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OTONOM PARK ROBOTU TASARIMI

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Anahtar Kelimeler

Otomatik yönlendirmeli araç, Çok yönlü hareket, Park robotu tasarımı, Sürüş sistemi, Taşıma kolu

Öz

Bu çalışmada otomatik otopark sistemlerinde kullanılmak üzere bir park robotu tasarımı sunulmuştur. Bu park robotu ile park sürelerinin azaltılabileceği, park katlarında bulunan mekanik ekipmanlardan tasarruf edilebileceği ve hareket kısıtlarını ortadan kaldırılabileceği öngörülmüştür.100 mm yükseklikte 2 eş modülden oluşan park robotu tasarımında Otomatik Yönlendirmeli Araçların (AGV) kullanım potansiyelinden faydalanılmıştır. Yürütme grubu ve taşıma kolları tasarımları ile hesaplamalarının incelendiği bu çalışmada yükseklik sınırına uygun olarak yeni tasarımlar geliştirilmiştir. Park robotunun yük ve hızına bağlı olarak yürütme grubu ve taşıma kolları için gereken güç hesabı ve dayanım analizi yapılmıştır. Analiz sonuçları incelendiğinde yürütme grubu temel parçalarının maksimum gerilme ve deformasyon değerleri, seçilen malzemelere bağlı olarak istenilen tolerans aralığındadır. Tekerlek mili için Von Mises gerilme değeri 143.98 MPa, poliüretan malzeme için deformasyon değeri 0.042 mm olarak ölçülmüştür.

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AUTONOMOUS PARKING ROBOT DESIGN

Keywords

Automated guided vehicle, Omnidirectional movement, Parking robot design, Driving system, Handling arm

Abstract

In this study, a parking robot design has been presented for use in automated parking systems. It is anticipated that this parking robot can reduce parking times, minimize the need for mechanical equipment on parking floors, and eliminate movement constraints. The design consists of two identical modules with a height of 100 mm, utilizing the potential of Automated Guided Vehicles (AGVs). This study examines the design and calculations of the drive unit and lifting arms, developing new designs that comply with height limitations. Based on the load and speed of the parking robot, power calculations and strength analyses were conducted for the drive unit and lifting arms. The analysis results indicate that the maximum stress and deformation values of the main components of the drive unit fall within the desired tolerance range, depending on the selected materials. The Von Mises stress value for the wheel axle was measured at 143.98 MPa, while the deformation value for the polyurethane material was determined to be 0.042 mm.

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Extended Abstract

Introduction

Automated Guided Vehicles (AGVs) are widely used in various industries for repetitive load transportation. By leveraging this potential in the automated parking sector, a parking robot design has been introduced. This parking robot is expected to reduce parking times, minimize the need for mechanical equipment on parking floors, and eliminate movement constraints. In our parking robot design, which consists of two identical modules with a height of 100 mm, the drive unit and lifting arms have been designed and analysed, leading to the development of new designs suitable for height limitations.

Objectives/ Research Purpose

Various design models can be used for the drive unit. Mecanum wheels provide excellent manoeuvrability in tight spaces due to their omnidirectional movement capability; however, they have low load-carrying capacities. The Driving-Steering (DS) wheel mechanism offers high manoeuvrability under heavy loads, but height constraints prevent us from using this mechanism. In our study, we propose a new drive unit design consisting of two wheels.

The method of vehicle transportation is crucial in automated parking systems, particularly for equipment savings. In the pallet-based transportation method, individual pallets are required for each vehicle, along with additional systems to transport these pallets. In our study, we aim to eliminate the need for pallets and their associated transport systems by implementing a robotic arm-based transportation solution.

