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A HYBRID LOCOMOTION MOBILE ROBOT WITH REAL-TIME MOTION MODE DECISION AND OBSTACLE AVOIDANCE

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Abstract: *In this study the design and development of a robotic system with hybrid locomotion, capable of step climbing and obstacle avoidance were conducted. The robot's motion system was a hybrid design, incorporating a three-wheeled leg mechanism that enables it to climb steps and traverse flat ground. A path planning and obstacle avoidance structure with the name of Direction Based Angle Calculation was proposed and tested. Furthermore, an algorithm that classifies the obstacles encountered by the robot according to their length and shape was proposed. Experimental tests, motion and transmission, obstacle avoidance, motion type determination was applied to measure the mechanical system and algorithm performances of robotic system. The outcome of these tests included the assessment of mechanical transmission and motion systems for step, obstacle climbing and linear ground movement. It was determined with all results from those applied tests that the mechanical transmission and motion systems are adequate for stair climbing and linear movement. Furthermore, it was observed that the developed direction-based angle calculation approach was sufficient for route planning and obstacle avoidance.*

Key words: *Hybrid locomotion system, Linear motion, Mechanical motion and transmission, Path planning and obstacle avoidance, Step climbing robot*

1. INTRODUCTION

The locomotion of robotic systems is strongly dependent on the planned operation environment. Those operation environments can be categorized as aerial, aquatic and terrestrial [1]. While the propellers and screws are generally more useful to use for aquatic and aerial operation systems, kinds of wheels, tracks, legs and combination of them can be selected for terrestrial environment conditions. Apart from the standard locomotion elements there is another tool as adaptive legs especially for the biologically inspired robots [2-5].
For the ground mobile robotic systems, various mechanical structures and mechanical architectures have been proposed for academic and industrial research. In these structures, there are three main categories as W (wheeled), T (tracked) and L (Legged). There are also four hybrids derived from the mains as LW (leg-wheel), LT (leg-track), WT (wheel-track) and LWT (leg-wheel-track). All these systems have their own pros and cons according to the performance criteria such as velocity, obstacle avoidance, climbing, motion and slope adaptation, motion adaptability for uneven terrain and energy efficiency [6-9]. The comparison chart of the performance of the locomotion systems shown in Figure 1.

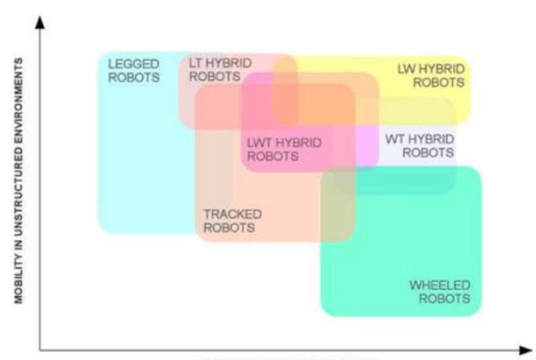

Fig. 1. Comparison chart of locomotion systems [6]

The mobility of robots in uneven environments is represented on the Y axis, while the performance metrics (velocity and energy efficiency) are indicated in X axis. The lower

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right is occupied by wheeled robots. This demonstrates better performance for the criteria of speed and energy efficiency.

However, these types of robots have lower levels of adaptability in unstructured environments when compared to other motion systems. Wheeled robotic systems have also less capability for obstacle climbing and struggling with the irregularities of the operation environment. This limits the mobility of the wheeled robotic system in uneven operation environments [10-12].

The tracked systems are placed in the middle of the chart. Tracked systems can have better performances for the criteria of obstacle climbing and coping with the irregularities of the operation environment than wheeled structures. However, they have less effectiveness for the velocity and energy consumption [13].

As clearly seen in Figure 1, the hybrid categories have been designed and developed to take benefits from the main categories of wheeled, tracked and legged. However, the total gain cannot be completely obtained because of the extra payload effects of the additional locomotion elements. Those hybrid systems are proper to use for operation environments that require velocity and obstacle climbing. The hybrid systems can mainly be constructed with four ways listed below [14-16]:

1. Connection of the legs to main structure of the wheeled robotic system
2. Combination of the wheel and legs to operate together
3. Utilization of retractable modules
4. Wheel placement at the end of the legs.

