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CONSIDERATIONS ON THE DYNAMICS OF A TRACKED UGV NEGOTIATING A LONGITUDINAL RAMP

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Abstract: *The interest for studying and developing UGVs has seen a rise in recent years, transitioning from prototypes to being used in many civilian and military applications. Since tracked UGVs display particular advantages in both offroad and urban environments, they present a clear advantage over robots with different type of propulsion systems. For studying the mobility of tracked robots, an analysis of the approachability of a longitudinal ramp is proposed. This paper aims to address this matter by first describing theoretically the mechanics of a tracked platform on this type of obstacle. To continue the analysis, models of a physical UGV and the ramp are created in a multibody simulation software.*
Keywords: *UGV, robot, tracks, mechanics, simulation, multibody, velocity, loads, motion.*

1. INTRODUCTION

In recent years, the use of automated systems in different fields has risen in both civilian and military applications [1]. Simple and mundane tasks previously performed solely by humans are now often kept for robots that are faster in the given tasks and also cheaper to maintain. This is not the only case. The use of unmanned solutions can help protect the human resource from dangerous scenarios where risks are involved. Thus, robots are already used where the operators would be exposed to dangerous environments, such as toxic or hazardous environments, unsafe buildings with a risk of collapse, natural disasters, high radiation, low oxygen, or extreme temperatures, for example are the firefighting or search and rescue missions [2], [3].

The same applies for military applications. Unmanned solutions are being developed by most defense companies. Many states already have in their endowment such equipment, being frequently used in combat [4], either for ground (Unmanned Ground Vehicles – UGV), air (Unmanned Air Vehicles – UAV) or for sea and maritime use (Unmanned Surface Vehicle – USV or Unmanned Under-water Vehicle – UUV). Until recent years, UAVs, or simply drones, were the most common unmanned solutions used in combat [5], but recently, especially in Ukraine, UGVs also become more common. This is further proven by the establishment of Unmanned Systems Forces [6].

2. CURRENT STATE AND RECENT DEVELOPMENTS OF UGVs

One of the most common ways of classifying UGVs are by their means of locomotion. Thus, there are three main types: wheeled, tracked and legged. The wheeled UGVs are the most common having many similarities with ordinary wheeled vehicles, being an advantage in terms of cost and complexity.

One of the main problematics for current wheeled robots is regarding the steering method [7]. Since these robots operate either remote controlled or autonomous, the steering cannot mimic the traditional steering system control. There are two main approaches – by rotating the wheels on an axis perpendicular to the vehicle plane (as it is the case for most conventional wheeled vehicles) or by changing the angular velocities of the wheels (skid-steering). The latter presents the advantage of a lower

complexity of the system and increased robustness, but implies power-losses and a complex control system. Another issue that skid-steering implies occurs on uneven terrain, due to complex kinematics of the UGV wheels that are positioned differently due to the compression of the suspension and movement of the articulated arms. Therefore, some of the present wheeled UGVs use a combined steering system by using skid-steering and having wheels with low angular displacement, providing advantages from both technical solutions [8] [9].



Fig. 1. Examples of UGVs. Tracked – THeMIS (top), wheeled – Mission Master SP (left), legged – Spot (right)

Legged robots present the best mobility when approaching obstacles like steps, stairs, gaps, but struggle in soft terrain. Also, their propulsion system is very complex especially due to the control system of the legs.

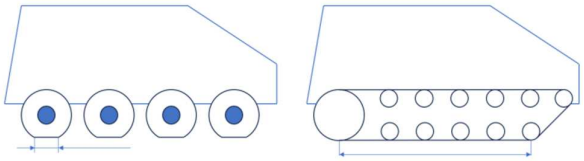


Fig. 2. Difference in contact area between wheeled and tracked UGVs (Author's own conception)

In soft and uneven terrain, the best performance is shown by tracked UGVs due to their increased contact area that decreases the ground pressure. Furthermore, the tracks increase the obstacle negotiation capability and keep the contact with the ground in rough and uneven terrain [10] [11].

