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Design of an Ergonomic Rotating Steering System on an Electric Cart Based on RULA Analysis (Rapid Upper Limb Assessment) and Using Solidworks Software

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Abstract: Designing material transportation equipment using human-powered carts is not efficient. An electric drive system can be an environmentally friendly system that can be implemented on three-wheeled carts, thereby replacing the role of humans in doing so. developing an electric drive device with a 48 V 1000watt Brushless DC (BLDC) type, 12 Ah lithium ion battery, so that it can reduce pollution problems and also meet the needs of the domestic automotive sector. This research aims to design and build a rotary steering drive system for a three-wheeled electric cart to make it lighter and easier. The steering seat frame functions to support the driver and a structural analysis was carried out using ergonomic analysis using the RULA method. Meanwhile, to determine the strength of the frame material and components of the cart steering system using SolidWorks software simulation. Based on the results of research on the design of the cart frame and steering system frame made of alloy steel with SolidWorks analysis for frame loading, it shows that the maximum stress value that occurs is still below the yield strength value of the material, the results of the frame loading safety factor value have exceeded the required value, so that very safe to withstand a load of 1962.33 N. Meanwhile, when loading the steering frame and steering mount, the maximum stress value that occurs is still below the material yield strength value, the resulting loading safety factor value has exceeded the required value, so it is very safe to withstand a load of 784.58 N. The results of the RULA method analysis on the ergonomic design of the rotary steering system show that the MSDs risk score for the new driver's posture after ergonomic intervention is 2 (two), which means the MSDs risk category is good, for the cart moving forward or backward. This means that the cart driver's posture is acceptable as long as it is not maintained. or recurring for a long time. Analysis of the power consumption of three-wheeled electric cart testing, namely the maximum value without load produces 571.14 Watts, while testing with load produces 583.68 Watts. This affects the use without load and with load on the performance/speed produced by the 48V1000 Watt BLDC motor. The prototype design of this three-wheeled electric cart has the advantage that it can be used on narrow roads and alleys in hotel or company yards.

Keywords: Steering System, Electric Cart, Solid Works, RULA, Ergonomics

1. Introduction

Brushless direct current (BLDC) electric motors are motors that have good efficiency, are more reliable, have a longer life and are cheaper. A motor that has a rotor part in the form of a permanent magnet and a stator part in the form of windings to produce a magnetic field. Changing the polarity of a BLDC motor is done electronically using a hall-effect sensor and rotary encoder. Because electric motorbikes are almost maintenance free, they don't require oil, new spark plugs or other routine repairs like combustion motorbikes do [1].

The drive system (steering) is one of the most important components in an electric car. Because the steering system functions to move the front wheels to turn right and left. The steering system is divided into several types, namely manual steering and power steering. In a manual steering system, the power required to turn the wheel from the steering wheel is rotated by the driver's power, while power steering is a steering system whose driving power is obtained from hydraulic or electric power using a drive motor [2].

Ergonomics is an effort in science, technology and art to design tools, machines, systems, organizations and environments that adapt to human abilities and limitations to achieve conditions that are healthy, safe, comfortable, productive and efficient by maximizing and optimizing the use of the human body [3]. Operators when carrying out activities at workstations can experience musculoskeletal disorders that occur due to repeated exposure to work at high or low frequencies, and long-term stress. Symptoms can vary, such as discomfort and pain [4]. Biomechanics is one of four areas of research on ergonomics. Research on human physical strength which includes human physical strength when working and how equipment must be designed to suit human physical abilities when carrying out these work activities [4, 5]. The high risk of man-machine interface occurring in construction work systems is material handling which cannot be avoided due to the nature of the task. Many studies have successfully proven that harmonization of the human-machine interface conditions workers to carry out their tasks in a natural working posture that excessive muscle exertion can be avoided and the risk of MSDs can be reduced. Sudiajeng et al [6] reported that ergonomic work station redesign in a carpentry workshop reduced working heart rate (16.7%), total MSDs score (17.3%), and total psychological fatigue score (21.5%) [7].