Methods/ Methodology

The parking robot, consisting of two modules, was designed by the authors using SolidWorks 2024 software. Each module comprises four independent drive units and four independently hydraulically actuated transport arms. The parking robot first moves underneath the vehicle and lifts it by its wheels using its arms to perform the transportation process. The drive unit of our parking robot consists of two independent polyurethane-coated wheels, each driven by an identical brushless DC motor. Polyurethane-coated wheels are highly resistant to wear and operate more quietly compared to other materials. Due to these properties, the use of polyurethane-coated wheels in automated parking systems under heavy loads appears to be suitable. In this section, resistance forces acting against movement are calculated to determine the required power for the drive unit. Additionally, in the scenario where the vehicle is being transported, the forces acting on the transport arms are analysed, and the hydraulic power calculation is performed. The necessary loading was applied to the drive unit wheel, and Von Mises stress and deformation values were examined using Ansys software.

Results/ Findings

This section presents the results of the analyses conducted on the drive unit wheel design. The materials used in the design are ductile materials. Equivalent (Von Mises) stress values and deformation amounts are provided along with the yield stress limit values. Upon examining the analysis results, it is observed that the maximum stress and deformation values of the drive unit's main components fall within the desired tolerance range, depending on the selected materials. The Von Mises stress value for the wheel axle was measured as 143.98 MPa, while the deformation value for the polyurethane material was recorded as 0.042 mm.

Discussion and Conclusions

The widespread use of AGVs across various industries worldwide is expected to contribute to the development of smart parking systems through their integration into automated parking systems. In our study, the uni-directional parking robot eliminates the need for separate pallets for each vehicle by utilizing a mechanical arm-based transportation method. In the design of the drive unit, mecanum wheels were not used due to their low load-carrying capacities, and DS wheel mechanisms were not feasible due to height constraints. As an alternative design, a two-wheel drive unit that meets the height limitation was proposed, and a structural strength analysis was conducted. Upon examining the analysis results, the maximum stress and deformation values of the main components of the drive unit were found to be within the desired tolerance range, depending on the selected materials. Future studies may evaluate alternative parking designs, cost analyses, and parking durations in an automated parking system where the parking robot is utilized. Additionally, a steering solution for a parking robot of this height remains a subject of research.

1.Introduction

Automatic parking systems offer many advantages over traditional parking systems. They provide faster access to cars and offer secure parking with less space and volume requirements (Wu, Xu, Gong, De Koster & Zou, 2019). In general, the system comprises entrance rooms, car lifts, shelf conveyors and shuttles systems on each floor, and steel pallets moving in the system for each vehicle. All of these components contribute to the overall investment cost. The use of parking robots may eliminate the requirement for many of these equipment, leading to cost reduction and increased car capacity. In addition, it is possible to reduce parking times.

A study by Wu et al. (2019) examined the design of a compact, relatively low-cost, and fast-responding automated parking system based on a real application. The system consists of entry rooms, vertical transmission systems at each floor level, and two elevators equipped with rotating turntables. Alternative models were presented for designers, taking into consideration time efficiency and system cost. By using the parking robot in these systems, alternative parking designs can be re-evaluated in terms of cost and speed.

Another study by Vis (2006) examines the literature on the design and control aspects of AGV systems used in production areas. AGVs are fully automatic driverless systems that meet transportation needs. They are commonly used in industrial applications and storage systems for repeated load transportation. (Vis, 2006). The advent of technological advances has led to the utilization of AGVs in a multitude of applications. We introduce a new application area by bringing the potential use of AGVs into automatic parking systems.

There are several design models available for the drive group of the parking robot. The use of Mecanum wheels has been evaluated from this perspective. In his study, Greffer (2008) examines the geometry of the Mecanum wheel in detail. Mecanum wheels are a mechanism with omnidirectional movement capability. Each wheel contains cylindrical and freely rotating barrel wheels placed at a certain angle to the wheel axis. Mecanum wheels, with four independently driven wheels, enable movement in any direction (forward, backward, right, left) as well as diagonal movement. The rotation direction of each wheel's angled rollers controls the vehicle's direction and movement style. Proper synchronization of the wheels' movements ensures the desired motion in the intended direction. Mecanum wheels are suitable for manoeuvring in narrow spaces (Grerrer, 2008). Due to their low load capacity, we are unable to use Mecanum wheels in our study.

