State of the Art of Tracked Unmanned Ground Vehicles

Ștefan-Tigran RADU, Lucian-Ștefăniță GRIGORE, Amado ȘTEFAN, Cristian MOLDER, Daniel CONSTANTIN, and Damian GORGOTEANU

***Abstract*—Nowadays, robots are used in many fields for performing mundane or repetitive tasks or for more difficult operations in harsh environments. One niche is represented by Unmanned Ground Vehicles (UGV) that use tracks for propulsion. This type of robot is frequently used in various missions by armies, firefighting or law-enforcement agencies. Because of the recent risks caused by conflicts worldwide, developing and studying such robots is of high interest. This paper aims to summarize the recent research in this field, bringing together information from different areas that contribute to developing such a robot. The novelty consists in the recent uses in modern conflicts, the lessons learned and the areas where improvement through research and development is needed.**

***Index Terms*—UGV, robot, unmanned, tracked, mobility, terrain, autonomy.**

I. INTRODUCTION

In recent decades, the rise of unmanned and autonomous systems caused changes in multiple fields, in both civilian and military applications. As technology advances, the modern weapons change and warfare is reshaping [1]. In order for a country to be able defend itself, it needs to be able to understand these changes and address the present challenges.

The advancements are very clear since the technology becomes more accessible even in civilian applications. In field such as agriculture and logistics, autonomous ground vehicles get used more frequently for repetitive tasks that involve little or no decision making. UAVs (Unmanned Aerial Vehicle) on the other hand are often used in transportation of goods (home deliveries) or for video. making them available even for hobbyists.

Ș.-T. RADU is with the Government Quality Assurance Representatives Directorate, General Directorate for Armaments, Bucharest, Romania (e-mail stefan.radu@dpa.ro).

L.-Ș. GRIGORE is with the Military Technical Academy “Ferdinand I”, Bucharest, Romania (e-mail: lucian.grigore@mta.ro).

A.-G. ȘTEFAN is with the Military Technical Academy “Ferdinand I”, Bucharest, Romania (e-mail: amado.stefan@mta.ro).

C. MOLDER is with the Military Technical Academy “Ferdinand I”, Bucharest, Romania (e-mail: cristian.molder@mta.ro).

D. CONSTANTIN is with the Military Technical Academy “Ferdinand I”, Bucharest, Romania (e-mail: daniel.constantin@mta.ro).

D. GORGOTEANU is with the Military Technical Academy “Ferdinand I”, Bucharest, Romania (e-mail: damian.gorgoteanu@mta.ro)

Figure 1. PackBot in use in the war in Afghanistan [3]

For military use, law enforcement, search and rescue and firefighting robots have been used since the beginning of the 2000s [2, 3], but in the last couple of years the interest has risen.

The need of using robots is usually rooted either in applications that are simple, repetitive and involve little to no decision making, or for missions where the safety of the personnel is at risk (e.g. unsafe environments, NBC - Nuclear, Biological, and Chemical risk, the mission is close to or in the combat area). Another application, which is the case for one of the first *proto*-UGVs - Goliath [4], is the use of the vehicle as a *kamikaze*. These types of UGVs are usually made with cheap materials or even scraps and they do not need to perform complex tasks. Their functions are generally limited to moving, transporting some sort of exploding materials and means to initiate the explosion at a given moment.

An example of crawler type UGVs used in civilian applications are robots used for inspecting or cleaning pipes [5, 6]. In this case, there are not only harsh conditions, but due to the smaller dimensions of some pipes, they are inaccessible to human workers.

One of the most common initial applications was EOD (Explosive Ordnance Reconnaissance) [2]. The rise of terrorist attacks and especially the ones after 9/11 [7] but also the war in Afghanistan where IEDs became a dangerous threat contributed to the need to improve the EOD equipment. UGVs presented a real advantage for scouting and for explosives disposal by protecting the personnel, keeping them at a safe distance. Another advantage of using a robot for such operations is that even though the UGV

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fails to neutralize the exploding device, it still transmits important data to the operator who can better assess the situation without being exposed to risks.

