

Figure 2. Isometric views of robots: a-) Robot 1, b-) Robot 2, c-) Robot 3 and d-) Robot.

2.1.2. Determining Flow Conditions

The analysis determined the flow conditions to be used, including parameters such as velocity, temperature, and pressure. The equations were numerically solved using the specified flow conditions and mathematical model through computers.

2.1.3. General Equations

The Fluent program uses finite volume methods to solve the integral equation that includes continuity, momentum, energy, and turbulence. Numerical methods are employed to solve these equations using the programs in the package. The continuity and momentum equations are analyzed using finite volume analysis with the aid of HAD. Solving these equations analytically is challenging in practice [14].

2.1.3.1. Continuity Equation

The continuity equation is a fundamental equation used in the field of fluid mechanics to express the conservation of mass. It is commonly applied in areas such as HAD. The equation defines the change in the amount of fluid mass in a control volume and states that the mass flow rate inside a control volume is equal to the mass flow rate across the control volume boundaries. Equation (1) illustrates the continuity equation.

$$\partial \bar{u}/\partial x + \partial \bar{v}/\partial y + \partial \bar{w}/\partial z = 0 \qquad (1)$$

Equation (1) demonstrates that the change in mass of a fluid in a control volume is due to the fluid moving in or out of this volume.

If the expression is satisfied, it shows that the fluid is continuous within the volume and satisfies the principle of mass conservation. The continuity equation, which is also used in HAD simulations, contributes to a better understanding of the fluid's motion and distribution. The equation expresses that the mass flow rate at a specific point is equal to the sum of the mass flow rates of all the fluids that combine or divide in that point.

2.1.3.2. Momentum Equation

The momentum equation is a fundamental equation that describes fluid motion. It is commonly used in applications such as HAD. In general, the momentum equation for a three-dimensional environment and a control volume is given by Equation (2)-(4). The equation is derived from Newton's second law of motion and specifies how the mass and velocity of a fluid change over time. The momentum equation for a three-dimensional environment and a control volume is typically expressed by Equation (2)-(4). It is important to maintain consistency in the use of this equation throughout the text.

$$\rho\frac{\mathrm{Du}}{\mathrm{Dt}} = \frac{\partial(-\mathrm{p}+\tau_{xx})}{\partial x} + \frac{\partial\tau_{yx}}{\sigma y} + \frac{\partial\tau_{zx}}{\sigma z} + S_{Mx} \quad (2)$$

$$\rho\frac{\mathrm{Dv}}{\mathrm{Dt}} = \frac{\partial(-\mathrm{p}+\tau_{yy})}{\partial y} + \frac{\partial\tau_{xy}}{\sigma x} + \frac{\partial\tau_{zy}}{\sigma z} + S_{My} \quad (3)$$

$$\rho\frac{\mathrm{Dw}}{\mathrm{Dt}} = \frac{\partial(-\mathrm{p}+\tau_{zz})}{\partial z} + \frac{\partial\tau_{xz}}{\sigma x} + \frac{\partial\tau_{yz}}{\sigma y} + S_{Mz} \quad (4)$$

2.1.3.3. Navier – Stokes Equation

The Navier-Stokes equations are a set of fundamental differential equations used to describe fluid motion. Equations (5)-(7) below provide the most useful version of the Navier-Stokes equations for the development of finite volume methods [14].

$$\rho\frac{\mathrm{Du}}{\mathrm{Dt}} = -\frac{\partial\mathrm{p}}{\partial x} + div(\mu grad u) + S_{Mx} \quad (5)$$

$$\rho\frac{\mathrm{Dv}}{\mathrm{Dt}} = -\frac{\partial\mathrm{p}}{\partial y} + div(\mu grad u) + S_{My} \quad (6)$$

$$\rho\frac{\mathrm{Dw}}{\mathrm{Dt}} = -\frac{\partial\mathrm{p}}{\partial z} + div(\mu grad u) + S_{Mz} \quad (7)$$

External flow problems refer to the hydrodynamic forces and moments that occur when a fluid moves over a stationary solid object or when a solid object moves within a stationary fluid [15]. The HAD method is a powerful tool for analyzing the flow around quadruped robot designs. Research in this field often focuses on unique solutions by examining specific designs and robot geometries.

The Finite Element Method is an engineering problem-solving approach that simplifies complex problems into possible solutions. It involves dividing the solution domain into numerous simple subdomains, called finite elements, which are connected to each other. This allows for the easy solution of problems that are divided into parts connected by numerous nodes and points. The surfaces of quadruped robots are divided into small pieces for flow analysis, and transitions are made from the pieces to the whole [16]. These examples represent general approaches used for CFD analysis of the flow around quadruped robot designs.