Because of these advantages, tracked vehicles are being used in multiple fields, where tasks involve risks for the human operator, like mining [12], firefighting [13] or military operations.



Fig. 3. DOK-ING NRE Support Rig [14]

Even though primitive forms of unmanned solutions can be tracked to the Second World War [15], real usage of UGVs has been seen only in more recent conflicts



Fig. 4. Firefighting robot [13]

The interest in developing tracked UGVs is proven also by the Next Generation Combat Vehicle Program [16] of the US Army which addresses the issue. The scope is to engineer three types of Robotic Combat Vehicles (RCV), light (less than 10 tons), medium (10 to 20 tons) and heavy (20 to 30 tons). After 2023, the program focused solely on developing the RCV Light, a UGV meant for the use with self-defense systems, anti-tank and other recoilless weapons, being considered *expandable*. This type of UGV has proven to be efficient in some scenarios [17], being more economically advantageous.

This shift can imply multiple things. One of the lessons learned from present conflicts is that it is more economic to use smaller, expandable equipment that is harder to detect. Another one is that the integration of complex systems, especially weapon systems, involves technical challenges.



Fig. 5. Kamikaze UGV used in Ukraine [18]

In the Ukraine War, the use of UGV became even more common. Having apparently a similar doctrine as the US, smaller terrestrial drones have been reported to be seen in combat. The importance of light UGVs is clear, both in systems extensively developed by established companies [19] and in improvised robots deployed for mine-laying or *kamikaze* type missions [18].

From the current state of technology and the field experience, it can be concluded that for military applications, the main focus is on developing and improving high mobility tracked UGVs with reduced dimensions. Their main tasks imply transportation, surveillance, reconnaissance, explosive deployment or EOD or engaging lighter targets.

3. PERFORMANCE CHARACTERISTICS OF TRACKED UGVs. APPROACHING THE LONGITUDINAL RAMP

For any type of mission presented in the previous chapter, it is of high importance for the UGV to have high mobility in rough terrain.

Since the UGV is essentially a remote controlled (or autonomous) vehicle, similar criteria can be applied for establishing its performance characteristics. Smaller UGVs are both used in urban and rough terrain missions. Because of this, they need to be able to approach both types of environments, if urban settings are defined by steps, stairs and sometimes ditches, the off-road conditions usually imply obstacles like ramps, bumps or fording.

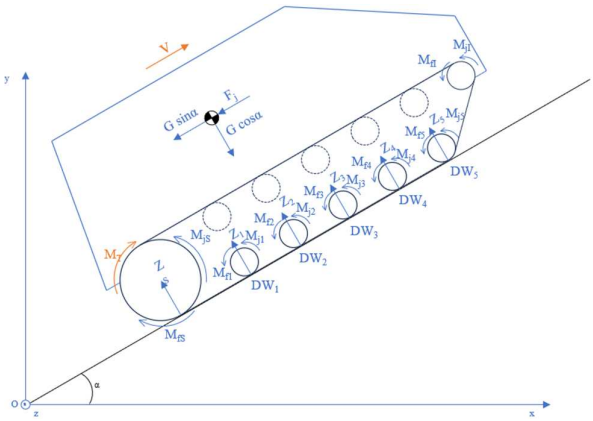


Fig. 6. Forces and torques on a tracked UGV approaching a longitudinal ramp (Author's own conception)

One of the main types of obstacles for both wheeled and tracked vehicles is the longitudinal ramp (or maximum gradient). Hence, in developing and improving tracked platforms, it is mandatory to understand the behavior when approaching a longitudinal ramp [20] [21].

The loads applied on the vehicle during the approach of such obstacle are presented in the figure above.