A study by Jiang, Zhang, & He (2020) proposes a new heavy-duty omnidirectional wheel arrangement that increases the operational and movement capacity of AGVs. The DS (Driving-Steering) wheel mechanism, which has four independent wheels and four independent steering systems capable of working under heavy load, can significantly increase the transportation efficiency and flexibility of AGVs by providing wide manoeuvrability (Jiang et al., 2020). The direction of each wheel can be adjusted independently through a separate drive mechanism, meaning each wheel can rotate at a different angle. This allows the AGV to move in a highly versatile manner, even in narrower spaces. Each wheel moves independently with its own drive motor and propulsion mechanism. This allows for much more precise speed and movement control of the AGV. When compared to Mecanum wheels, it has advantages such as high manoeuvrability and strong carrying capacity (Sun, Liu, Zhao, & Wei, 2019). Although this wheel mechanism is very suitable for our study, its direct use is not feasible due to our height limitations.

The method of transporting vehicles represents a fundamental feature of the operational functionality of the parking robot. In their studies Shen, Qiu, Wu, Lin, & Wu (2021), examined mechanical arm-based exchange and platform-based exchange in parking robots in terms of vehicle exchange technologies. In the mechanical arm-based transport solution, the robot directly enters under the vehicle, and mechanical arms or gripping mechanisms surround each tire of the vehicle to transfer it (Shen et al., 2021). In the pallet-based transport solution, the vehicle first parks on a pallet, and the robot then enters under the pallet to transfer the vehicle along with the pallet (Shen et al., 2021). Since the aim of our study is to reduce the equipment used in automated parking systems and, consequently, the costs, a mechanical arm-based solution has been preferred in our design, eliminating the need for a platform.

The aim of this study is to design a parking robot for use in automated parking systems, minimizing the equipment requirements in these systems. The design consists of two identical modules with a height of 100 mm, utilizing the potential of Automated Guided Vehicles (AGVs). This study examines the design and calculations of the drive unit and lifting arms, developing new designs that comply with height limitations. Based on the load and speed of the parking robot, power calculations and strength analyses were conducted for the drive unit and lifting arms. In our design, each module includes four independent drive units and four independent handling arms. Each drive unit consists of two independent polyurethane-coated wheels, operated by a separate drive mechanism of our custom design (Figure 1).

Due to the height limitations in the design, the DS wheel mechanism has not been preferred. Additionally, mecanum wheel mechanisms have not been used in the design due to limited load capacity. The solution to the steering problem of a parking robot at this height is a topic for future research. The parking robot in this study will move in a single direction. The design of the parking robot aims for it to lift the vehicle by gripping its front and rear wheels with the hydraulic drive mechanisms in the handling arms, thereby eliminating the need for steel platforms, floor conveyors, and shuttle systems, and performing the parking operation.

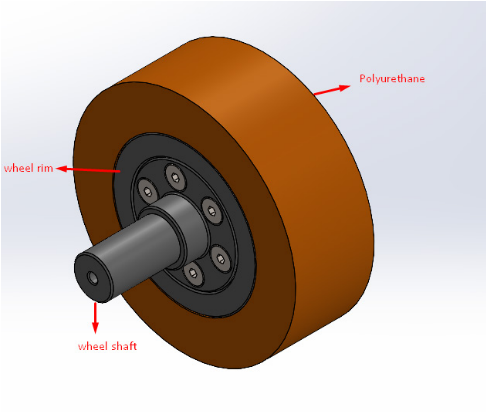


Fig. 1. Polyurethane coated wheel

2.Methods/ Methodology

The parking robot that we designed is constructed from two identical modules, each of which is capable of independently lifting the front and rear wheel pairs of cars. These design modules are shown in Figure 2. The designs were created by the authors using Solidworks 2024 software. Each module is equipped with four independent drive units. In addition, each module is equipped with four independently operating and hydraulically driven carrying arms. The parking robot first enters under the vehicle and lifts it from its wheels using its arms. The necessary parameters for the design are provided in Table1.

