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DEVELOPMENT AND IMPLEMENTATION OF AN UNMANNED GROUND VEHICLE FOR OFF-ROAD APPLICATIONS

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Abstract: *In the last decade, discoveries have been made using autonomous mobile robotic systems, and these systems are gaining increasing attention. Considering unsuitable environments for humans, unmanned ground vehicles (UGVs) or similar systems have obvious advantages so utility opportunities naturally lead to worldwide recognition. Developing and conducting research on such devices are among the main goals of mechatronics and robotics studies. Various control systems and many high-capacity sensors have been developed to integrate these UGV systems together with branches of science and related technologies. The potential applications of UGV systems in the field are vast and range from civilian use for accident prevention to dangerous reconnaissance missions for military purposes. In this study, the UGV was developed with a compact chassis and four-wheel drive for a variety of field and off-road applications. The developed system was equipped with skid steering and low speed (<1 m/s) applications were mainly targeted. Adaptive capabilities could be enhanced by integrating additional electronic systems or sensory equipment. The prototype had a maximum carrying capacity of 5 kg and could be remotely controlled with remote control. The vehicle design was examined using FEM analysis and the structural stability of the design was verified. Besides, field tests were also conducted to evaluate the actual performance of the prototype. The prototype moved in a straight line at a maximum speed of 6 km/h, an active operating time of 28 minutes was observed at maximum payload, and a zero turning radius was possible with skid steering.*
Key words: *FEM Analyses. Remote Control. Robotic Systems. Off-Road Applications. Unmanned Ground Vehicles (UGVs).*

1. INTRODUCTION

Unmanned Ground Vehicle (UGV) applications are gaining more and more significance in human environments nowadays. Tasks such as human rescue, reconnaissance and transportation generally require following a path, avoiding obstacles (both expected and unexpected) and sometimes exact location acquirement. General description of UGVs is given as mobile robotic platforms with an ability to operate autonomously at times, and they are usually preferred for inaccessible environments. A basic example of such systems can be given as Clearpath's Husky mobile platform UGV. This vehicle is commercially available in the market and is shown in Figure 1.

Robotic technologies are expanding rapidly in areas such as search and rescue, space exploration special weapons and tactics operation, healthcare and national defence in the last decade [1].

Fig. 1. A basic example of mobile robotic platform UGV, Husky

Unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) are claimed to be very valuable when military operations of reconnaissance and disarming explosives are considered. It is predicted that the perceptive ability and action capabilities of the robotic systems would eventually reach to an extend that these systems could be able to complete tasks beyond their human operators' skill and perception. Potential future operations are expected to be affected greatly by such improvements. Multiple platforms such as ground and aerial sources could supply information for future robotic systems, enabling many complex applications. One good example would be the taking over (or manipulating) of an UAV by the UGV in order to utilize the streaming video capability of the UAV for evaluating the route choices towards the predefined targets.

General definition for unmanned ground vehicles goes as, an unmanned ground vehicle (UGV) is a vehicle that operates on the ground without an onboard human operator on the vehicle. Unmanned ground vehicles are utilized with sensors when observation of environments is aimed, and they can further process the input to make decisions about how to proceed with the task at hand by the utility of more complex control setups. Autonomous operations or tasks with feedback mechanism requirement can be achieved with Inertial Measurement Unit (IMU) units and special purpose navigation sensors for both aerial and ground robots. Different techniques are addressed for controlling the unmanned ground vehicles.

2. LITERATURE REVIEW

Robotics is recognized as a very important component of competitiveness and flexibility in production processes. Different designs, robots and subsystems with special task capabilities can also be used in non-manufacturing areas. Agricultural applications, transportation, healthcare, security (military or public), and more services are strongly referred to as future uses, so global robot sales will naturally be extended to excess [1-3].

Classification of the robots is made according to the type of locomotion. Robots can have various types of motion systems such as wheels, legs, wings, propellers, and other vehicles. According to this definition, unmanned ground vehicles correspond to wheeled mobile robot systems [4].