The first approach is relatively uncomplicated. The wheels or legs can be used according to environmental conditions alternatively. The main disadvantage of these types of structure is the extra weight because of the additional locomotion system [17]. In the combination of the wheel and leg structure, the wheels and legs cannot produce motion by itself. For the movement collaborative action is required. The main advantage of these types of system is the requirement of less actuation components. In the third approach, robotic systems are equipped with retractable modules and these modules can be used as wheel or leg according to the environment conditions. Although it seems like an interesting and functional method, it is a complicated and not reliable one because of the low shock resistance [18]. In the last hybrid method, the wheels can be directly connected to the end of the legs. By this way the structure can create the linear motion with the rolling of the wheels and can climb the obstacles with the help of the legs [19].

(Bruzzone et al. [20]) studied analysis and experimental tests of the step climbing capability of their wheel-track-leg robotic system. The robotic system had relatively small sizes with dimensions of 450x350x130 mm. Its payload was determined as 0.5 kg. They structured the robotic system with the combination of two driven wheels, rotating legs, tracks and omni wheels. Their experimental test results showed that the robotic system could step up to 165 mm.

(Dalvand et al. [21]) developed MS Rox robotic system with hybrid locomotion system. The driving unit was created as Star wheel. This structure was engineered to navigate the steps and climb the obstacles and stairs. The Star wheel was a three-legged wheel hybrid locomotion unit. It was equipped with rotary axes to perform the linear and climbing movements. Four units of Star wheel locomotion units were connected to the body of the robot. According to movement requirements, MS Rox could traverse the ground with the wheel rotation motions of the wheels and climb the obstacles with rolling motion.

(Xing et al. [22]) designed and developed the ASR-III robotic system which had the features of multi-pedal, vectored waterjet, hybrid locomotion and amphibious spherical. It was constructed a wheeled-legged, waterjet composite propulsion system with a lifting and supporting wheel mechanism (LSWM) and waterjet propulsion mechanical legs. The LSWM was designed to provide the ability to support the body and flexibly on smooth terrain. The composite drive structure enhanced the adaptability of the robotic structure to the amphibious environment with two modes of motions on land as gliding and walking and an underwater movement mode with vectored thrusters. They evaluated the efficiency of the system by conducting forward and backward kinematic models.

(Lu et al. [23]) proposed a hybrid leg-wheel locomotion system with the name of HyTRo which transforms mechanically. Their structure could demonstrate three modes of locomotion, such as wheel roll, quadruped walking and leg-wheel mode. They selected the obstacle types as stairs, large ledges and ditches for experimental tests. They reported that the proposed locomotion structure was successful for environmental adaptation and passing the selected types of obstacles.

In this study, design and development of a mobile robotic system with hybrid locomotion system was conducted. Hybrid locomotion was created with a three wheels motion system. Three-wheel mechanisms could provide linear motion with wheel rolling for ground mobility. This mechanism could rotate around on its connection shaft to create entire rolling motion to climb the obstacles and steps. A transmission system was designed and developed for transition from linear movement to climbing. This transmission system was constructed using helical gears to transform the motion. The main gear center gear was actuated using a linear actuator for transformations of the motion modes. System could determine the motion type automatically with integrated distance sensors and developed algorithm for this. A real time path planning and obstacle avoidance algorithm with the name of Direction Based Angle Calculation was also developed. All those functions of the robotic system were tested experimentally, and the obtained results were presented.

2. MATERIAL AND METHOD

2.1 Mechanical Structure

In the course of the mechanical design process, a number of issues were given due consideration, including the following: modularity for the purpose of facilitating ease of assembly; a compact structure for the purpose of ensuring sufficient payload capacity; a lightweight structure for the purpose of decreasing energy consumption; proper tolerances for the purpose of facilitating component assembly; and the mechanical strength of the parts. The design of the parts and assembly processes conducted using Autodesk Inventor Software. Part list and exploded view and engineering drawings including general dimensions documents were created. These documents were useful to decide and to source the required parts and hardware. The general design view of the robotic structure was shown in Figure 2.

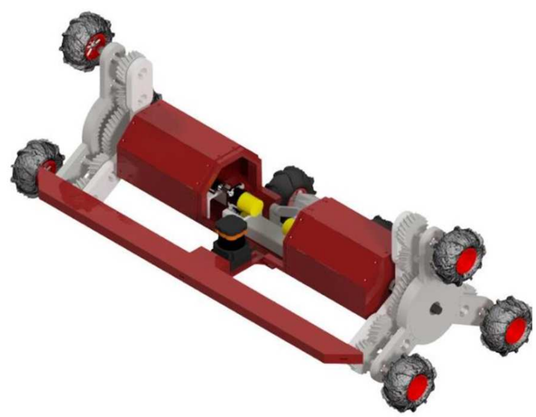

Fig. 2. General design view of the robotic structure

The dimensions and weight of the robotic system were crucial aspects as they directly affected the motion capacity and energy consumption. It was considered to keep the system lightweight and easy to move. The total weight was about 10.5 kg with all the mechanical components and electronic hardware. The general dimensions were presented in Figure 3 and Table 1, respectively.