2.1.4. Passive Flow Control Methods

Passive flow control is a method of flow control that is achieved by changing the geometry of the aerodynamic structure, which is widely studied, within the system without consuming energy [14]. In a flowing medium, there is a certain flow structure around an object. The process of removing this flow structure from the normal flow structure is called flow control. There are two types of flow control methods. There are two types of flow control methods based on energy consumption in flow control: active flow control methods and passive flow control methods. Passive flow control is a flow control method that is generally achieved by changing the shape of the object being studied aerodynamically without expending energy on the system [17]. Aerodynamics is the branch of science that studies the movement of objects in the air and their interactions with air [14].

2.1.4.1. Optimising Body Geometry for Flow Control

Geometric modifications, particularly in studies on quadruped robot designs, can effectively direct the flow, reducing Cd and improving the robot's aerodynamic performance. Pipes or holes cut into the robot's surface can also reduce Cd by creating a specific effect on the fluid. There are two types of flow control schemes based on energy consumption: active flow control schemes and passive flow control schemes.

The Cd factor is a dimensionless value used to measure an object's air resistance. A lower value indicates less air resistance. Cd is influenced by the object's shape, position, fluid properties (such as fluid type, density, velocity, etc.), and angle of attack [18]. Reducing Cd results in decreased air resistance and improved aerodynamic performance. Lowering the Cd value can lead to increased energy efficiency. Reducing the air resistance of an object can improve the energy efficiency of fast-moving vehicles, resulting in lower fuel consumption and energy costs.

The low Cd value of vehicles supports fuel savings, particularly in automobiles, and can also reduce emissions.

Additionally, lower air resistance is often associated with lower energy consumption, which can help to reduce environmental impacts. Reducing Cd offers several advantages, including the reduction of environmental impacts such as the use of fossil fuels and carbon emissions.

These methods can improve aerodynamic efficiency, which is particularly important for transportation vehicles and fast-moving systems. Passive flow control methods can be used to achieve this, and there are several general strategies available. However, the most effective strategies may vary depending on the specific application or design of the quadruped robot.

2.1.4.2. Volume Barriers and Surface Modifications

Geometric changes and surface modifications can reduce the drag coefficient (Cd) generated by the flow. For instance, adjusting the aerodynamic profile or adding volume barriers to specific regions on the body surface can improve flow steering and reduce Cd. Additionally, discrete holes or cavities placed on the surface of the robot can reduce Cd by inducing vortices as the flow passes over them. This type of passive control strategy can be effective for low-velocity flows. The Ansys Fluent program was used to perform flow analysis. A solid model was placed on the ground within an area of 700 mm x 1000 mm x 2000 mm, and a model cavity was created as shown in Figure 3. The Fluent program ensures convergence by balancing equations at each point in the solution set. The severity of the error in the solution for each fluid variable is indicated by the residual. The report predicts an area velocity of 0.7 m^2. The analysis employed a SIMPLE least squares cell-based, k-Omega SST turbulence model with k-Omega as the standard initialization. The walls were treated as standard. Technical abbreviations were explained when first used. The language is clear, objective, and value-neutral. The text is free from grammatical errors, spelling mistakes, and punctuation errors. The content of the improved text is as close as possible to the source text.

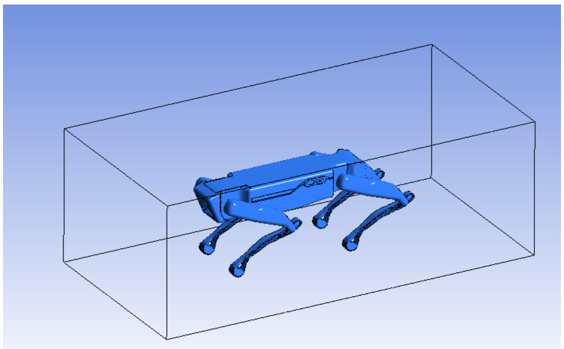


Figure 3. Model appearance in the “design modeler” interface and model space [14].

The Fluent® program was used to perform the analysis on a computer with an Intel(R) Core(TM) i7-4720HQ CPU @ 2.60GHz 2.59 GHz and 16 GB RAM.