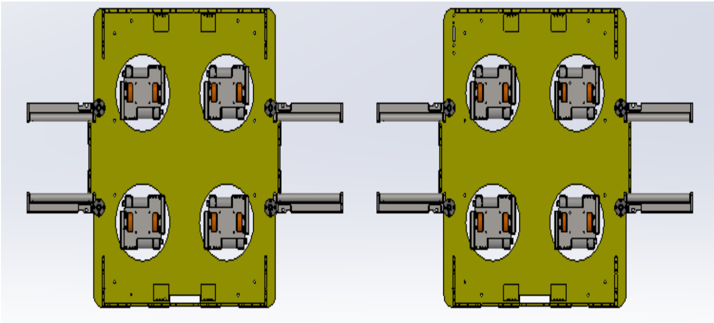


Fig. 2. The Parking Robot Comprises Two Identical Modules

Polyurethane is highly resistant to wear. It ensures that the wheels last longer in harsh conditions. It has the capacity to absorb vibrations and shocks. While moving on different surfaces, polyurethane-coated wheels provide more stable movement by preventing damage to the vehicle's electronic and mechanical components. Polyurethane-coated wheels operate more quietly compared to other materials. In these aspects, the use of polyurethane-coated wheels under heavy loads in automatic parking systems seems suitable.

The medium carbon content of CK 45 steel material makes it wear-resistant and high-strength. This property ensures the material's durability under high tension and force applications. Thanks to its medium carbon content, CK 45 steel material is highly machinable and can be shaped through processes such as turning and milling. This provides an advantage for the production of customized parts suitable for design specifications. This material meets the strength and durability requirements in applications like machine components and transport systems. For this reason, CK 45 steel has been preferred for the wheel shaft and wheel rim of the parking robot.

Table 1. Necessary Parameters for the Design

Maximum Load	Robot Weight	Velocity	Total Height	Floor	Wheel Diameter
2500 (kg)	700 (kg)	1 (m/s)	100 (mm)	Concrete	90 mm

This study adheres to research and publication ethics.

2.1 Drive Unit

The types of motors used in the drive group of AGVs are geared DC motors, brushless DC motors, and servo (Moshayedi, Li, & Liao, 2019). These motors are selected based on their impact on the flexibility and accuracy of AGV movement (Moshayedi et al.,2019). Brushless motors are generally more efficient due to their design. Since they lack brushes, there is no friction loss, and they have a longer lifespan. They are typically used in applications that require speed control but do not require precise positioning. In addition to being cost-effective, they are suitable for applications that demand less precision and control.

The drive group of our parking robot comprises two independent polyurethane-coated wheels, each driven by an identical brushless DC motor (Figure 3). The resistances against motion may be classified into four categories: rolling resistance, air resistance, acceleration resistance, and incline resistance (Xing, Yang, Zu, & Yu, 2019). The total force required to overcome these resistance forces and the required torque value can be calculated to obtain the power value (Xing et al., 2019).