Ergonomics studies related to product design based on human body dimensions are anthropometry consisting of a collection of numerical data on the characteristics of the human body including size, shape and strength in order to create an efficient, comfortable, safe, healthy and effective work environment [8, 9]. Ergonomic interventions will improve occupational safety and health, reduce skeletal muscle complaints and can increase work productivity [10, 11]. Tricycle ergonomics analysis of flexible seat components and flexible steering handlebars using the RULA (Rapid Upper Limb Assessment) method found in CATIA and SolidWorks software. The smaller the RULA value, the design is still ergonomic and safe for the rider [12].

This happens because the price of commercial vehicles such as three-wheeled motorbikes is still quite high and difficult for the MSME community to reach. From this case, an innovative idea emerged to design and make a three-wheeled electric cart with a rotary steering system that can be used on narrow roads or alleys as a means of logistics at a more affordable and environmentally friendly price.

2. Research Methods

This research is a type of experimental research through Research and Development of rotary steering systems on three-wheeled electric carts. This method is used to obtain a rotary steering design that is safe and comfortable for the user and the material used can meet the appropriate strength requirements for the steering frame and cart chassis. The electric cart prototype with a rotary steering system was developed to meet the demands of an environmentally friendly mode of transport for goods and can be used on narrow roads in company or office areas. The parameters studied include: rotary steering design, materials used in the steering frame and cart chassis and battery power consumption. Data from testing the electric cart prototype was Analyzed using the RULA method and SolidWorks software.

2.1. Test Method

Before carrying out testing, create a design drawing for the rotary steering system on a three-wheeled electric cart using SolidWorks software,

1. Using SolidWorks software
   1) Determine the material specifications used in the steering frame and cart chassis.
   2) Identify the loads that occur on the frame and then input them into SolidWorks software.
   3) Determine the load point from SolidWorks software analysis results for the prototyping process.
2. Using RULA worksheet data to measure body posture by:
   1) Divide the driver's body observations into 2 groups, namely A which consists of the neck, upper arm, lower arm, wrist, back,
   2) and B measures load (load/force), and activity score.
   3) Assess each operator's working posture using RULA into A and B scores.
   4) Determine the RULA score from the combined results of calculating score A and score B.
   5) Determine the action level of the driver's working posture.
3. Battery power consumption

Electric carts run without load and are loaded.

Electric Cart

Electric motorbikes are vehicles without fuel that are driven by a dynamo and accumulator. Electric carts are cost-effective, cheap and environmentally friendly vehicles and do not require fuel oil. Where the accumulator can store electrical energy and convert the electrical energy into mechanical energy (motion), the movement energy is in the form of rotation from the motor on the wheels of the electric cart. The concept of an electric cart is actually simple and relatively the same for every type of electric vehicle. The battery provides the electric current needed to supply the motor or dynamo. The amount of current and voltage required by the motor is regulated by the controller. All electric vehicles have the main components needed, namely: electric motor, battery and controller.

2.2. Steering System

The steering system on a vehicle uses two systems, namely, tie rod and does not use tie rod. Tie rod is a vehicle spare part that is usually used in four-wheeled vehicles, which is located between the steering gearbox and wheel knuckle. This tool has an elongated shape that connects the end of the steering rack to the front wheel. The shape of this tool depends on the type and steering system used. The way this tie rod works is by continuing the movement that occurs in the steering system, namely, from the steering gear to the steering knuckle on the wheel. So, when the steering wheel is moved or rotated by the driver, the rotation of the steering column will be transmitted towards the wheels. Meanwhile, those that do not use a tie rod function to control the direction of the vehicle so that the direction of the vehicle is in accordance with the driver's wishes. The power to control the direction of the vehicle uses hand power, which is transmitted to the wheels via the steering column (handlebars) and front fork. The way the steering system works, which does not use tie rods, is like the way a motorbike steering system works, when the handlebar is turned, the forks immediately move simultaneously [13].