Papadakis mentioned that different disciplines such as computer vision, machine learning, robot perception and artificial intelligence create a space for unmanned ground vehicle (UGV) motion planning. Among all relevant methodologies, 3D terrain information was used, and this information was obtained through LIDAR, colour, stereo range data or various other sensors. Acquisition of the data often involved a combination of these data and potentially dynamic or static vehicle models expressing the interaction between the terrain and the vehicle itself. Papadakis's research highlighted the contributions of various disciplines to the perception and analysis of the landscape, expressing the critical similarities and differences between disciplines used in the field to inspire future developments [5].

Zhang et al. proposed a navigation algorithm for unmanned ground vehicle (UGV) using Wireless Sensor and Actuator Networks without coordinates. The algorithm consisted of two steps, one of which was calculated in an amount called the level of jump from the target point. In the second step, node clusters were evaluated to get potential choices to direct the UGV towards the target point. While the main direction of the vehicle was determined by the target nodes, the alternative driving paths were checked and the movement of the UGV was controlled by the listeners mounted on the vehicle [6].

Vandapel et al. studied the use of 3D data to improve the performance of an unmanned ground vehicle (UGV), especially in vegetated environments. Registration of 3D local ground ladar data along with aerial 3D data enabled absolute localization and the data was also utilized to compute traversability maps needed by the planner. Recovery of the load bearing surface was achieved by filtering vegetation with the utility of both ground and aerial data [7].

Chengalva referred to an unmanned ground vehicle with a sensor system and a computer system. The vehicle, stated in the author's patent, was able to communicate with a remote location, and the data of the sensor system were evaluated by the computer system to run a series of operations that the operators sent via the remote-control system [8].

3. MATERIAL AND METHOD

3.1 Vehicle Specifications

Mainly the vehicle is designed with the assumption of off-road applications which involves unstable sandy or slippery surfaces with slopes up to a degree. These environments naturally suggest low-speed operations ranging from search and rescue to agricultural applications. Payload capacity is assumed to be around 5 kg when the frame size, chosen actuators and power of the vehicle are considered. Many different sensor types can be mounted on the frame of the vehicle for additional utility in the case of necessity. Development of the unmanned ground vehicle is carried out using the parameters and properties listed in the following table (Table 1).

Table 1

Unmanned ground vehicle (UGV) basic specifications

Specifications of the UGV	
Payload capacity of the vehicle	5 kg
Speed of the vehicle (maximum)	1.76 m/s (6.46 km/h)
Slope of surface (maximum)	10 °
Drive type	4 x 4
Actuators utilized for locomotion	80W DC electric motors x 4
Steering Method	Four-wheel skid steering
Motor driving method	Pulse Width Modulation (PWM)
Total cruising duration	30 min
Vehicle total weight	25 kg

Other than chassis of the vehicle, there are many components such as relays, microcontrollers, actuators and related wiring.

Newton's Second Law is appropriate to calculate the driving force requirements. Along with the mass of the vehicle, the rolling friction coefficient and slope of the terrain are the most important parameters. Air drag force is also taken into account even though it has negligible effect on the ground vehicle due to the limited operational design speed, and the geometry of the vehicle is not very complex to generate significant amounts of air drag. Maximum torque requirement can be obtained by summing all these parameters, then electric actuators can be selected properly in order to propel the vehicle by suppling the correct amount of torque. When selection of battery units is considered, power consumption is calculated with full load capacity assumption for the worst-case scenario in order to assess total cruising duration.

The following table (Table 2) gives the relevant calculations according to vehicle design variables. These calculations create a layout for analysis and field test verifications.