Figure 2. Colossus UGV manufactured by Shark Robotics used for extinguishing the fire at Notre Dames, Paris [8]

Another field where the use of robots can contribute to better protection of human personnel and the fulfilment of more complex missions is firefighting [9]. Because of the harsh environment related to fires, such as smoke, low oxygen, high quantities of CO and CO_2 and also because of the risks related to explosions or falling debris, UGVs can protect the rescuers and get close to the affected areas. They can be equipped with hoses for extinguishing fires; cameras used for search and rescue missions or platforms for transporting the victims.

In more recent years, robots are used more and more in complex warfare situations. Now we can observe that it is common for many armies worldwide to use both UAVs and UGVs for reconnaissance in open fields or urban environment, for neutralizing different targets or for transportation of goods. Thus, important procurement programs start to appear, such as, in the case of the US Army, the RCV (Robotic Combat Vehicle) which is part of the NGCV (Next Generation Combat Vehicle) family of vehicles [10].

The war in Ukraine and the war in Gaza brought a different perspective relating to what modern warfare is and how robots are reshaping it. Different types of UAVs and UGVs, expensive and improvised alike are being used at present.

In the following chapters there will be a summary of the recent development in the field of UGVs, the recent uses and how they succeeded or failed their missions. Following this, different types of modern UGVs will be presented with their corresponding performances and limitations. Building from this information, the main areas of interest will be determined and described. Finally, conclusions regarding the state of the art of the tracked UGVs will be drawn with regard to the current main points of focus.

II. Mobile Robotics. Types of UGVs. Tracked UGVs

Multiple fields concur in the field of robotics. In the case of mobile robots (either UGVs, UAVs or even UUVs - Unmanned underwater vehicles) they take the form of a vehicle capable of operating in its designed environment. These types of robot work as an integrated system (embedded real-time system) that uses sensors for the perception of the environment, actuators to perform different actions and a control system [11].

The development of UGVs. compared to UAVs for example, face some difficulties with regard to the terrain complexity. Not only do UGVs need to be able to identify and avoid obstacles in real time, such as walls, trees etc., but they also need to be able to approach slopes, gaps and steps. They also need to be able adapt to different types of terrain, from rigid surfaces, to soft and muddy terrain or sand.

Since mobile robots are usually based on a type of vehicle, when describing UGVs, one of the fundamental classifications is based on the means of propulsion. Therefore, three main types of terrestrial robots can be identified: legged-, wheeled and tracked robots. From the three, the most complex, but less common is the legged UGV. One such example is *Spot* (manufactured by Boston Dynamics) that has even been used in some military training [12].

When comparing wheeled to tracked UGVs, the same principles from conventional ground vehicles are applicable. The tracked vehicles present better performances in terms of mobility in difficult terrain [13, 14] because of the greater surface compared to wheeled vehicles. Multiple studies [13-15] show that even though wheeled vehicles perform better on rigid roads and at higher speed, in off-road applications the tracked ones are superior.

On the other hand, one of the disadvantages of the tracked platforms are related to higher productions costs and higher complexity.

Another important limitation is regarding the steering. Generally, tracked platforms use skid-steering which require considerable power due to a “plowing” effect (the shear forces generated by the tracks). This complex phenomenon has a negative effect in terms of trajectory control. Furthermore, the skidding of the platform is subjected to the nature of ground that the platform is moving on.

Studies [13, 14] show that wheeled platforms with lower weights (less than 10 tons) show comparable performance characteristics in terms of mobility. Hence, some light weight UGVs (as it will be presented in the next chapters) are designed on a wheeled platform as a trade-off between mobility and cost of production.

In this paper, we will focus on the UGVs designed on a tracked platform because of their versatility and advantages in off-road conditions.