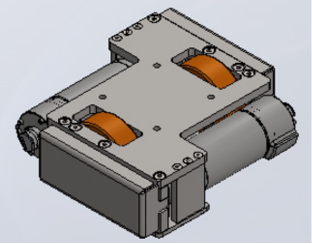


Fig. 3. Drive Unit

$$\sum F = F_f + F_w + F_J + F_i \quad (1)$$

$$F_f = fM_g \quad (2)$$

$$F_J = Ma \quad (3)$$

$$F_i = Mg sin\beta \quad (4)$$

$$F_w = -kv \quad (5)$$

$$\sum T = \sum Fr \quad (6)$$

$$P = T\omega \quad (7)$$

In this context, F_f represents rolling resistance as described in Equ.2, F_J represents acceleration resistance as described in Equ.3, F_i represents incline resistance, F_w represents air resistance, M represents the total weight of the parking robot and the load to be carried, g represents gravitational acceleration, r represents wheel radius, and represents angular velocity. In the absence of air resistance, the incline resistance F_i and air resistance F_w forces are considered to be zero when the parking robot operates on a flat surface (β=0). The parking robot is desired to achieve a speed of 1 *m/s* in 2 seconds. So, the acceleration will be 0.5m/s^2. The coefficient of rolling resistance is defined as f = 0.01 (Yang, Wang, Fan, Zhang, & Liu, 2019) (Dal, 2006). The results of the calculations indicate that rolling resistance is F_f = 314 N, acceleration resistance F_J = 1600 N, total torque value T = 86.12 Nm and power value is P = 1912 W.

2.2 Carrying Arms Mechanism

The parking robot has a total of eight carrying arms, as shown in Figure 4. The arms comprise a body that is capable of free rotation and cylinders carried by the body. The arms are each driven by a hydraulic mechanism and are capable of independent operation. It is assumed that the weight of the vehicle is distributed equally to all four wheels during transportation and that the force applied to each arm is equal.

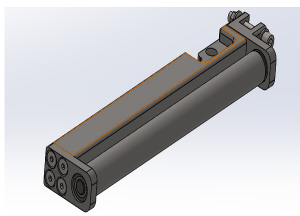


Fig. 4. Carrying Arm

The force distribution during lifting of the car wheels is shown in Figure 5. G is the amount of the vehicle's weight per wheel. The force applied by the parking robot, designated F, can be decomposed into two components: the vertical component, designated F_a, and the horizontal component, designated F_b. In the design, the angle between the force applied by the arms towards the wheel centre and the horizontal is measured as 60^0 degrees. The relevant forces can be determined using the following sin-cos laws (Yang et al., 2019):

$$F = \frac{G}{2sin\theta} \tag{8}$$

$$F_a = Fsin\theta \tag{9}$$

$$F_b = Fcos\theta \tag{10}$$

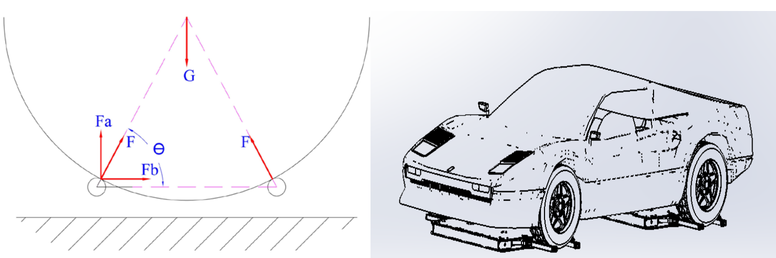
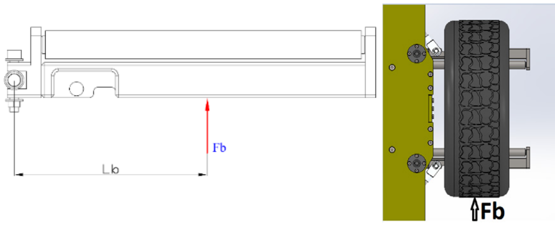


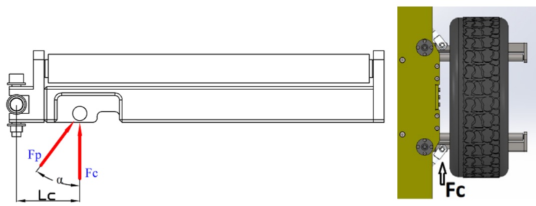
Fig. 5. The forces generated when the parking robot raises the wheel