The main condition for the static equilibrium of the platform on the ramp is:

$$F_T = Gsin\alpha + R_f + F_j \quad (1)$$

$$Z_S + Z_1 + Z_2 + Z_3 + Z_4 + Z_5 = Gcos\alpha \quad (2)$$

where R_f is the resistance of the ground and the propulsion system, F_j is the inertial resistance and F_T is the traction force and is defined as:

$$F_T = M_S \frac{p_t z_t}{2\pi} \quad (3)$$

where M_S is the torque of the sprocket, p_t is the track pitch and z_t is the number of teeth.

Except the sprocket, all the other wheels only have resistance torques – inertial (M_j) and caused by friction (M_f). For the tracked vehicle in the figure above, since the sprocket also acts as a support wheel, all lower wheels have a normal contact force (Z_i).

The first part in climbing the ramp involves climbing with the most forward lower wheel. If the tracked platform does not have any suspension, the intermediate wheels will be suspended and the track will lose contact with them.

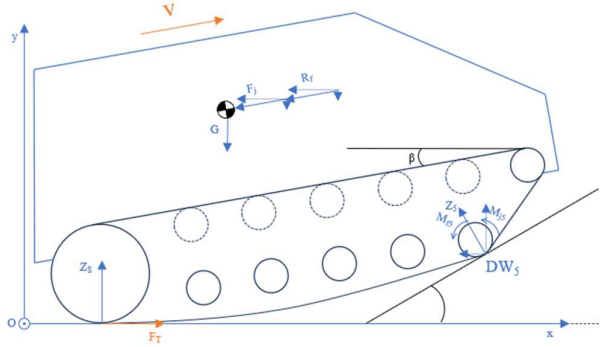


Fig. 7. Forces on a tracked UGV starting to climb a longitudinal ramp (Author's own conception)

This implies that the weight of the platform will solely be supported by the sprocket and most forward wheel.

$$Z_S + Z_5 sin\beta = G + F_j cos\beta + R_f cos\beta \quad (4)$$

$$Z_5 cos\beta = F_T - F_j sin\beta - R_f sin\beta \quad (5)$$

Finally, the platform will reach the edge of the ramp and just before the center of mass will pass it, the entire weight will be supported by the remaining wheels.

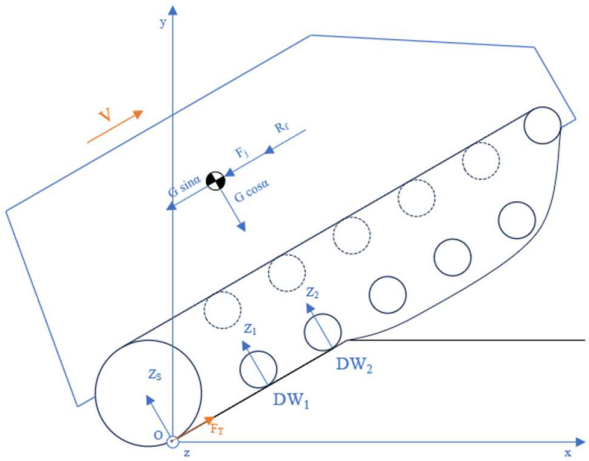


Fig. 8. Forces on a tracked UGV on a longitudinal ramp before dropping (Author's own conception)

$$Z_S + Z_1 + Z_2 = Gcos\alpha \quad (6)$$

$$F_T = Gsin\alpha + F_j + R_f \quad (7)$$

After the center of mass will pass the edge of the ramp, the platform will drop. During this time, an increased bushing tension is expected to be seen due to the fact that the vehicle will decline with the track supported on the edge.

4. DEVELOPING A TRACKED UGV MODEL IN A MULTIBODY DYNAMICS SIMULATION

Within the scope of this work, the dynamic behavior of a tracked UGV was studied. The platform consists of a steel chassis with two tracks rigidly attached. It is equipped with two DC Motors connected to a gearbox (consisting of a worm gear and a planetary gearbox). To the gearbox axis, two identical sprockets are attached.