2.3. Software SolidWorks

SolidWorks is one of Dassault Systems Corp.'s products. which is intended for engineering design and drawing. The basic principles of using SolidWorks are not much different from other 3D parametric software such as Autodesk Inventor. SolidWorks is a design and build program that is widely used to work on product design, machine design, mould design, construction design, and for other purposes, especially in the engineering field according to the research carried out. SolidWorks is equipped with tools used to calculate and analyse design results such as stress, strain, and the influence of temperature, wind, etc. SolidWorks itself is also a model based on parametric features, where all objects and relationships between geometrics can be modified again even though the geometry is already finished without needing to start over from the beginning [14].

2.4. Design Ergonomics

A series of work is required to achieve the best design, such as design planning and development, starting from idea discovery, analysis and continuing with a series of stages such as development, concept, system and detail design, prototyping, production process, product evaluation or testing, and completed at the stage distribution. Problem solving for good design must recognize humans and their activities, such as size, posture, position in activities, behaviour and ways of human activities. Assessing this, ergonomic considerations need to be taken [15].

2.5. Rapid Upper Limb Assessment (RULA)

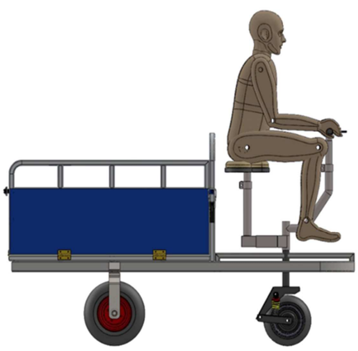
The RULA method is a method that uses target body posture to estimate the risk of disorders of the musculoskeletal system, especially in the upper limb disorders, such as repetitive movements, work that requires exertion of strength, static muscle activity in the musculoskeletal system and others. The assessment using the RULA method is a systematic and rapid assessment of the risk of disturbances by pointing to the part of the worker's body that experiences the disturbance. Analysis can be carried out before and after the intervention given will be able to reduce the risk of injury. In this application, the RULA method can be used to determine work priorities based on injury risk factors. This is done by comparing the scores of different tasks evaluated using RULA. This method can also be used to find the most effective actions for jobs that have relatively high risks [16].

2.6. Brushless DC Motor (BLDC)

Brushless DC motors or also called Brushless DC motors (BLDC Motors) are a type of synchronous motor. Where the magnetic field produced by the rotor and stator is at the same frequency. BLDC motors do not experience slippage, as happens in ordinary induction motors. This type of motor has permanent magnets on the "rotor" and on the stator. After that, by using a simple circuit (simple computer system), we can change the electro-magnetic current produced by the motor when the rotor rotates. BLDC motors are often used in various fields such as; automotive industry, health and robotic automation fields. BLDC motors have many advantages compared to DC motors and ordinary induction motors. Brushless DC (BLDC) motors are the ideal choice for applications that require high reliability, high efficiency, and a high power-volume ratio. Advantages of BLDC motors [17].

3. Results and Discussion

The results of the design of a rotary-steered three-wheeled electric cart with the following specifications:



Electric Cart Dimensions:
- Length: 2000 mm
- Width: 900 mm
- Height: 350 mm
- Rear wheelbase: 730 mm
- Front wheelbase: 900 mm
- Lowest distance to the ground: 200 mm
- Frame material: Alloy steel

Components used:
- Drive: Type BLDC 48V electric motor
- Power: 1000 watts
- Battery: Lithium Ion 12 Ah
- Front Tire: R10 inches
- Rear tire: R10 inches
- Suspension: Spring
- Brakes: Dish Brake
- Max speed: 40 km/hour
- Max carrying capacity: 200 Kg

Figure 1. *Swivel Steering Tricycle Electric Cart.*

3.1. Analysis of Design Results

Simulation analysis is carried out using static features by SolidWorks Premium 2020 software. Simulation with this software is useful for carrying out analysis to prove the validity of a design [18]. The results of the data from this static feature are that the parameter values can be seen as follows:

1) Strain
   Strain can be said to be the level of deformation which can lengthen, shorten, enlarge, shrink, and so on.
2) Displacement
   Namely the movement of material from the starting point to the ending point which has been exposed to compressive force or force from the pressing process [19].
3) Stress
   Stress itself is a reaction force or force that works to return an object to its original shape per unit area evenly distributed on its surface.