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III. Examples of Tracked UGVs. Use of UGVs in Modern Warfare

As presented in the introduction, multiple tracked UGVs are being used in both civilian and military fields. In the case of the latter, modular systems present the advantage of creating a family of vehicles with similar characteristics. One such example is the THeMIS UGV which is in use in multiple NATO (North Atlantic Treaty Organization) countries. Having small dimensions (240 cm × 205 cm × 115 cm) and an unladen mass of 1650 kg with an available payload of up to 1200 kg, it is a versatile support UGV [16].

Table I. THeMIS' Performances

Max. speed	20 km/h
Max. gradient	31°
Max. fording depth	600 mm
Pull Force	15 000 N
Min. turning radius	0 m
Range (hybrid)	15 h
Range (silent/electric)	1.5 h
Line of sight	1.5 km

The powertrain is diesel-electric and the drive system uses rubber tracks. For environmental perception it uses a LiDAR system together with optical sensors, thermal and IR (Infrared Sensor) imaging. For navigation it can be directly controlled by the operator, it can use waypoint navigation or follow-me function. Its intended use is for support in transportation of goods or wounded personnel, for ISR (Intelligence, surveillance and reconnaissance) type activities, combat (being equipped with remote controlled weapon stations), breaching and EOD operations.

Figure 3. THeMIS in CARGO configuration [17]

THeMIS UGVs have been recently deployed in the Ukraine war [17]. Their main use is for victim transportation and for carrying ammunition and other supplies to the front lines, because of their light weight and tracked propulsion, replacing conventional trucks. Their small dimensions decrease the risk of being observed by the enemy.

KRAMPUS is another UGV recently deployed [18]. The Ukrainian-made UGV has small dimensions and uses electric motors for each rubber track. There are very little to no technical details available other than the use of RPV-16 launchers. The use of such robots signals the interest for smaller dimension multi-purpose tracked UGVs.

Recently included in the endowment of the Turkish Armed Forces, an even smaller UGV is the BARKAN manufactured by the Turkish company HAVELSAN [19].

Table II. BARKAN's Performances

Max. speed	13 km/h
Unladen mass	380 kg
Payload	200 kg
Min. turning radius	0 m
Range	3 h

Its scope covers the same range of transportation, ISR, combat (7.62 mm weapon system, 40 mm grenade launcher) and EOD.

Figure 4. Ripsaw M5

The Next Generation Combat Vehicle program of the US Army takes into consideration the use of Robotic Combat Vehicles (RCV) [10]. In the beginning of the program, the interest was to develop three independent systems RCV Light – less than 10 tons with self-defense systems, anti-tank missiles and recoilless weapons, being *expandable* in combat, RCV Medium – 10 to 20 tons for engaging light to medium armored threats, and RCV Heavy – 20 to 30 tons that should be able to defeat all known enemy armored vehicles and be as survivable as a crewed system.

During 2023, the focus shifted to developing firstly the RCV-L.

From this program, there have been developed and still under testing UGVs by McQ, Textron Systems, General Dynamics Land Systems and Oshkosh Defense.

Table III. Ripsaw M5 Performances [20]

Combat Weight	10.5 t
Dimensions (LxWxH)	234×105×59.5 in
Payload	8 000 lb
Max. speed	25 mph
Max. speed	25 mph

For improved situational awareness, the Ripsaw M5 (Textron Systems) is using 360° cameras that, by the use of AI, supports object identification, an integrated UAV and a smaller dimension UGV, and a multi-spectral surveillance system. For combat purposes it can be equipped with medium caliber cannons, weapon station and C-UAS (Unmanned Aircraft Systems) systems.

In the last years, there has been a lot of interest in creating a control system for adapting an existing platform to become unmanned. Because most armies are stocking old vehicles that become outdated either in terms of firepower or survivability, by turning them into UGVs through automation, they can be used without endangering personnel. The focus for research was on commonly used platforms. One such example is the M113 [21]. In 2023, the Australian Army tested remote controlled M113s [22]. In the meantime, FNSS developed the Shadow Rider UGV on the M113 [23].