Table 2

Force calculations and power requirement

	c_{slope}.	m (kg)	g (m/s^2)		Result (N)
F_{slope}	0.11	25	9.81		27.25
	c_r	m (kg)	g (m/s^2)		
F_{roll}	0.6	25	9.81		147.15
		m (kg)	a (m/s^2)		
F_{accel}		25	0.1		2.5
	c_d	ρ (kg/m^3)	A (m^2)	(V_{wind}^2)/2	
F_{air}	1.225	1.3	0.09	0.5	0.072
F_{total}					176.97
Required Power	F_{total}	V (m/s)			Result (W)
P	176.97	1.79			317.58
Required Torque	P (W)	w^1 $(rad/s)^1$			Result (Nm)
T	317.58	14.13^{-1}			22.48

3.2. Vehicle Design

Terrestrial utility was the main design purpose for development of the UGV. The cost and efficiency were also considered during the design and material selection. Significant parameters were chosen to be payload capacity along with the weight of the vehicle itself, active operational duration, environmental conditions (such as slope and frictional coefficient) and rolling resistance. The extreme design conditions for the development of the vehicle were taken as 10° slope on sandy surface for low-speed (~ < 1 m/s) operations. CAD software was used to draw the components, then the created components were assembled in order to obtain the full model in computer environment. Materials were selected as aluminium 6063 T6 for chassis profile along with motor holder plates. Plain carbon steel was selected for the rims and wheel-motor shaft coupling disk.

Internal clearance of between the top cover and bottom plate was used for locating the electrical components and other components necessary for UGV locomotion. Full assembly is depicted in Figure 2. These sections were planned to contain the electronic components and wiring along with batteries. Top cover protected these delicate components from outer hazards, dust and other means.

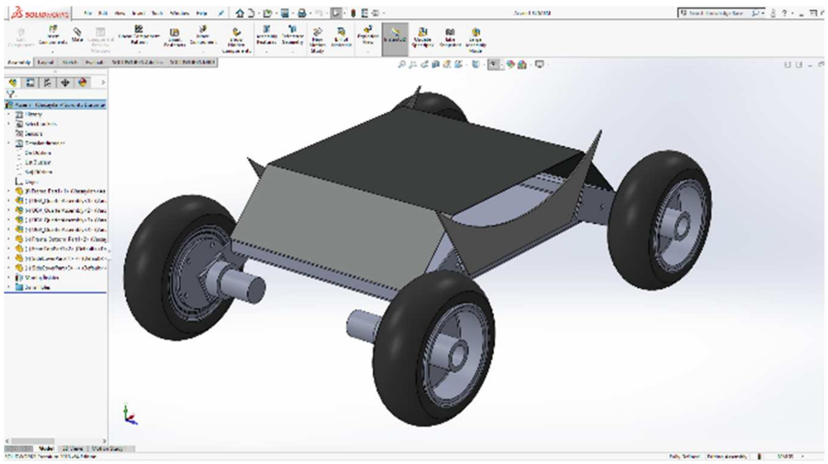

Fig. 2. Full assembly of the CAD model

Brushed direct current (BDC) electric motors were chosen as main actuators so as to propel the designed vehicle. In addition to altering the heading of the vehicle, relays enable the forward and backward locomotion by controlling the direction of the wheel rotation on both sides of the vehicle.

The assembled prototype was subjected to many different control algorithms during indoor experiments, efficiency and controllability through remote controller was evaluated as well. Structural stability, straight line movement along with turning characteristics were investigated, and additionally torque calculations and power units were verified during the indoor experiment stages. Figure 3 illustrates the indoor testing stage.

Fig.3. UGV indoor testing phase

3.3. FEM Analysis

Unmanned ground vehicle chassis was inspected through CAD software simulations. For the structural analysis, wheel assembly discs were taken as stationary while chassis was exposed to a force of 400N. This force amount was directed perpendicular to the vehicle chassis, towards ground. Figure 4 illustrates the structural analysis setup.