3. RESULTS AND DISCUSSION

This study analysed the states of four quadruped robot models (named Robot (1)-(4) [14]) at different speeds, as shown in Figures (2)-(5) [19-21]. The results indicate that an increase in speed leads to an increase in pressure acting on the robots, particularly at the front and in the direction of the angle of attack of the fluid. Figures (4)-(7) present the velocity and velocity vector representations, revealing the direction of motion and speed of the robot. The analysis highlights the velocity drops observed at the joints of the robot, indicating a complex aerodynamic interaction in these regions.

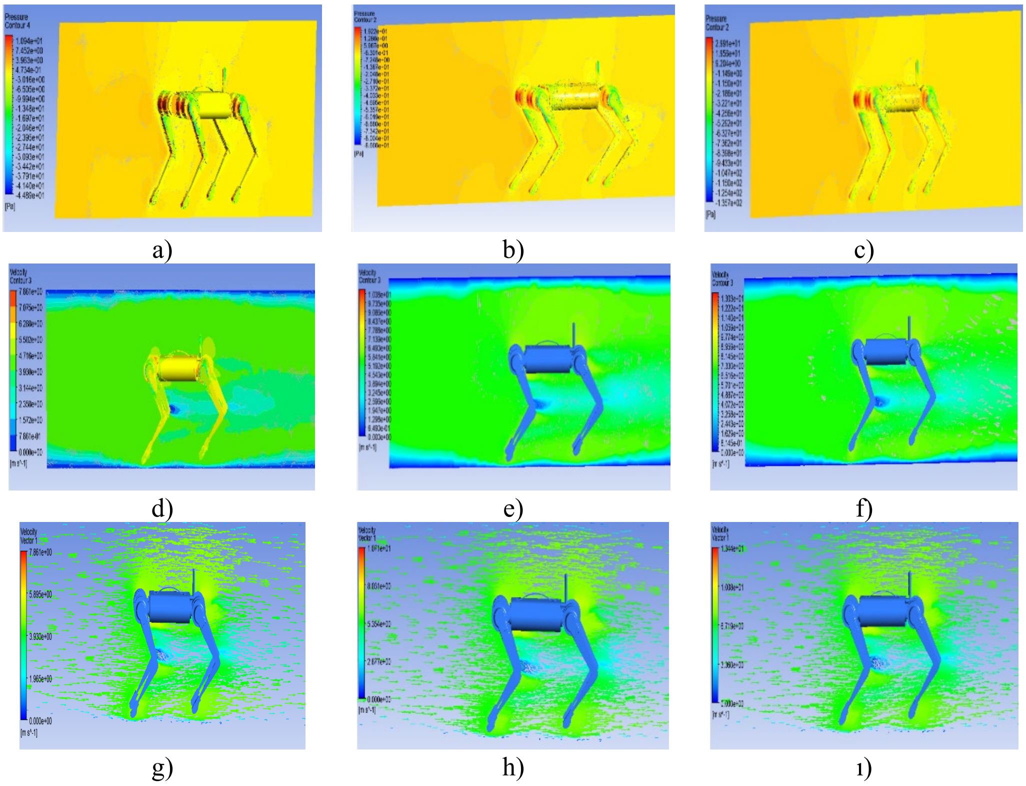


Figure 4. The CFD analysis of Robot 1 was conducted for speed variables of 15, 20, and 25 km/h (from left to right); The pressure results are shown in a), b), and c), while the speed results are shown in d), e), and f). The speed vector representations are shown in g), h), and i).