Another example of a converted outdated tracked platform is the ZMA-X developed by Aselsan from the Turkish Army's ACV-15, that can be used both manned and unmanned [24].

Figure 5. Remote controlled M113 [21]

In order to achieve such an automation, new systems need to be added that can interoperate and address the following: *Vision* – through the use of sensors (cameras, radars, lidars), the operator is able to perceive the environment in which the vehicle is working and to understand the terrain, obstacles and possible targets; *Movement* – the conventional driving (by using levers, cranks and pedals) needs to be adapted by use of actuators; *Remote control* – the long distance operator needs to be able to send commands to the afore-mentioned actuators based on the vision system data; *Localization* – giving the position, heading, paths and speed of the vehicle; *Communication* – the means by which the UGV transmits the collected data; *Human-Machine-Interface* - for the operator to be able to communicate with the vehicle.

The conversion from an older vehicle platform to an UGV, even though it is complex and it requires a long R&D process, it has the advantage of enhancing the lifetime of older equipment. They can be used either for combat, transportation, reconnaissance or even as tactical decoys. The war in Ukraine showed that during a war of attrition, all the existing resources need to be used, thus reusing older weapons can be an advantage.

The Ukraine war has proven the necessity for fast development of robots for defense purposes [25]. The immediate threat and the advancements in technology determined the establishment in 2024, of *Unmanned Systems Forces* [25] for specific missions involving air, ground or naval robots.

A trend seen in the Ukraine war is related to cheaper, more affordable UGV's. A rise of expandable robots is seen in modern warfare. Studies through combat simulations have proven that the usage of less expensive UGVs, that are considered as having low survivability, (as is the case for the RCV-L mentioned earlier in this study) can have a positive effect in combat [26].

Figure 6. Kamikaze UGV used in Ukraine [27]

In recent months, the Ukrainian Forces have been using different types of expandable UGVs [27, 28]. Their missions vary from simple transportation of supplies, to mine laying or mine clearing, reconnaissance and even assault missions with ground robots equipped with weapon stations.

Small dimension unmanned systems are more difficult to be detected by the opposing forces and can approach the targets easier. The usage of *kamikaze* UGVs (packed with explosive materials) that get closer to enemy trenches are becoming more common [28].

IV. MOBILITY OF TRACKED UGVS

As presented in the previous chapters, one of the key characteristics of the UGVs used in military, search and rescue or law-enforcement applications (as is the case for other human-controlled ground vehicles) is their mobility. As earlier detailed, tracked drive (in most cases) provides superior mobility compared to wheels.

Thus, studying the UGVs when approaching different obstacles is of high importance.

In the developing phase of a ground robot, there are multiple factors that impact the design such as: mission profile (urban or off-road), the terrain configuration and consistency, expected obstacles and performances [11].

Common obstacles in military applications include gap crossing, crossing walls and steps, fording, maximum gradient and lateral slope [29]. The expected approachable obstacles define the geometrical configuration of the tracked platform.

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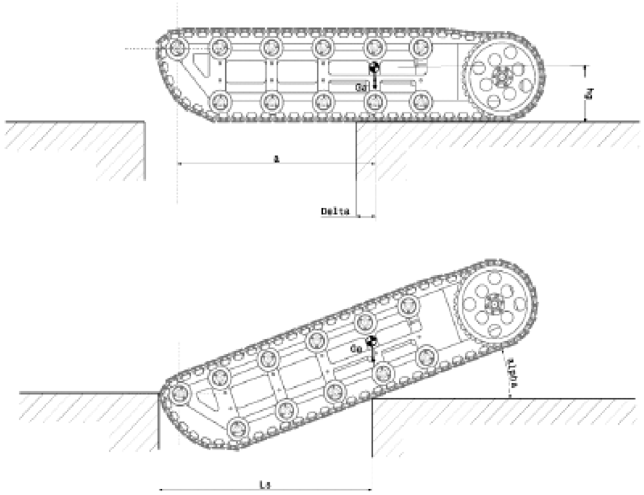