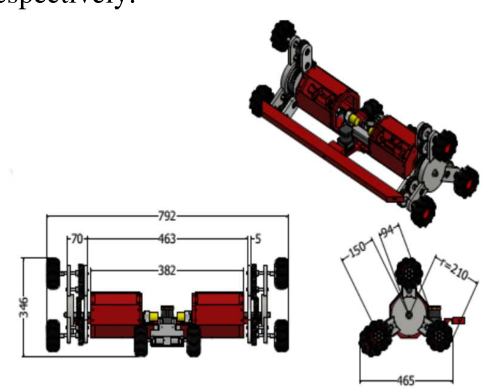

Fig. 3. Dimensions of the robotic system

Table 1. Dimensional information of the system

No	Name of the Dimension	Value (mm)
1	Maximum length	792
2	Chassis length	464
3	Cover length	382
4	Gear system length	70
5	Maximum height	346
6	Maximum width	466
7	Maximum radius	210
8	Chassis radius	150
9	Cover radius	95
10	Gap between inside cover and gear	5

Exploded view and part list of the system were given in Figure 4 and Table 2, respectively.

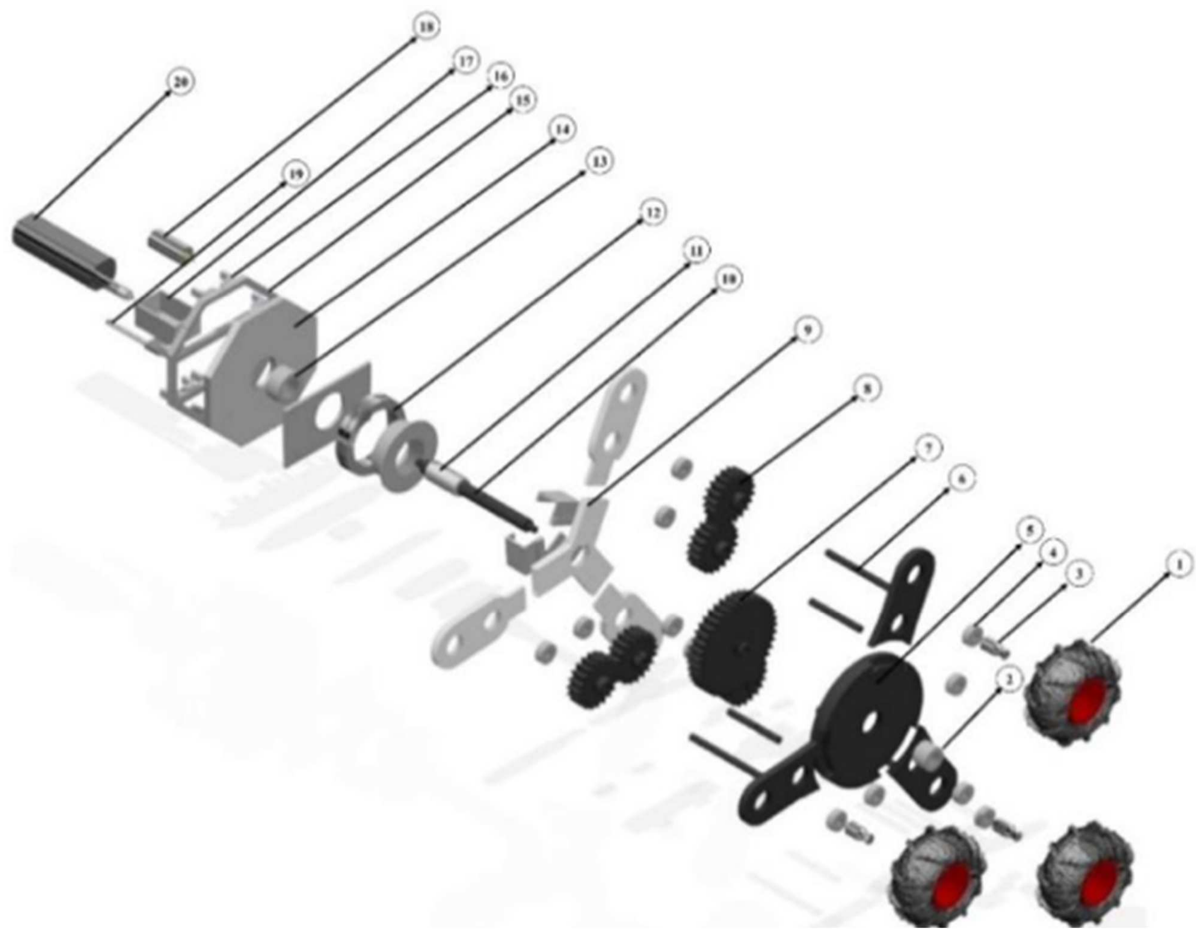

Fig. 4. Exploded view

Table 2. Part list

No	Name of the Components	Pieces
1	Wheels	8
2	Housing rubbers	2
3	Shaft to wheel connectors	8
4	Bearings	24
5	Outer covers	2
6	Shafts	12
7	Gears	2
8	Inner-outer gears	12

9	Inner covers	2
10	Main shafts	2
11	Couplings	2
12	Axial bearing	2
13	Ball bearings	2
14	Covers	2
15	Frames	2
16	Brackets	18
17	Motor covers	2
18	DC motors	2
19	Linear motion guides	2
20	Linear actuators	2

2.2 Material Selection and Prototyping

The mechanical components of the robotic system except motor wheel connector and shaft were designed and produced using PLA (Polylactic Acid) material using FDM (Fused Deposition Modelling) method. The rationale behind this selection was to leverage the benefits of the PLA material, including its biodegradability, high printing speed, and lower layer height requirements [24]. The infill type and density were determined as hexagonal and 50%, respectively, with the objective of reducing material consumption while ensuring sufficient structural strength [25]. Motor-wheel connectors and shafts were manufactured using S 235 steel, the wheels were selected with the diameter and width of 120 and 60 mm, respectively.