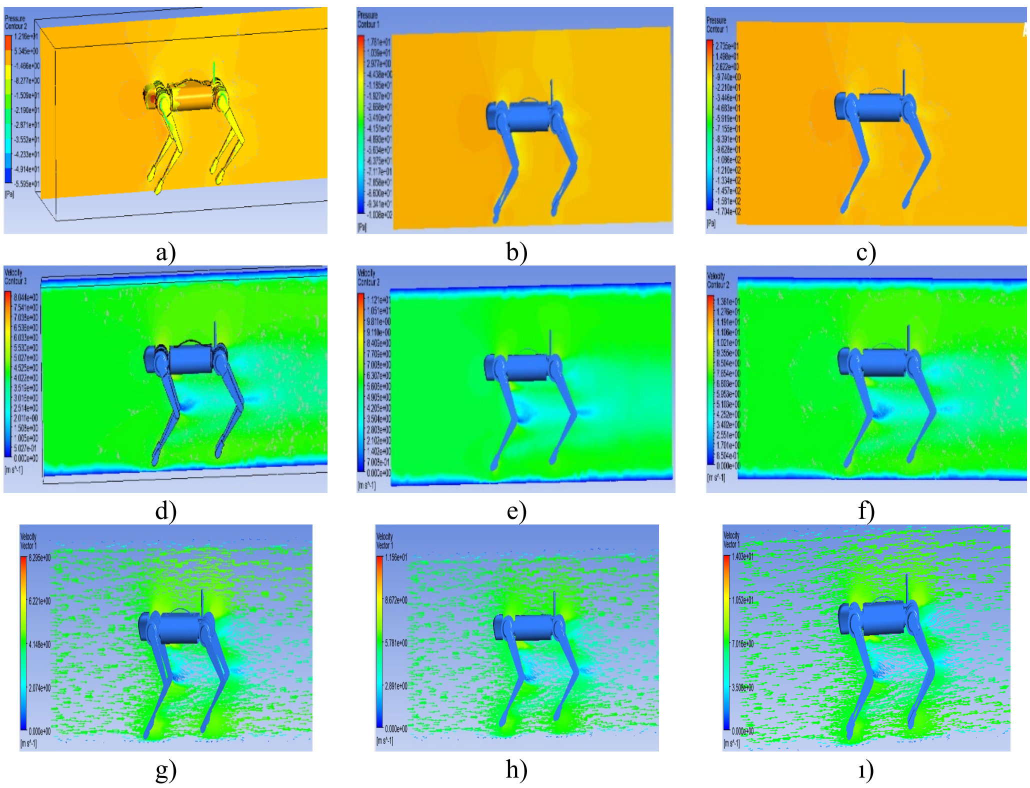


Figure 5. The CFD analysis of Robot 2 was conducted for speed variables of 15, 20, and 25 km/h (from left to right); The pressure results are shown in a), b), and c), while the speed results are shown in d), e), and f). The speed vector representations are shown in g), h), and i).

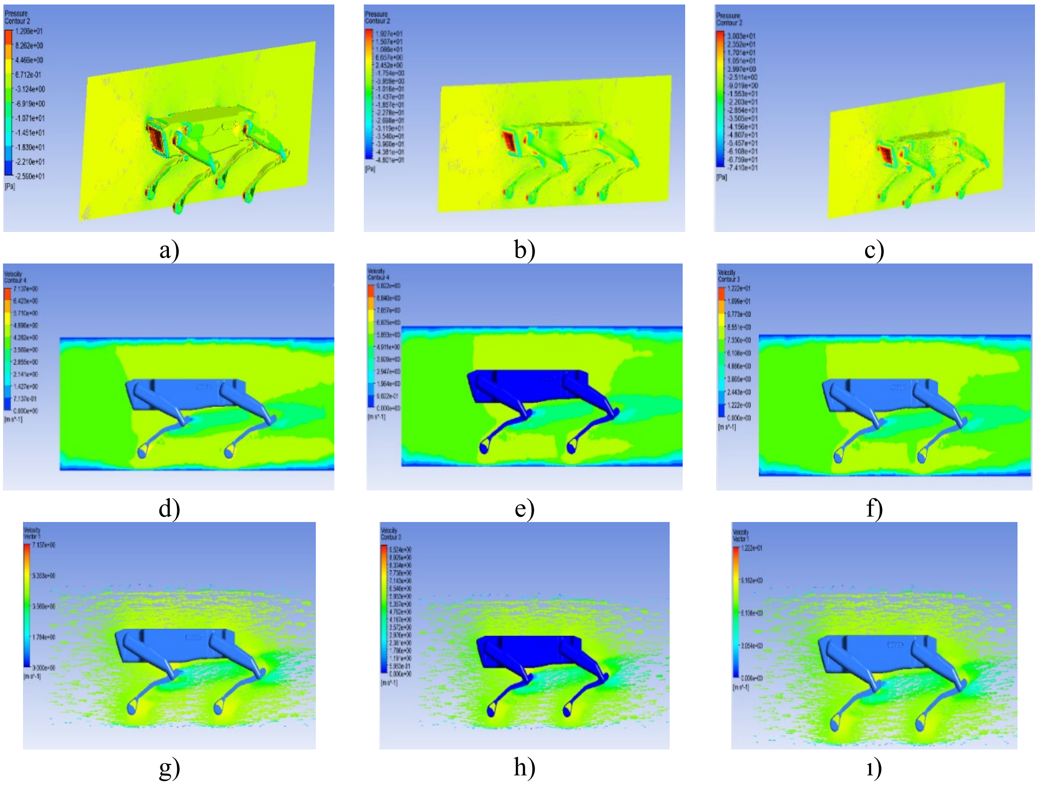


Figure 6. The CFD analysis of Robot 3 was conducted for speed variables of 15, 20, and 25 km/h (from left to right); The pressure results are shown in a), b), and c), while the speed results are shown in d), e), and f). The speed vector representations are shown in g), h), and i).