3.2. Loading on the Frame

The load on the front frame is 120 kg and the driver is 80 kg, so the total load on the frame is 200 kg or 1961.33N. The maximum strain that occurs is 2,940e-03N/m2 which is shown in the red area and in the displacement simulation analysis the largest value when loading the cart frame is shown in red with a value of 6,703e+00mm as in Figure 2.

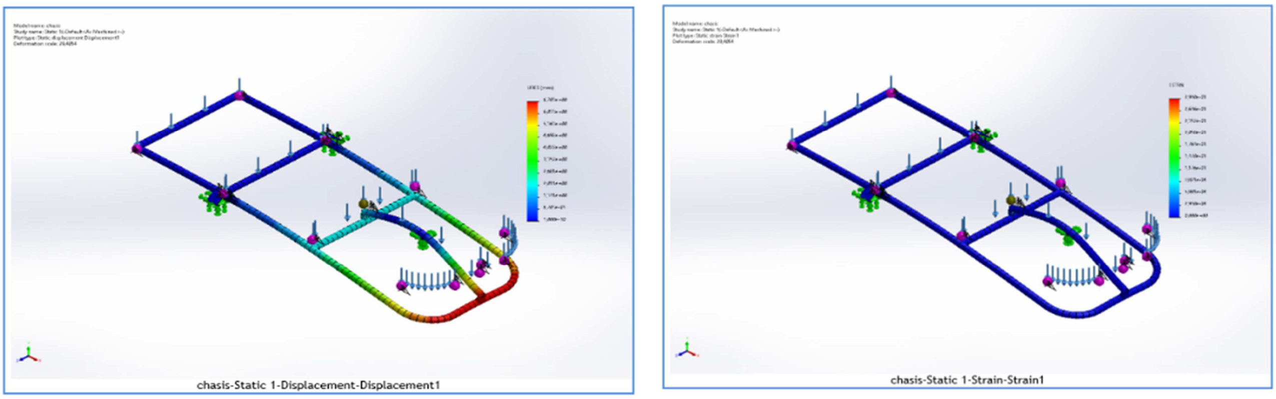


Figure 2. *Displacement and Strain Analysis in Frame Loading.*

Based on the simulation results, it is known that the maximum stress value obtained is 1.661e+08 N/m2. which shows that the maximum stress value that occurs is still below the yield strength value of the cart frame material [20].

To find out that the frame load on a two-wheeled electric cart is safe to use, the safety factor value can be calculated, namely:

$$Sf = \frac{\sigma\, yield\ strength}{\sigma\, \max von\ mises}$$

$$= \frac{6{,}20422 \text{ x } 10^{8} N/_{m^2}}{1{,}661 \text{ x } 10^{8}\, N/_{m^2}} = 3.73$$

The results of the safety factor value for the loading of the two-wheeled electric cart frame have exceeded the required value, so it is very safe to withstand a load of 1962.33 N.

3.3. Front Steering Frame Loading

The first known simulation analysis value is strain, that the initial load given to the front steering frame is 784.53 N and the maximum strain that occurs is 5.877e-04N/m2 as shown in red and the simulation analysis displacement value is the largest the front steering frame loading is shown in red with a value of 1.327e+00mm as in Figure 3.