Upon calculation, the resultant force F is determined to be 3540 N, the vertical force F_a is 3066 N, and the horizontal force F_b is 1770 N. Given that the location of the piston about the pivot point of the arm is closer. The vertical force applied by the piston arm can be found using the following formula:

$$\sum M = F_b L_b = F_c L_c \tag{11}$$



(a)



(b)

Fig. 6. Horizontal Forces on the Arm

(a) Vertical Force on the Wheel **(b)** Vertical Force Applied by the Piston

Fc is the vertical force applied by the piston, L_b=220 mm is the distance between the wheel contact point and the pivot point of the arm (Figure 6-a) and L_c =110 mm is the distance between the pivot point of the arm and the point where the piston applies the vertical force (Figure 6-b). It is determined that the vertical force generated by the piston, Fc, is 3540 N. When the carrying arms are completely opened, the angle α = 37 is determined between the piston and the arms. Therefore, the sine-cosine law can be used to determine the force generated by the piston (Yang et al., 2019):

$$F_p = \frac{F_C}{cos\alpha} \tag{12}$$

The piston force is calculated to be 4432.5 N. Therefore, by determining the piston force, we can find the required pressure and power. The pressure and power values can be found using the following Equations (Eq. 13 and Eq. 14)

$$p = \frac{F}{10A} \ (bar) \tag{13}$$

$$P = \frac{pQ}{600\eta} \ (kW) \tag{14}$$

A represents the area of the piston in cm^2, Q represents the flow rate of the fluid in cm3/s, while is the efficiency value. The effective area of the piston is A = 12.56 cm^2, the flow rate is Q=1.5 cm^3/s, and the efficiency is =0.8. The pressure is calculated to be p=44.1 bar, the power is P=0.137 kW.

2.3 Finite Element Analysis

The finite element method is a numerical technique that analyses a system's components, including their elements, connections, material properties, contact definitions, and solutions within constraining conditions (Yang et al., 2019). The parameters of the analysis are defined by constraints and boundary conditions, which specify the conditions under which the analysis is conducted. The application of finite element analysis enables the determination of the system's mechanical stability under the applied load conditions (Yang et al., 2019).

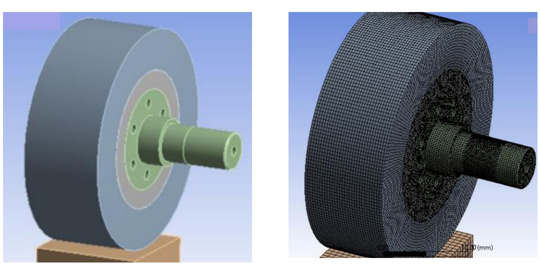
The techniques described in this section have been applied to drive group wheels, before the implementation of the necessary forces and boundary conditions for the analysis, the models created with the Solidworks program have been appropriately meshed. A structural analysis was conducted using the ANSYS program to determine the stress distributions and deformations at critical points in the structure. The objective of this analysis, 25% of which was added for safety margin under static load, was to determine the mechanical safety and durability of the structure (Kutay, 2009).

The materials and mechanical properties of the components that form the wheel are presented in Table 2. Polyurethane material is an elastomer-based polymer material. It presents the properties of ductile materials. The point at which the material undergoes plastic deformation is considered the yield point and is evaluated as the yield limit (URL-1; URL-2).

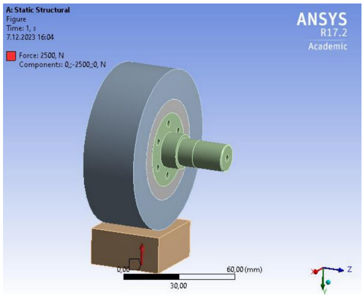
Table 2 Mechanical Properties of Materials