2.3 Motion Analyses

Motion calculations and analyses were conducted to calculate the forces effective on the climbing motions of the robotic system. The torque, power and angular velocity requirements which useful for the actuator and energy source selection were determined using these analyses. The robotic system was assumed as a rolling down object on an inclined plane for climbing motion analysis (Figure 5). The angle of the slope of the plane was decided using the height and length dimensions values of the ladder step.

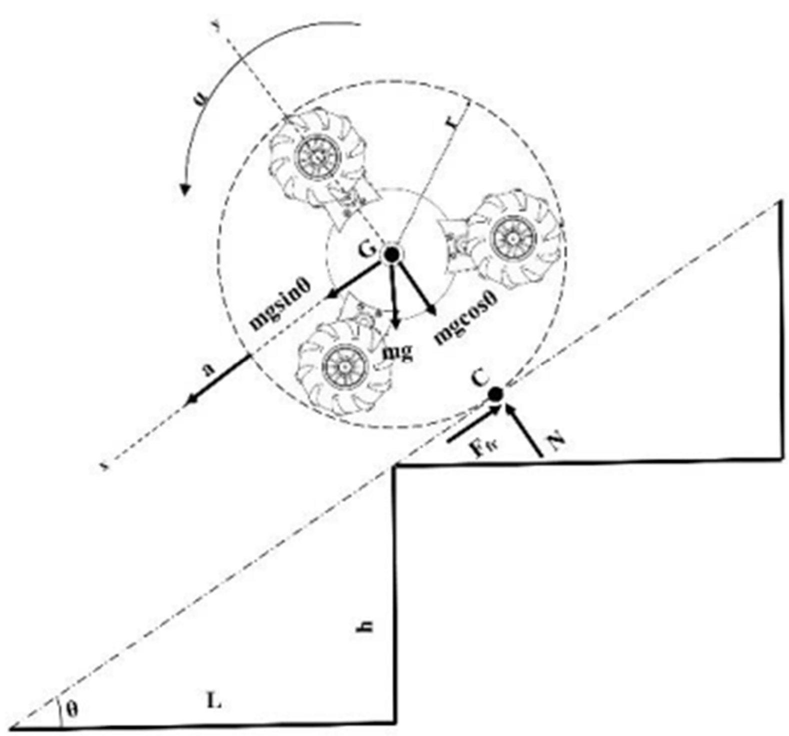

Fig. 5. Rolling down object assumption for climbing motion analysis

The step's height and length were designated as 150 mm and 300 mm, respectively. The angle of slope (θ) was calculated to be 30°. The forces, torque and power parameters were calculated for the condition of equilibrium. It was determined as, if the calculated minimum parameters of the equilibrium were applied as reversely, the structure could avoid the rolling down and could have forward motion. The forces and the moments were calculated using the equations below:

$$\Sigma F_X = F\ mgsin\theta - F_{fr} = ma \quad (1)$$
$$N - mgcos\theta = 0 \quad (2)$$
$$\Sigma M_g = I\alpha \quad (3)$$
$$F_r = mr^2\alpha \quad (4)$$