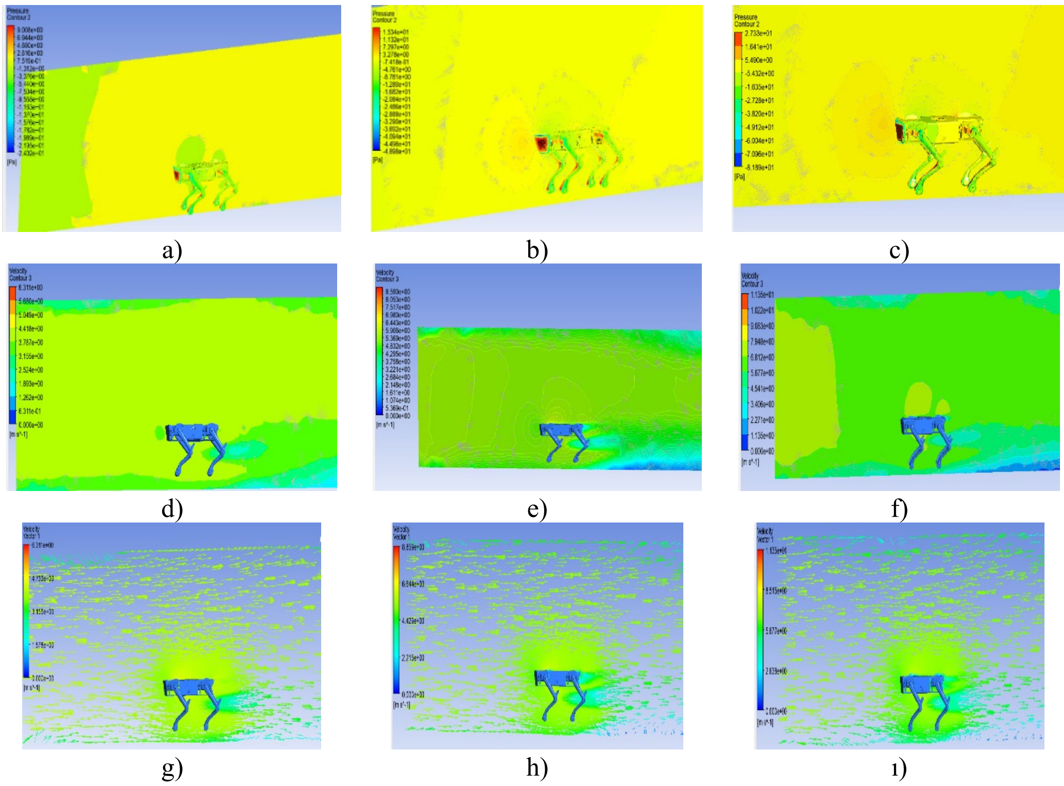


Figure 7. The CFD analysis of Robot 4 was conducted for speed variables of 15, 20, and 25 km/h (from left to right); The pressure results are shown in a), b), and c), while the speed results are shown in d), e), and f). The speed vector representations are shown in g), h), and i).

Figures (2)-(5) show the tight mesh structure of the regions that significantly affect the aerodynamic structure of the model. Boundary definitions were made, and the mesh file was sent to the setup department. The solution domain boundaries are defined as follows: the inlet has a constant velocity boundary condition where the fluid enters, the outlet has a constant pressure condition where the fluid exits, and the wall is the edge surface of the rectangular volume bounding the experimental area where the wall boundary condition is applied.

The analysis focused on the model space of the quadruped robot drawing data. The wall was defined as a boundary condition.

After performing 1000 iterations and using the Cd coefficients given in Table 2, the flow analysis yielded the Cd value that affects the quadruped robots. The aerodynamic Cd is provided in Equation (8) below. Here, the density (ρ) is a function of the free flow velocity (V) and the front view area (A_{front}) [14].

$$Cd = \frac{F_D}{1/2\rho V^2 A_{front}} \tag{8}$$

It concludes that Robot 4 has the lowest Cd value among Robot 1, Robot 2, and Robot 3, indicating higher aerodynamic efficiency. The paper evaluates the aerodynamic performance of quadruped robots at speeds of 15, 20, and 25 km/h by comparing their Cd values. According to the ranking, Robot 4 has the best aerodynamic performance with the lowest Cd value, indicating that it can increase energy efficiency by minimizing air resistance. Robot 3 follows in second place, while Robot 2 ranks third.