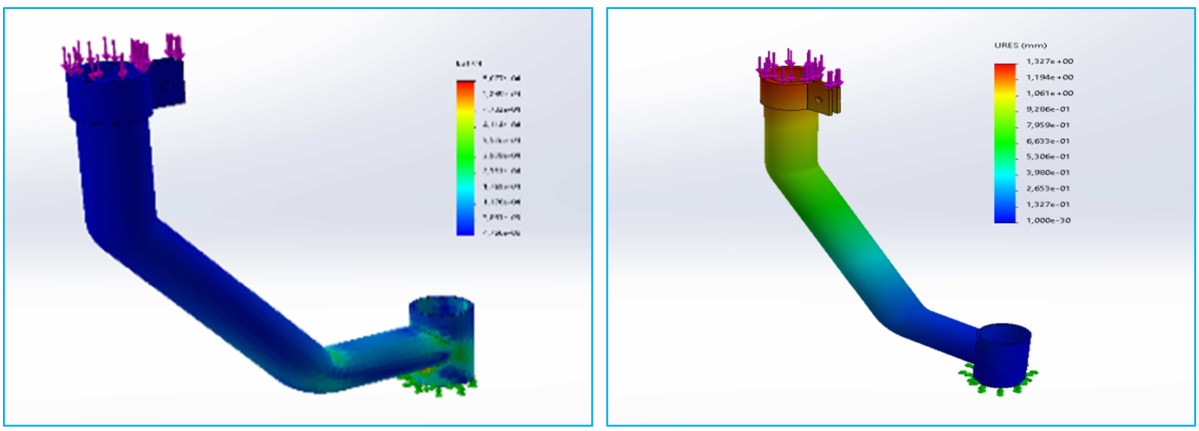


Figure 3. *Strain and Displacement Analysis of Front Steering Frame Loading.*

According to the simulation results in Figure 3, it can be seen that the maximum stress value obtained is 1.706e+08 N/m2. shows that the maximum stress value that occurs is still below the yield strength value of the material for the front steering frame of the three-wheeled electric cart.

To find out that the frame loading on the front steering wheel is safe to use, the safety factor value can be calculated, namely:

$$Sf = \frac{\sigma \, yield \; strength}{\sigma \max von \; mises}$$

$$= \frac{6{,}20422 \text{ x } 10^{8} N/_{m^2}}{1{,}706 \; x \; 10^{8} \; N/_{m^2}} = 3.65$$

The resulting safety factor value for the front steering frame has exceeded the required value, so it is very safe to withstand a load of 784.53 N.

3.4. Steering Seat Frame Loading

The first known simulation analysis value is strain, that the initial load given to the front steering frame is 784.53 N and the maximum strain that occurs is 2.046e-04 N/m2 as shown in the red area as in Figure 4.