Fig. 9. The drivetrain of the UGV. The figure illustrates a detail from the robot's fabrication phase. (Author's own conception)

The track link is a 2-pin type, made of a steel core and protected by a layer of rubber. The assembly is made by 58 tracks engaged by the sprocket. In order to limit the lateral movement, instead of a central guide, two lateral guides fixed to track links.

Table 1

Characteristic of the UGV used for analysis [22] [23]

Parameter	Value
Fully equipped mass	250 kg
Maximum speed	1 m/s
Maximum gradient	45°
Maximum lateral slope	30°
Maximum step height	225 mm
Maximum ditch length	800 mm
Average ground pressure	78.25 Pa
Minimum turning radius	0 m
Track width	143.5 mm

The UGV propulsion system uses 5 lower double-wheels at 6 track supporting double-wheels, the front one acting also as an idler.

The characteristics of the robot are given in Table 1.

For a better understanding of the behavior of the UGV in different scenarios, with limited costs, simulation can be used. For dynamic behavior, a multibody simulation software is advised. There are multiple available options, but for the scope of this study, Recurdyn (*FunctionBay*) was chosen, due to the fact that it has integrated a specialized toolkit for tracked vehicles. The dimensions of the main components (sprocket, track link, double-wheels) were used to modify the preexisting components from the software's library. Since the tooth profile can be defined only by a list of coordinates, multiple points were extracted from the CAD and transferred into the modelling software. The chassis was imported directly from the CAD keeping the original mass, center of mass and inertial parameters.

The real UGV track links are not identical with the library model since they do not have a central guide, rather they each have two lateral guides that prevent the phenomenon of track derailment (track throwing). For the simulation from the present paper, it is not a critical point since there are no turns or lateral slopes and the forces on the transverse (Z axis) are negligible. In the future, this could be solved by modifying the sprocket carrier width and total width and by adding a central guide. This central guide will act as the two lateral guides from the physical model. The results should, of course, be interpreted correspondingly.

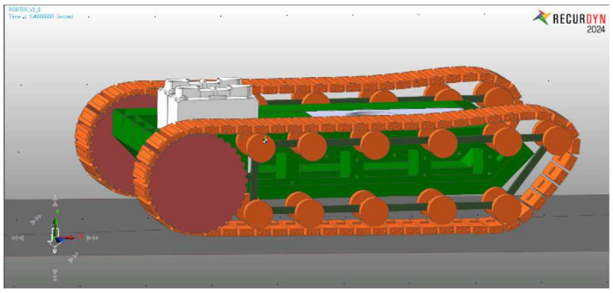


Fig. 10. The finished model (Author's own conception)

The UGV does not have any type of suspensions and the idler wheel is identical to the other double-wheels. It is fixed by 2 screws that can be used to tighten or loosen the track. Since, it does not have any other type of mechanism (by use of springs and dampers for example), it will be only constrained with a cylindrical joint (*Revolute joint*) and if a more tensioned or loosen track is desired, the positions of the idler and of the cylindrical joint will be moved longitudinally.

For the purpose of this work, there were 2 scenarios simulated – moving on a straight rigid road and approaching a longitudinal ramp. The modelled ramp is 58% (30°). Since the simulation can face errors because of perfectly straight edges, and since in real practice, sharp edges are not used, the edges were filleted with 100mm radius.

For the scope of this paper, it is assumed that the UGV will approach the ramp with a constant velocity, the angular velocity of the sprocket being 0.5 rpm.