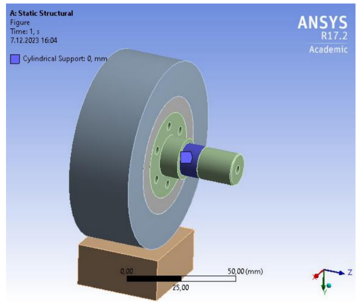
Mechanical Properties	**Polyurethane**	**DIN 1.1191 Steel**
Density (kg/m^3)	1130	7800
Young Modules (Pa)	$2.41x10^9$	$2.10x10^{11}$
Poisson Ratio	0.3897	0.28
Yield Strenght (MPa)	41.3	565
Yield Strain	400%	10%

The parking robot is equipped with a total of 16 wheels. The wheel includes a wheel axle, rim, and a polyurethane coating on the rim. Figure 7-a presents a simplified view of the wheel, while Figure 7-b illustrates the mesh form. In defining the boundary conditions, the force is applied from below the ground (Figure 7-c), and a cylindrical support boundary condition is applied to the bearing surface (Figure 7-d).



(a) **(b)**





(c) **(d)**

Fig. 7. Polyurethane-Coated Wheel

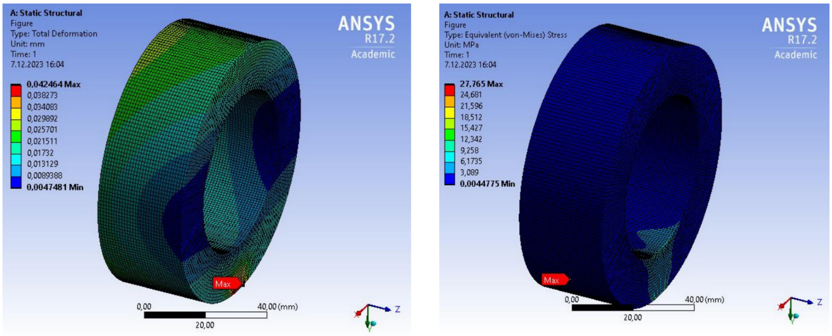
(a) Simplified Illustration **(b)** Mesh Illustration **(c)** Applied Force **(d)** Bearing Surface Boundary Condition

3. Results/ Findings

This section presents the results of the analysis conducted on the design of the drive group wheel. The materials utilized in the design are ductile. Equivalent (Von Mises) stress values and deformation amounts have been presented the yield stress limit values. The red regions in the provided diagrams represent the areas of highest stress and deformation and the blue regions represent the areas of lowest stress and deformation.

Because the parking robot is capable of transporting vehicles with a max. weight of 2500 kg, and the weight of the robot itself. It has been determined that a static load of 250 kg should be applied to each wheel in this analysis, conducted under a static load with a 25% safety margin. In the existence of these loads, multiaxial stresses that occur in ductile materials have been reduced to uniaxial equivalent stresses. These have then been compared with the yield stresses. If the equivalent stresses exceed the yield limit, permanent deformation or fractures will occur in that region. If the applied stresses are equivalent to those occurring below the yield limit, non-permanent deformations will occur in the elastic region.

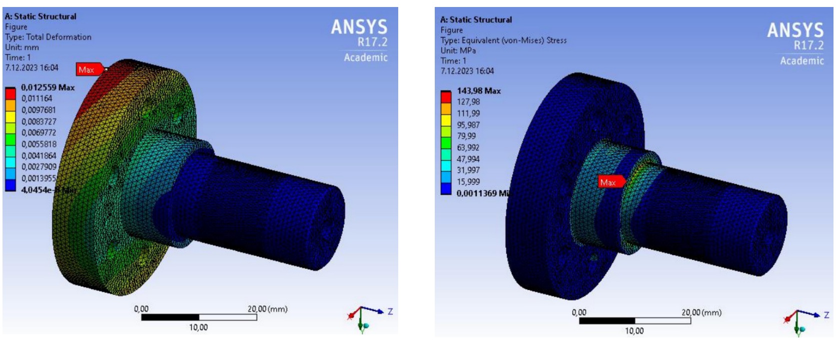
Upon analysis of the results, it was observed that during the transportation of a vehicle within the allowed weight range, the polyurethane coating a maximum deformation of 0.042 mm (Figure 8-a) and a stress value of 27.76 MPa (Figure 8-b). The stress value is below the assumed yield limit for the polyurethane material (Table 2). In the wheel shaft, had a maximum deformation of 0.012 mm (Figure 9-a) and a stress value of 143.98 MPa (Figure 9-b) have been observed in the bearing region. The stress value is observed to be below the yield limit of the steel material (Table 2). The values found on the MatWeb website have been considered for the permanent deformation limit. (URL-1; URL-2)