The maximum force calculated with mass and translational acceleration was more than the slippage force of the wheel and ground, the rolling and climbing motion occurred as expected. The maximum force was calculated with the equation given below:

$$mgsin\theta = \frac{3}{2}ma = Fmax \quad (5)$$

The maximum translational and angular acceleration were found as;

$$a_m = 2gcos\theta\mu \quad (6)$$
$$a = \frac{2}{3}sin\theta \quad (7)$$

The total rolling torque was calculated as the sum of the moments of the rotational and translations moments:

$$\Sigma M = 3/2mar \quad (8)$$

In where:

$\sum Fx$	*Total translational force*
N	*Reaction force at point of C*
Ia	*Torque*
a	*Translational acceleration*
a_m	*Maximum translational acceleration*
α	*Angular acceleration*
μ	*Static friction coefficient*
r	*Radius of robotic system*

2.3 Electronic System

The electronic system was designed to control the motions of the robotic system. Raspberry pi 3b was selected as the main controller of the system. Distance sensors were used for motion decision mechanisms and transitions from the linear to climbing movement. The system was equipped with Hokuyo 30 LX lidar for obstacle avoidance and path planning structure.

2.4 Motion Mode Decision Structure

The motion-mode decision algorithm structure was created to control the movements of the robotic system. The system first checked the height of the obstacle that might be ladder step or obstacle object. According to the height of this obstacle the control algorithm could decide the movement. If there wasn't any obstacle or the height of the obstacle was in the range of pass (up to 120 mm) the robotic system passed this obstacle with linear movement. If the height was between 120-200 mm, the transition was activated with a transmission system. The center gear was pushed with linear actuator, gear was placed into the center of the transmission system. Then the entire rolling was activated robotic system could climb the obstacle or step with three-wheel entire rolling motion. If the obstacle is higher than 200 mm, then path obstacle avoidance mode was activated, and robotic system could continue its movement with the help of the direction-based angle calculation algorithm structure. The flowchart of the motion type decision mechanism was shown in Figure 6.

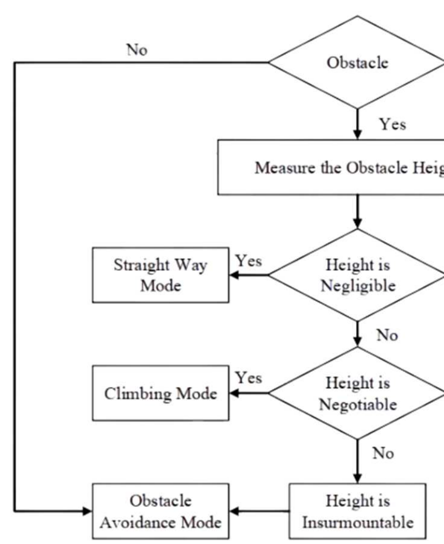

Fig. 6. Flowchart of the motion type decision system

2.5 Path Planning and Obstacle Avoidance Structure

After the determination of the motion requirement as being obstacle avoidance, the robotic system endeavored to ascertain the safest path by means of direction-based angle calculation. In this structure, the FOV (field of view) of the robotic system was divided into five regions with the data obtained from the lidar (see Figure 7).

The reaction distance was determined to be 1,600 mm, which was twice the length of the robotic system. The motion reactions to obstacle avoidance are illustrated in Figure 8.

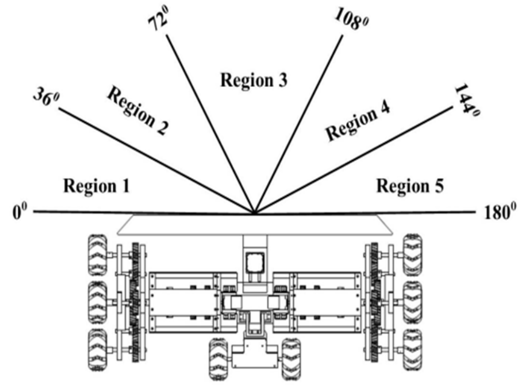

Fig. 7. Regions of the direction-based angle calculation structure

Name of the Situation	Regions					Reaction of the System
	Region 1	Region 2	Region 3	Region 4	Region 5	
Fire Search						Try to Find the Fire Source
Front Obstacle			■			Turn Right (Smooth
Front Left Obstacle		■				Turn Right (Smooth
Left Obstacle	■					Turn Right (Smooth
Front Left Obstacle	■	■				Turn Right (Smooth
Front Right Obstacle				■		Turn Left (Smooth)
Right Obstacle					■	Turn Left (Smooth)
Front Right Obstacle				■	■	Turn Left (Smooth)
Left Corner		■	■			Turn Right (Sharp)
Right Corner			■	■		Turn Left (Sharp)
Obstacle		■	■	■		Turn Right (Sharp)
Left Corner	■	■	■			Turn Right (Sharp)
Right Corner			■	■	■	Turn Left (Sharp)
Corridor		■		■		Move Forward
Corridor	■				■	Move Forward
Corridor	■	■		■	■	Move Forward
Trap	■	■	■	■	■	Stop the Motion