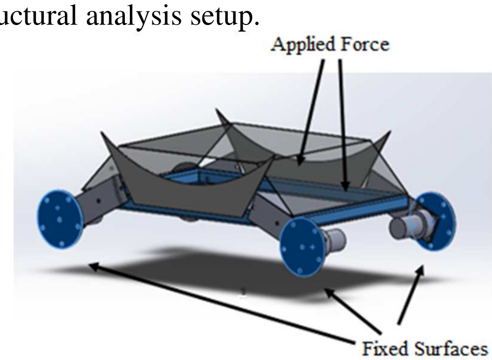

Fig. 4. FEM analysis of UGV chassis

The coupling which connects the BDC motor output shaft to the wheels is structurally inspected as well. The purpose of this analysis is to verify the stability and durability of the coupling under the anticipated operational conditions. Wheel assembly hubs are taken as fixed point and the torque is applied on the smaller outwards cylindrical cross-section. The fixed points and the torque application are illustrated in Figure 5. The torque is transmitted through the wheel-motor shaft coupling so this component is crucial and needs to be investigated with FEM analyses whether it is appropriate under design conditions of the vehicle.

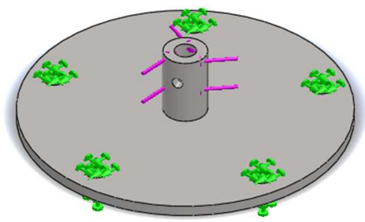

Fig. 5. Wheel-motor shaft coupling FEM analysis

4. RESULTS AND DISCUSSION

Off-road applications mostly required a solid body with considerable stiffness, and grip was very significant to achieve manoeuvrability and sound locomotion at times. Developing a vehicle to overcome these obstacles, the UGV had a compact chassis design with skid steering and acceptable stability.

Four-wheel locomotion enabled better power distribution on complex off-road surfaces when compared to front wheel drive or rear wheel drive counterparts. Wheel-chassis assembly had a rotational link and springs to provide sufficient grip in order to propel the UGV efficiently, and they also supplied the vehicle extra adaptability on rougher environments.

The implemented prototype was able to move at desired low speeds ranging from 0.1 – 1 m/s and zero radius turning motion falls within the capabilities of the vehicle. Compact chassis with small width (385 mm) was appropriate for confined space applications or agricultural field applications where the ground vehicles were required to move without damaging vegetation between crop lines. The implemented UGV model is shown in the next figure (Figure 6).

Fig. 6. The final stage of UGV prototype

The implemented UGV had 230 mm of ground clearance which was sufficient for mildly rough off-road conditions. Threaded special purpose 13” tires were equipped in order to obtain sufficient grip at sandy or low coefficient of friction surfaces. Combined with the spring system, locomotion on bumpy off-road surfaces could be carried out. However, excessive grip could impede manoeuvrability by preventing skid motions resulted during turns, especially lateral skid needs to be investigated for optimization.

Special purpose electronic development boards were used for relay control thus giving direction to the vehicle. MOSFETs on the other hand, enable the speed control with additional components such as diodes and metallic coolers. Future controller card upgrades could simply make autonomous operations possible with embedded compass, inertia measurement unit (IMU) and external global positioning system (GPS) module.

The stresses exerted on the chassis and related components are illustrated in Figure 7. It was obvious that the critical points were located at shaft-wheel hub connection and wheel extension assemblies due to weight of the vehicle. In addition to that, torque transmission took place through the motor shaft-wheel coupling, it was proper to assume this section as the most critical section.

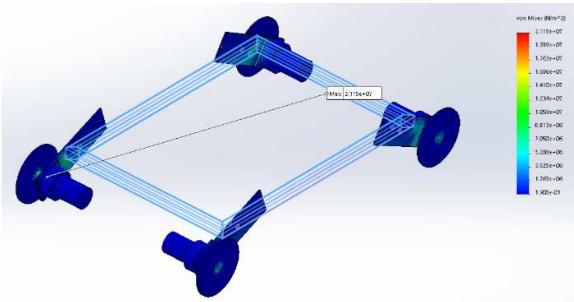

Fig. 7. FEA result of the UGV indicating stresses exerted on the chassis and wheel hub assemblies

Displacement of the chassis was studied as well, and under the applied load the maximum displacement was observed at the middle points of unsupported sections. The maximum amount of deflection (displacement) was around 0.12 mm and this amount was acceptable for the utility considerations of the vehicle and almost negligible. Displacement distribution on the chassis is illustrated in Figure 8.