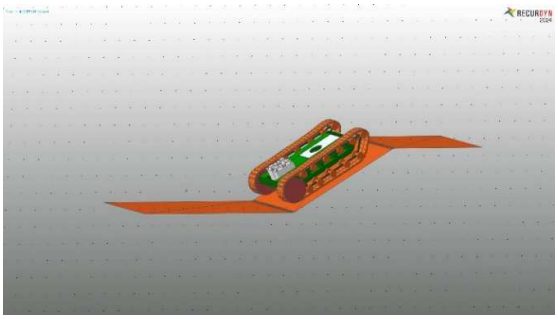


Fig. 11. UGV approaching the longitudinal ramp (Author's own conception)

5. SIMULATION RESULTS AND ANALYSIS

The simulation for moving on a straight rigid road was performed in order to measure vertical and longitudinal accelerations. In practice, as seen in the previous chapters, UGVs are equipped with multiple special equipment such as observation or weapon systems. By the nature of a tracked platform (especially in the case of a track made from multiple links and not a complete rubber track), the movement implies vibrations in both vertical and longitudinal directions [20]. These vibrations have a negative influence on the platform components (through fatigue [22]) and, in the case of conventional, manned, tracked vehicles, can affect the health of the human operators [23].

The vertical vibrations are caused by the rolling wheels (in this case also the sprocket) moving from one track to another, while the longitudinal ones are caused by the sprocket pulling the rear part of the track and at the same time pushing the upper part.

Especially since this vehicle does not have a suspension system, understanding the pattern of these vibrations, their amplitude and observing the means for lowering them, can aid in designing a preliminary stabilization system of the observation system. Furthermore, it can be addressed how this vertical and longitudinal acceleration can negatively impact the transportation of different materials.

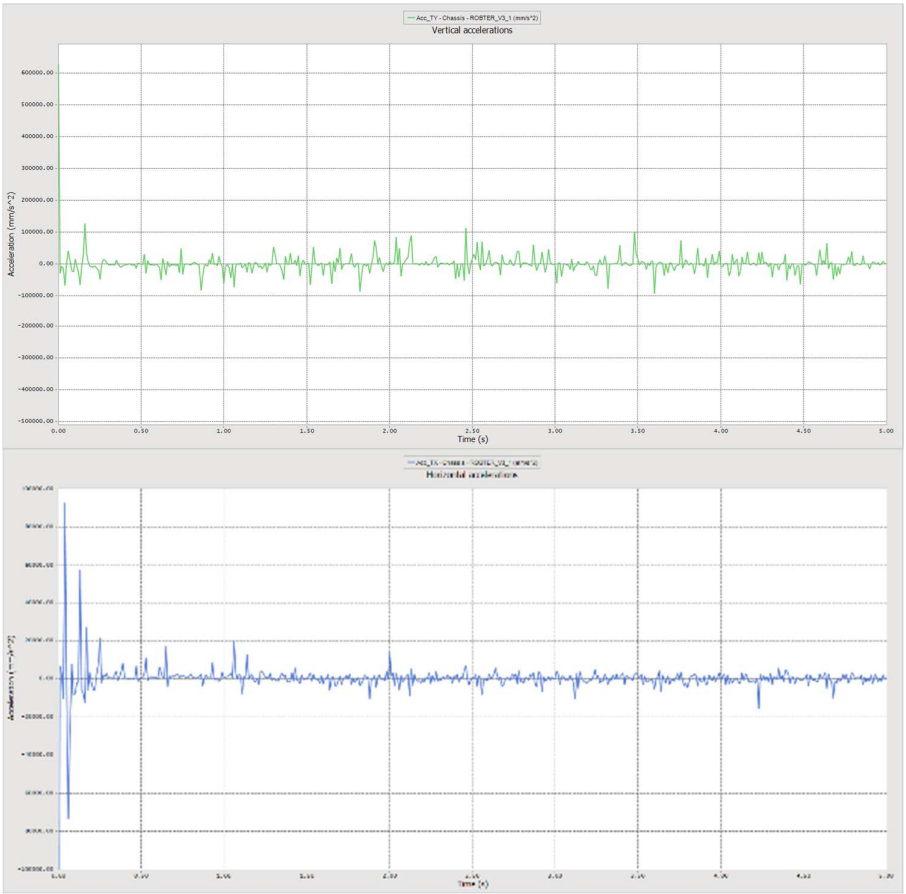


Fig. 12. Vertical and horizontal accelerations when moving on a straight rigid road

For the ramp, the simulation was timed in order for the UGV to reach the upper platform. One of the main points of focus for this simulation was to observe the torque values for the sprocket. Since there are no turns and both tracks behave the same, the results were similar from left to right. Therefore, all the following displayed plots are only for one track of the UGV.