Fig. 8. Motion reactions

3. RESULTS AND DISCUSSION

3.1 Motion Analysis Results

The motion analyses calculations were conducted using Matlab Software with created scripts (Figure 9). For those calculations, total mass defined as 10.5 kg, static friction coefficient was selected as 0.75 and radius of robotic system was defined as 210 mm. The maximum force was calculated as 200.7 N which was more than the slippage force of 51.5 N. It resulted from this information, the entire rolling for the climbing could be conducted by the robotic system. The rolling acceleration and torque were also calculated as 3.27 m/s^2 and 10.8 Nm, respectively.

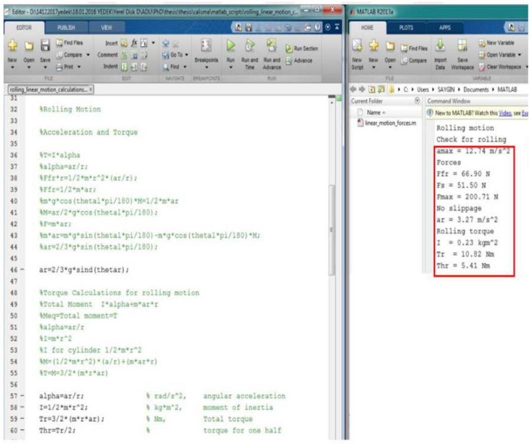

Fig. 9. Torque and acceleration results

The speed of the robotic system was desired as 1m/s. The angular velocity and power requriement was found as 46 rpm and 52 watt, respectively (Figure 10).

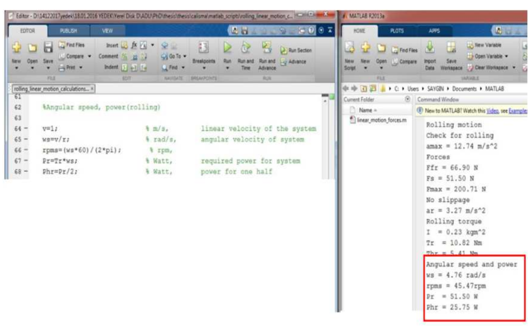

Fig. 10. Angular velocity and power requirement analyses results

Dynamic analyses simulations were also conducted in Ansys Rigid Body Dynamics environment (Figure 11) to check the results obtained from the Matlab numerical calculations. The calculated angular velocities were applied to DC motors for simulation. The similar results with the numerical calculations were obtained from the simulations as 3.5 m/s^2 rolling acceleration, 10.1 Nm torque and 0.97 m/s speed.

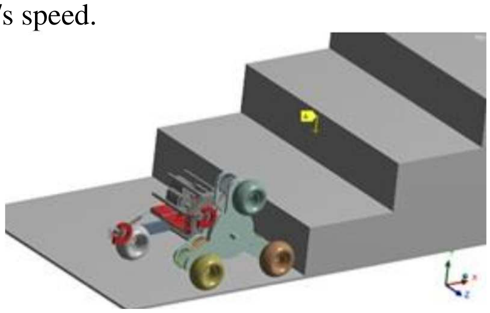

Fig. 11. Climbing simulation

Using the data from the numerical analyses and simulation results, the Dc motors for actuation and power sources were selected. The calculated values were divided into 2 as the system was driven by 2 dc motors and these motors were selected with the specs of 5.2 Nm torque, 80 rpm and 40-watt power. The lipo type batteries with specs of 14.8 V, 3 Ah and 44 Wh energy output was determined as power sources of the structure.

3.2 Transmission and Transition System Test Results

For the experimental tests of the transmission and transition systems, a test bench was constructed (Figure 12). The performance of the motion decision algorithm structure and mechanical system performance were tested. Distance sensors were placed to trigger the transition from linear to climbing motion and vice versa. It was observed from these experimental tests that the motion decision algorithm could properly activate the transition between the motion modes according to the measured height data. The mechanical structure also performed well. The center gear could place the center of the transmission gear system properly and conducted the entire rolling motion. When the path was without any obstacle or ladder step, the center gear was pushed back and triggered the linear movement.