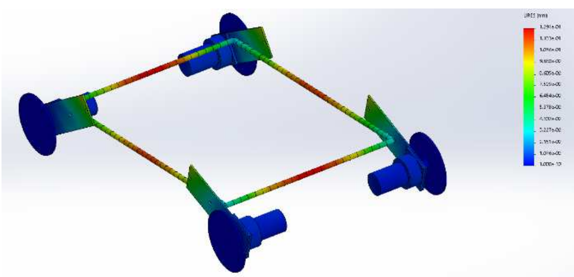

Fig. 8. FEA result of the UGV indicating displacement of chassis deflection

On the other hand, if strain was evaluated according to FEM analyses, it was expected to have more strain on the stress concentrated sections. As a complete opposition to displacement, strain was observed at the wheel-motor shaft coupling and wheel-chassis assembly plates. Along with weight of the vehicle, dynamic loads and torque transmission were going to take place at these sections thus maximum strain analyses verifies the design considerations. The maximum amount was strain is pointed out as $2.553x10^{-4}$.

Along with wheel hub assemblies, the chassis is analyzed structurally. With the current material selection, the analysis results indicate that the factor of safety is around 6 for the weakest or most critical sections of the chassis.

Wheel-motor shaft coupling disk draws attention as the reaction forces exert combined stresses when added to torque transmission for locomotion of the vehicle. Implemented structural analysis indicates that factor of safety values for these sections are significantly greater than 6 which is obtained for unsupported chassis sections. The factor of safety values are calculated to be around 12.5 for wheel-motor shaft assembly coupling disk, thus assumption of safe operation under design conditions are verified in the light of these analysis results. In the following figure (Figure 9), wheel-motor shaft assembly is closely shown, and from the colored scale and probed data the factor of safety is indicated as 13.45 with the current material selection. The minimum factor of safety is almost half of this value due to the utility of aluminum material for the main chassis where the wheel-motor shaft assembly components are manufactured from steel (ST37). Closer values of factor of safety would be expected if the same material was considered for these sections.

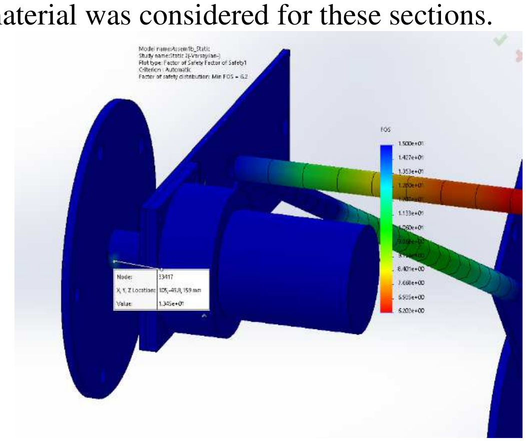

Fig. 9. Structural static analysis for the flanged coupler of the UGV

Structural analysis is separately carried out for the wheel-motor shaft coupling disk in order to ensure this part’s integrity due to the transmission of torque to the wheels which in turn propel the whole body of the unmanned ground vehicle. The separate study indicates the minimum factor of safety under excessive torque application to be over 4.5. This result verifies the coupling is able to survive safely throughout possible off-road application conditions. Material selection for this part can be reviewed when weight reduction is desired with lower weight alternatives. The Figure 10 illustrates the factor of safety distribution of the coupling part.