(a) **(b)**

Fig. 8. Polyurethane Coating Analysis Results

(a) Deformation Amount **(b)** Von Mises Stress Value



(a) **(b)**

Fig. 9. Wheel Shaft Analysis Results

(a) Deformation Amount **(b)** Von Mises Stress Value

In their study, Yang et al. (2019) conducted a finite element analysis for a 2000 kg load and calculated the maximum stress value in the structure of the parking robot as 200.9 MPa. Also, the height of the robot in this study is 170 mm. In our study, for a 2500 kg load, a total stress value of 143.98 MPa was determined on the wheel axle of the drive unit. Our drive unit consists of two wheels and the height of the robot is 100 mm.

4. Discussion and Conclusions

In this study, we present a new application area by incorporating the potential use of AGVs into automated parking systems. By using the parking robot in these systems, alternative parking designs can be re-evaluated in terms of cost and speed. Our parking robot design comprises two identical modules. Each module includes four drive units and four carrying arms, each capable of independent operation. The modules cooperate to elevate the vehicle from its front and rear wheels via the carrying arms, thereby enabling it to be parked in the desired location. In the design of the parking robot, SolidWorks software was used, while Ansys software was used for the analysis.

Due to their low load capacity, we are unable to use Mecanum wheels in our study. Also, although DS wheel mechanism is very suitable for our study, its direct use is not feasible due to our height limitations. Instead, we present a drive unit design consisting of two wheels. Since the aim of our study is to reduce the equipment used in automated parking systems and, consequently, the costs, a mechanical arm-based solution has been preferred in our design, eliminating the need for a platform.

In this study, power calculations were conducted to determine the required load and movement speed. The analysis of the basic components of the drive unit was performed using the finite element method. The materials used in the design are ductile, equivalent (Von Mises) stress values and deformation amounts have been examined, taking into account the yield limit values. According to the calculation and analysis results.

- The yield limit accepted for the polyurethane material is 43.1 MPa (Table 2). The stress equivalent to the material under load at the contact area with the ground has been calculated as 27.765 Mpa. The value is below the yield limit, which places it within the elastic region, thereby indicating a safe zone. The deformation observed in the polyurethane material at the contact area with the ground was found to be 0.042 mm. The material presents an elongation capacity of up to 400% until reaching the breaking point. It has been demonstrated that the deformation quantity is within the safe zone.
- The yield limit accepted for the wheel shaft manufactured from CK45 steel is 565 Mpa (Table 2). The stress equivalent to the material under load in the bearing region has been determined to be 143.98 MPa. The value in question is below the yield limit, which places it within the elastic region, thereby indicating a safe zone. The deformation amount occurring in the wheel shaft is 0.012 mm. The elongation capacity of up to 10% until exceed the breaking point ensures that the deformation amount remains within the safe zone.

The widespread use of AGVs across various sectors around the world is expected to contribute to the development of smart parking systems through their integration into automated parking systems. This product can eliminate the need for steel platforms, stacking conveyors, and horizontal transportation mechanisms for each vehicle. The use of parking robots in automated parking systems, which require significant investments, may lead to cost savings, increased parking entry and exit speeds, and reduced space requirements. If cost reductions occur, it could facilitate the widespread acceptance of smart parking systems. Additionally, the solution to the steering problem of a parking robot at this height will be a topic for future research. This article will inspire new studies by evaluating all these possibilities.

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