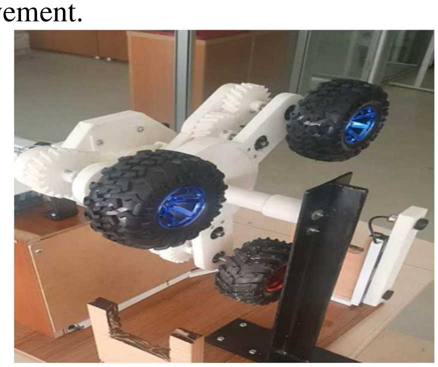

Fig. 12. Test bench of motion system

3.3 Obstacle Avoidance and Path Planning Structure Test Results

The obstacle avoidance and path planning structure were constructed via the obtained data from Hokuyo lidar. The system was created according to proposed direction-based angle calculation algorithm. The different cases were simulated on the test bench to observe the reactions of the structure to the different placed obstacles. It was observed that the structure could react properly and provide correct motion signals for obstacle avoidance and path planning (Figure 13).

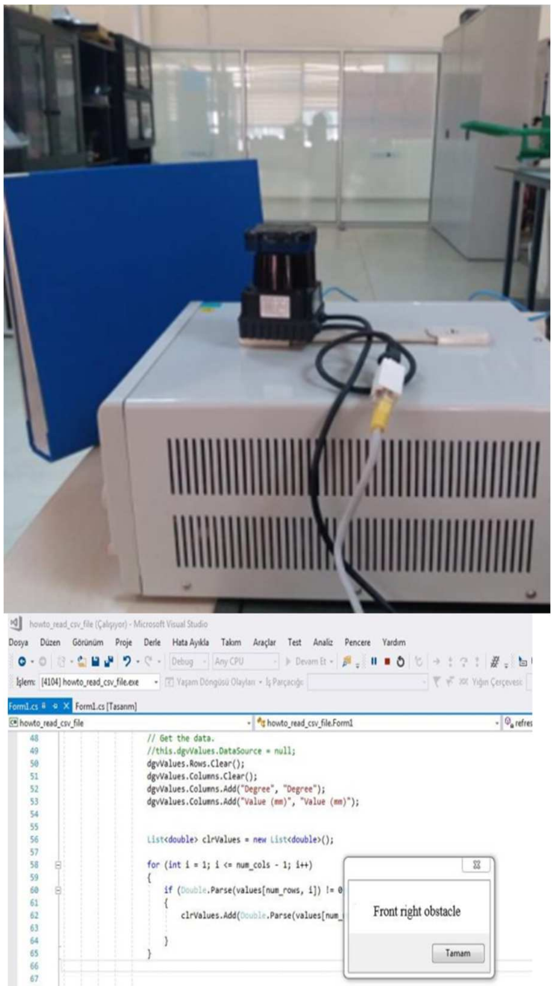

Fig. 13. Path planning and obstacle avoidance structure tests

3.4 Operational Test Results

The obstacle avoidance and step climbing capabilities of the robotic structure were tested in operation environment. In the first case, the obstacles were placed in different directions and the reactions were observed. The robotic system could detect the place of the obstacles and pass them properly as structured with direction-based angle calculation algorithm (Figure 14).

Fig. 14. Obstacle avoidance tests

In the second case, the motion decision and step climbing capability of the system were tested. It was observed from these tests that the structure could determine the type of obstacle, and it could climb it by activating the entire rolling motion (Figure 15).

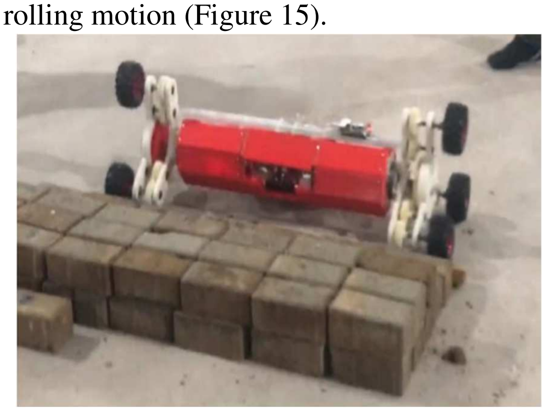

Fig. 15. Climbing test

In comparison with previously reported robotic systems employing hybrid locomotion mechanisms, the proposed robotic platform introduces a unique combination of mechanical and algorithmic innovations that significantly enhance its functional performance. Prior studies, such as Bruzzone et al. [20], presented a compact wheel-track-leg configuration with basic stair climbing ability; however, their system was limited in payload capacity and lacked autonomous mode transition capabilities. Similarly, Dalvand et al. [21] implemented the MS Rox robot with a star-wheel design, capable of alternating between linear motion and climbing through rotary mechanisms, yet it relied on predefined commands rather than real-time sensory input for locomotion decisions.