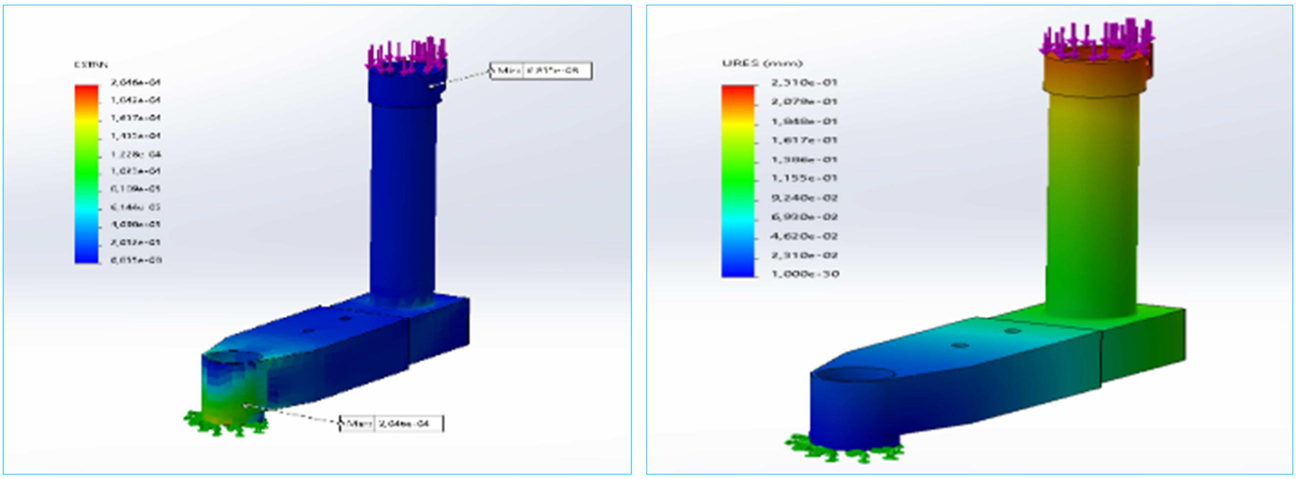


Figure 4. *Strain and Displacement Analysis of Steering Seat Frame Loading.*

It can be seen that the maximum stress value obtained is 5.203e+07N/m2. which shows that the maximum stress value that occurs is still below the yield strength value of the cart steering chair frame material. To know that the frame load on the steering chair is safe to use, the safety factor value can be calculated, namely:

$$Sf = \frac{\sigma \, yield \; strength}{\sigma \max von \; mises}$$

$$= \frac{6{,}20422 \text{ x } 10^{8} N/_{m^2}}{5{,}203 \; x \; 10^{7} N/_{m^2}}$$

$$= 11.9$$

The results of the safety factor value for the loading of the wheel chair frame of this cart have exceeded the required value, so it is very safe to withstand a load of 784.53 N.

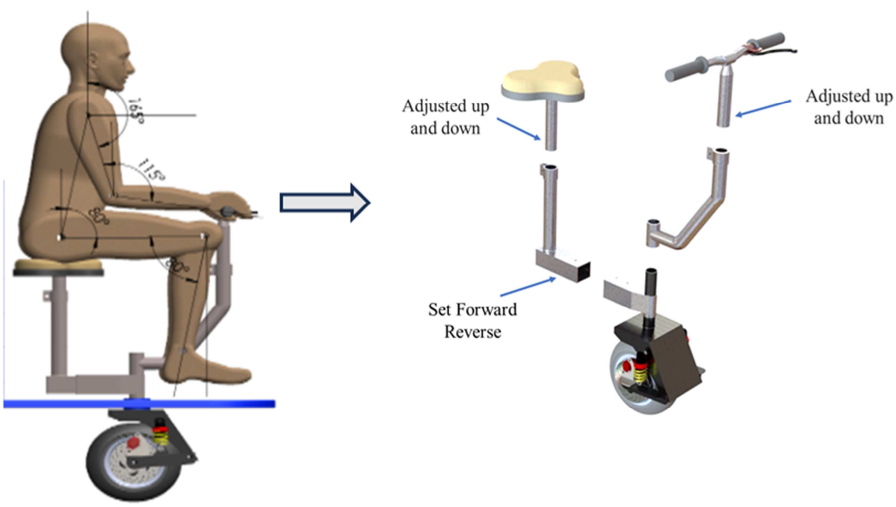


Figure 5. *Rotary Steering System Design.*

3.5. Ergonomics Analysis with RULA

The design of the rotary steering system in the position of the driver's seat relative to the handlebars really determines the driver's comfort level when controlling the cart. Simulations on the 5th, 50th and 95th percentile mannequins using SolidWorks software as shown in Figure 5, produce the best driver's seating position. Obtained measurements such as seat height and steering handlebar distance are designed to be able to be adjusted in height and distance according to the driver's anthropometric measurements.

Ergonomic analysis using anthropometry of Indonesian adult men was carried out to determine the analysis of the results of the design of the cart steering system on the risk level of work movements using the RULA (Rapid Upper Limb Assessment) method which was then used to determine the MSDs risk level category. RULA is a tool to make it easier to calculate the level of work risk due to the workload that has been given, the work risk includes the neck and arms. Figure 6 shows the conclusion of the work procedure using RULA. Based on the calculations that have been carried out, the following explanation is obtained:

	Left	Right
Apper Arm Posture score	2	2
Lower Arm Posture Score	1	1
Wrist Posture Score	1	1
Wrist Twist Posture Score	1	1
Neck Posture Score	1	1
Trunk Posture Score	1	1
Leg Posture Score	1	1
Muscle Use Score	0	0
Force Score	0	0