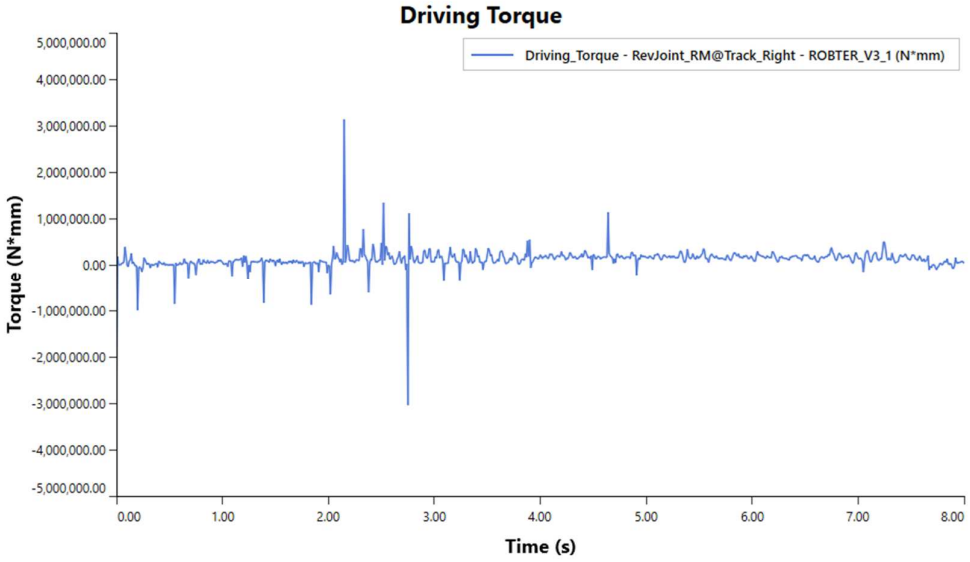


Fig. 13. Driving torque when approaching the ramp

The results show an average of 117 Nm for the sprocket with the velocity of the center of mass of the chassis of 0,382 m/s. The spikes represent the beginning of the climb.

Another important point was the vertical and horizontal forces from the joints of the double-wheels and of the sprocket. This is important especially to verify the effort at the joints. To evaluate this, the magnitude of the horizontal and vertical forces was plotted.

Considering double-wheel 1 (DW1) the first one from sprocket, it can be observed that DW5 (blue) has the most stressed joint due to being the first in absorbing the shock and also because it is loaded by the track being pulled between the idler and DW4.

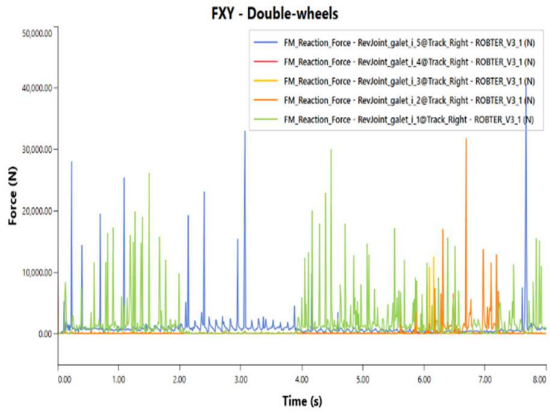


Fig. 14. Loads on the joints of the double-wheels

For DW2 (orange) the load appears between the time it is close to the upper edge of the ramp and shortly after, when the track is pulling it. This is due to the fact that it is close horizontally to the center of mass. Shortly after the CM passes the edge, the platform drops. This is shown also by the last peak for DW1.