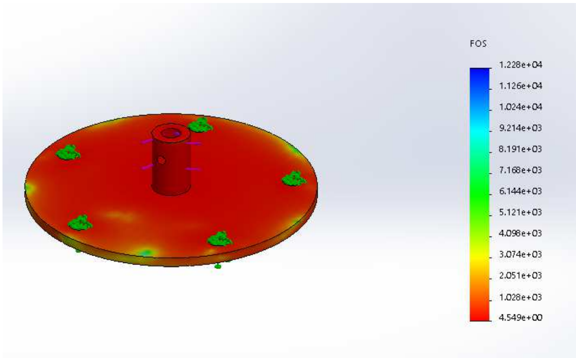

Fig. 10. Structural static analysis for the wheel-motor shaft coupling disk

5. CONCLUSION

The Unmanned Ground Vehicle manufactured in this study was able to travel at a maximum speed of 6 km/h along a straight path, the vehicle was able to achieve a minimum turning radius of zero as it had skid steering.

The maximum payload of 5 kg was safely handled at mild rough off-road surfaces. The designed compact unmanned ground vehicle prototype was analysed and manufactured in this study for low speed (< 1 m/s) off-road applications. Along with field experiments, the prototype implemented was able to safely carry a maximum payload of 5 kg on sandy off-road conditions having lower coefficient of friction when compared to paved road surfaces. A primitive spring system was utilized to enhance grip for rough terrains which were the target environment for potential unmanned ground vehicle applications.

Increasing the chassis weight was observed to improve the grip of the wheels thus making turns crispier, yet this kind of change would impede the agility of the vehicle as the response of the actuators would be slower with more power consumption.

The FEM analyses illustrated that the designed model structure was acceptably stable with the current material selections. Factor of safety plots expressed a minimum value of greater than 6 for the critical sections which the stresses were concentrated due to payload and chassis assembly and it was safe to assume that the vehicle would hold its integrity throughout potential off-road applications.

Field test implementations also verified these results as the vehicle was able to carry out basic tasks under pre-defined design conditions.

6. ACKNOWLEDGEMENT

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Dezvoltarea și implementarea unui vehicul terestru fără pilot pentru aplicații off-road

Rezumat: În ultimul deceniu s-au făcut descoperiri folosind sisteme robotizate mobile autonome, iar aceste sisteme capătă o atenție din ce în ce mai mare. Luând în considerare mediile nepotrivite pentru oameni, vehiculele terestre fără pilot (UGV) sau sisteme similare au avantaje evidente, astfel încât oportunitățile de utilitate conduc în mod natural la recunoașterea mondială. Dezvoltarea și efectuarea cercetărilor asupra unor astfel de dispozitive se numără printre principalele obiective ale studiilor de mecatronică şi robotică. Au fost dezvoltate diverse sisteme de control și mulți senzori de mare capacitate pentru a integra aceste sisteme UGV împreună cu ramuri ale științei și tehnologiilor conexe. Aplicațiile potențiale ale sistemelor UGV în domeniu sunt vaste și variază de la utilizarea civilă pentru prevenirea accidentelor până la misiuni de recunoaștere periculoase în scopuri militare. În acest studiu, UGV a fost dezvoltat cu un șasiu compact și tracțiune integrală pentru o varietate de aplicații de teren și off-road. Sistemul dezvoltat a fost echipat cu servodirecție și au fost vizate în principal aplicațiile cu viteză mică (<1 m/s). Capacitățile de adaptare ar putea fi îmbunătățite prin integrarea unor sisteme electronice suplimentare sau echipamente senzoriale. Prototipul are o capacitate maximă de transport de 5 kg și poate fi controlat de la distanță cu telecomandă. Designul vehiculului a fost examinat folosind analiza FEM și a fost verificată stabilitatea structurală a proiectului. În plus, au fost efectuate și teste pe teren pentru a evalua performanța reală a prototipului. Prototipul s-a deplasat în linie dreaptă cu o viteză maximă de 6 km/h, s-a observat un timp de funcționare activ de 28 de minute la sarcină utilă maximă.

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