	Left	Right
Apper Arm Posture score	2	2
Lower Arm Posture Score	1	1
Wrist Posture Score	1	1
Wrist Twist Posture Score	1	1
Neck Posture Score	1	1
Trunk Posture Score	1	1
Leg Posture Score	1	1
Muscle Use Score	0	0
Force Score	0	0

Figure 6. *Analysis of Forward or Reverse Driver posture and Rula Score Sheet.*

Based on the results of the body posture analysis, all scores are plotted in the RULA assessment worksheet (Figure 6). The research results show that the MSDs risk score for the new work posture after ergonomic intervention is 2 (two), which means the MSDs risk category is good, for both forward and reverse drivers. This means: the cart driver's posture is acceptable as long as it is not maintained or repeated for a long time.

3.6. Power Consumption Analysis

Based on the test results of a three-wheeled electric cart with a 48v1000 watt BLDC motor drive, the first test was carried out under unloaded conditions, namely the weight of the cart was 90kg and the driver's weight was 55.7kg, so a total of 145.7kg, and the second test was carried out under load conditions, namely the weight of the cart was 90kg, the driver weighs 55.7kg and the load weighs 100kg so the total is 245.7kg. The test results are as in table 1 as follows.

Table 1. *Test Data Without Load and With Load.*

Condition	Testing	Total Weight (Kg)	Speed (Km/h)	Voltage (Volt)	Electric Current (amperes)	Power Consumption (Watts)	Mileage (Meters)	Travel Time (seconds)
	1	145,7	28	50,7	10,8	547,56	20	16
	2	145,7	28	49,0	11,2	548,80	20,5	16,5
Without Load	3	145,7	29	49,9	11,1	553,89	21	17
	4	145,7	29	48,9	11,5	562,35	22	17
	5	145,7	29	50,1	11,4	571,14	20	16
	Average	145,7	28,6	49,7	11,2	556,748	20,7	16,5
	1	245,7	23	49	11,5	563,50	21	18
	2	245,7	23	51	11,2	571,20	21	18,5
With Load	3	245,7	22	50	11,5	575,00	20	19
	4	245,7	23	49,5	11,7	579,15	21	18,7
	5	245,7	22	51,2	11,4	583,68	20	19,7
	Average	245,7	22,6	50,14	11,46	574,506	20,6	18,78

Based on table 1 above, namely the test results for the 48V1000 Watts BLDC motor. The first test was carried out 5 times without load, getting an average speed of 28.6 km/h, a voltage value of 49.7 volts and a current of 11.2 amperes. Meanwhile, the second test was carried out with a load, getting an average speed of 22.6 km/h, a voltage value of 50.14 volts and a current of 11.46 amperes. Calculation analysis of the power produced in each test without load and using load can be calculated using the equation below, namely:

$$P = V \times I$$

$$P = 49{,}7\ V \times 11{,}2\ A$$

$$P = 556{,}748\ \text{Watts}$$

Below is a graph of the average speed measurement results when the test was carried out 5 times without load and with load.

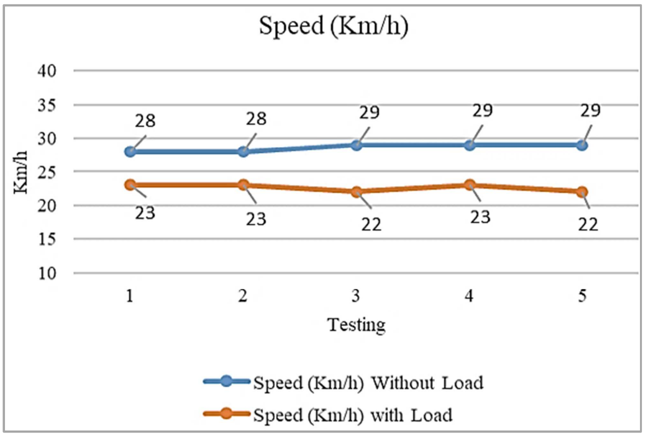


Figure 7. *Graph of cart speed values without load and with load.*

Based on Figure 7, when tested 5 times without a load, the speed of the three-wheeled electric cart got a maximum speed value of 29 km/hour, while testing with a load got a maximum speed value of 23 km/hour. This affects the use without load and with load on the performance/speed produced by the 48V1000 watts BLDC motor.