More complex systems, such as the ASR-III amphibious robot by Xing et al. [22] and HyTRo-I by Lu et al. [23], demonstrated multi-modal locomotion with advanced mechanical designs, including retractable or transforming limbs. Nonetheless, these systems often require elaborate mechanical complexity or external control inputs and do not feature an integrated, sensor-based decision-making structure. Furthermore, many prior systems do not incorporate real-time path planning or adaptive obstacle avoidance directly into the control architecture, which limits their operational autonomy in unpredictable environments.

The robotic system developed in this study addresses these limitations through the integration of three key innovations: (1) a hybrid three-wheel mechanism capable of both linear rolling and full-body climbing through an internal gear-based transformation system actuated by a linear actuator; (2) a motion-mode decision algorithm that utilizes real-time height data from distance sensors to autonomously switch between locomotion modes; and (3) a direction-based angle calculation method for real-time path planning and obstacle avoidance, implemented through lidar-based environmental sensing.

Together, these elements result in a robotic system that is not only mechanically capable of traversing varied terrains—including stairs and irregular surfaces—but also autonomously adaptive, responding dynamically to environmental inputs without the need for operator intervention. This comprehensive combination of modular mechanical design and intelligent decision-making algorithms sets this study apart from existing work, establishing it as a novel and practically applicable solution for mobile robotics operating in complex, real-world environments.

4. CONCLUSION

In this study, comprehensive design, development, prototyping, motion analyses and experimental tests of the mobile robotic system with hybrid locomotion were conducted and presented. Hybrid locomotion was constructed with a three-wheel mechanism capable of providing linear and climbing movements.

Transmission and transition systems were developed for ground and step obstacle climbing operations. The transmission system was created using helical gears and linear actuation mechanism to push and to pull the center gear to trigger the movement types.

The motion analyses and simulations were conducted to check the capability of the structure for the desired movements and for actuator and power supplier selection. A motion decision structure which can determine the required movements automatically was presented. A direction-based angle calculation algorithm was developed to path planning and obstacle avoidance.

Test benches were structured, and experimental tests were applied to observe the performance of all mechanical structures and developed motion decision, path planning and obstacle avoidance algorithms. Operational tests were performed to observe the movement capacity, obstacle avoidance ability and step climbing actions of the robotic systems. From all those studies and conducted tests it could be concluded that a mobile robotic system structure equipped with the three-wheel mechanism hybrid motion system was created and constructed properly.

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Un robot mobil de locomoție hibrid cu decizie în timp real în modul de mișcare și evitarea obstacolelor

Rezumat: În acest studiu s-a realizat proiectarea și dezvoltarea unui sistem robotizat cu locomoție hibridă, capabil să urce scările și să evite obstacolele. Sistemul a fost proiectat și fabricat pentru a funcționa atât în medii interioare, cât și în exterior. Sistemul de mișcare al robotului a fost un design hibrid, încorporând un mecanism de picioare cu trei roți care îi permite să urce scări și să traverseze terenul plat. A fost propusă și testată o structură de planificare a traseului și evitarea obstacolelor cu denumirea de Calcul unghiului bazat pe direcție. Mai mult, a fost propus un algoritm care clasifică obstacolele întâlnite de robot în funcție de lungimea și forma lor. Teste experimentale; Mișcarea și transmisia, evitarea obstacolelor, determinarea tipului de mișcare au fost aplicate pentru măsurarea performanțelor sistemului mecanic și al algoritmului sistemului robotizat. Rezultatul acestor teste a inclus evaluarea sistemelor de transmisie mecanică și de mișcare pentru urcatul scărilor și deplasarea în linie dreaptă. S-a determinat cu toate rezultatele din acele teste aplicate că sistemele mecanice de transmisie și mișcare sunt adecvate pentru urcarea scărilor și mișcarea liniară. În plus, sa observat că abordarea dezvoltată de calcul al unghiului bazată pe direcție a fost potrivită pentru planificarea rutei și evitarea obstacolelor.

Cuvinte cheie: Sistem de locomoție hibrid, Mișcare liniară, Mișcare și transmisie mecanică, Planificarea traseului și evitarea obstacolelor, Robot de urcare a treptei

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