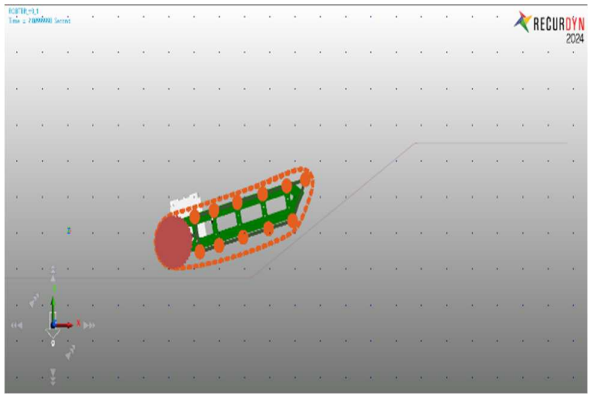


Fig. 15. UGV approaching the ramp (Author's own conception)

The absence of any loads on all wheels except DW1 between T = 2 s and T = 4 s is caused by the track losing contact shortly, the wheels being completely suspended. This further explains the effort from DW1.

Using this data, it can be verified that these loads are fully supported by the affected components.

For the bushing tension of track, the values are fairly constant with the exception at T =5.9…7.5 s, where the UGV is passing the upper edge of the ramp. This increases the tension of the track for a short time.

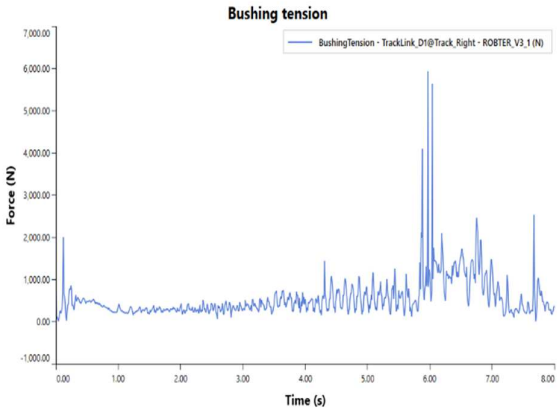


Fig. 16. Bushing tensions

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7. CONCLUSIONS AND FURTHER RESEARCH

In the first two chapters the importance for studying tracked UGVs in the current technological and geopolitical context was presented. It was shown that there is a clear trend in developing and using UGVs in multiple fields, especially in military applications. In this branch, lightweight UGVs with smaller dimensions are used for aiding the personnel or performing simple tasks, rather than operating complex missions autonomously.

The theoretical behavior of a tracked platform on a longitudinal ramp was presented by describing the important stages in approaching this obstacle. Later, a real UGV was modelled in a specialized multibody simulation software. The obtained results display the expected behavior from the previous chapter.

For future work, a first step would be improving the model by adapting the sprocket and track link for a central guide in order to be able to evaluate the lateral guides and their ability to prevent track derailment.

Following this, validation of the model is required by testing the physical model in similar conditions and comparing the results.

Lastly, other types of obstacles in different configurations can be simulated to estimate the mobility of the UGV.

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Considerații privind dinamica unui UGV șenilat pe o pantă longitudinală

Rezumat: Interesul pentru studierea și dezvoltarea UGV-urile a avut o creștere în ultimii ani, făcând trecerea de la prototipuri, la utilizarea pe scară largă în aplicații civile sau militare. Având în vedere că UGV-rile șenilate prezintă avantaje atât în teren greu, cât și în mediul urban, oferă un avantaj clar față de roboții cu altfel de propulsoare. Pentru studierea mobilității roboților șenilați, se propune analizarea capacității de abordare a pantei longitudinale. În cadrul acestui articol va fi prezentată problematică întâi prin analizarea teoretică a mecanicii unei platforme șenilate pe acest tip de obstacol. Pentru a continua analiza, un UGV existent a fost modelat împreună cu panta într-un program de simulare de tip multi-corp.

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