Robot 1 has the highest aerodynamic resistance compared to the other models' Cd values and ranks last in the analysis.

This ranking is a crucial step in objectively evaluating the aerodynamic performance of quadruped robots. Robot 4 stands out with the lowest Cd value, indicating an advantageous position in terms of energy efficiency and fast movement capabilities. This supports fuel savings and reduces environmental impact. However, it is important to consider these factors in the context of specific design and application, as the suitability of each robot for particular tasks may vary.

These analyses demonstrate that robots have the potential to enhance energy efficiency and optimize mobility. The analysis of the design and dimensional characteristics of the robots reveals that the aerodynamic structure has a significant impact. The study examines the aerodynamic properties of robots with different geometries and dimensions, as shown in Figure 8.

Table 2 shows the Cd average percentage calculations for Robots (1)-(4) following the examinations. Robot 4 demonstrated an aerodynamic efficiency of 95% compared to Robot 2. Robot 3's aerodynamic efficiency was found to be 28% according to Robot 2. Furthermore, Robot 2's aerodynamic efficiency was determined to be 76% compared to Robot 1.

The aerodynamic structure of the charged quadruped robots is a critical factor for long-term use, as inferred from these findings.

Table 2. Shows the Cd values and averages of robots at various speeds.

Speed	**Cd value (xE-28)**			
	Robot 1	**Robot 2**	**Robot 3**	**Robot 4**
15	5,57	4,49	3,23	2,45
20	3,14	2,53	1,82	1,38
25	2,01	1,62	1,16	8,83
Average	3,57	2,88	2,07	1,57
Average (%)	-24%	**Reference**	28%	95%

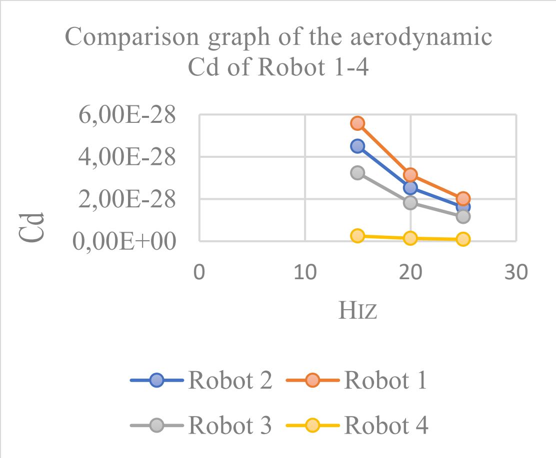


Figure 8. Comparison graph of the aerodynamic Cd of Robot (1)-(4).

4. CONCLUSIONS

This study concentrates on the design of quadruped robot technology, with a specific emphasis on their aerodynamic performance. The significance of aerodynamic factors in the design process has been emphasised, particularly in robots that move at high speeds, where these factors must be optimised.

Flow analysis using the CFD method enabled a detailed study of the flow structure around the quadruped robots. These analyses revealed the potential of passive flow control methods for reducing Cd. The study's findings demonstrate that these methods have the potential to enhance the energy efficiency of robots and optimize their motion capabilities.

One of the study's main focuses is the comparison of the aerodynamic characteristics of quadruped robots with varying geometries and dimensions. The investigation revealed that different designs have a significant impact on aerodynamic efficiency. The efficiency of the robots was found to be affected by air resistance due to their geometric dimensions. The efficiency of the robots was found to be affected by air resistance due to their geometric dimensions. Larger robots experience higher air resistance, resulting in lower energy efficiency. It is important to note that these observations are objective and based on the analysis of robot models. Conversely, smaller robots experience less air resistance and have higher energy efficiency.

Based on these results, it is concluded that considering the effect of geometric dimensions on drag is crucial for designing efficient and energy saving robots. This can lead to the creation of optimised structures and motion systems in future robot design processes. In particular, Robot 4 showed higher aerodynamic efficiency compared to the other models.

The study highlights the critical role of the aerodynamic structure in the long-term use of rechargeable quadruped robots. Optimising energy consumption through high aerodynamic efficiency enables robots to move longer and more effectively.

The aim of this study is to contribute to the development of more sustainable and aerodynamically efficient robotic systems by emphasising the importance of aerodynamic performance as a design parameter.

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