Below is a graph of the results of calculating power consumption during testing without load and with load.

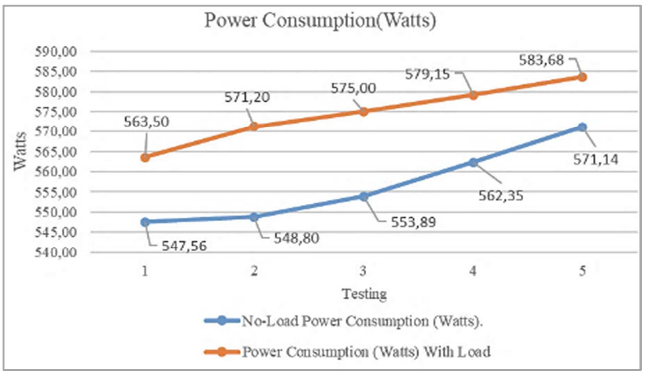


Figure 8. *Graph of power consumption values without load and with load.*

Based on the two graphs above, the maximum value obtained in the test without load resulted in a power consumption of 571.14 Watts, while the test with load resulted in a power consumption of 583.68 Watts. This affects the use without load and with load on the performance/speed produced by the 48V 1000 Watts BLDC motor. Several other factors from a three-wheeled electric cart can influence the power consumption value of a 1000 Watts BLDC motorbike, namely environmental conditions, track conditions, battery performance, character when riding, also have an influence.

Vehicles can move at specific speeds due to the use of the thrust force generated by the work of the electric motor. The electric motor produces energy which is then transferred to the wheels via the vehicle's connecting mechanism. The vehicle structure includes the wheel axle, bearings and levers. If the condition of the components on the cart is good and proportional, the percentage of power transmitted from the electric motor to the wheels can be higher or vice versa.

4. Conclusion

Based on the results of designing and testing a prototype of a three-wheeled electric cart with a rotary steering system with a BLDC 48V1000 watt drive, it can be concluded as follows:

1. Design analysis using the Solidworks program for a cart frame and steering system made from alloy steel:
   a. For frame loading, it shows that the maximum stress value that occurs is still below the yield strength value of the cart frame material. The results of the safety factor value for loading the frame of this two-wheeled electric cart have exceeded the required value, so it is very safe to withstand a load of 1962.33 N.
   b. Loading of the steering frame and steering seat shows that the maximum stress value that occurs is still below the yield strength value of the material. The safety factor value for loading the steering frame and seat has exceeded the required value, so it is very safe to withstand a load of 784.58 N.
2. The results of the Rula method analysis on the ergonomic design of the rotary steering system show that the risk score for MSDs in the new driver's posture after ergonomic intervention is 2 (two), which means the MSDs risk category is good, for the cart moving forward or backward. This means that the cart driver's posture is acceptable as long as it is not maintained. or recurring for a long time.
3. Power consumption analysis for testing three-wheeled electric carts, namely the maximum value obtained in the test without load, resulting in a power consumption of 571.14 Watts, while the test with a load resulted in a power consumption of 583.68 Watts. This affects the use without load and with load on the performance/speed produced by the 48V1000 Watt BLDC motor. Several other factors that can influence the power consumption value of a 1000Watt BLDC motorbike, namely environmental conditions, track conditions, battery performance and the driver's character when driving, also have an influence.

The prototype design of this three-wheeled electric cart has the advantage that it can be used on narrow roads and alleys in hotel or company yards. In the future, it needs to be further developed in further, more complex research on several supporting components such as better brake and lighting systems so that it is safe for users.

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