Figure 7. Gap crossing

The position of the center of gravity on the longitudinal axis limits the ability to cross a certain gap. In normal use, the platform approaches perpendicularly the gap until the center of gravity is very close to the edge (distance Δ). By continuing the movement, a torque generated by the gravity will pull the vehicle downwards by angle α. The maximum gap is when the *fall* is stopped in a point on the horizontal axis that passes through the center of the front wheel. It is important to state that this scenario applies to gaps with rigid edges. If h_g is the height of the center of gravity, r is the radius of the front wheel, a is the distance from front wheel to the center of gravity, the following geometric equations can be defined

$$tg\alpha = \frac{h_g - r}{a} \tag{1}$$

$$L_{gap} = a\cos\alpha + r\left(1 - \sin\alpha\right) \tag{2}$$

$$L_{gap\max} = a\cos\left(arctg\frac{h_g - r}{a}\right) + \left[1 - \sin\left(arctg\frac{h_g - r}{a}\right)\right] \tag{3}$$

It can be observed that the height of the center of gravity has a negative influence on the maximum length of the gap, but the distance a has a positive influence. It is important to state that for some tracked platforms, it might be of interest to approach a gap with the front and with the rear.

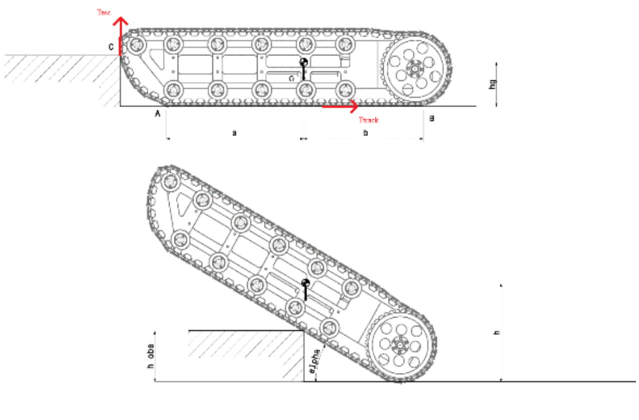

Figure 8. Step climbing

Step climbing can be split into two different stages, the first one involves approaching the obstacle, followed by climbing it.

One of the first constraints in approaching step-like obstacles comes from the height of the front wheel. For the maximum approachable step, the height of the center of the front wheel will be equal to the height of the step. A vertical force appears at the contact between the track and the obstacle T_{asc} and a horizontal one between the track and the ground T_{trak} which are constrained by the friction coefficients φ_{trak} and φ_o. For the platform to be able to approach the step, the torque generated by the traction force should be greater than the one generated by gravity.

$$T_{trak} = \varphi_{trak} G \tag{4}$$

$$T_{asc} = \varphi_o T_{trak} = \varphi_o \varphi_{trak} G \tag{5}$$

It can be observed that besides the geometrical configuration, the biggest constraints for step and wall climbing are the traction force and the friction coefficients.

For approaching gradients, the limitations are based on the traction characteristics.

The mobility performances of a UGV also depend on the terrain consistency.

In the above examples, the assumption was that the ground is rigid. In the case of deformable terrain (such as mud or sand), the behavior changes. The advantage of tracked vehicles is given by the large surface area which implies lower pressure on the ground. Generally, it can be defined as

$$p_{avg} = \frac{G}{2bL_a}, \tag{6}$$

where b is the width of one track and L is the length of the track that is in contact with the ground.

In the case of a UGV with elastic suspension, the contact area increases and the pressure decreases.

The mobility performance on deformable terrain involves using multibody models and can be currently performed through different simulation software. The results include details regarding the efforts in the track elements, sinkage and slip. This represents a very important subject at present because it is also linked with the control of the UGV.

V. Steering of Tracked UGVs. Steering Control

As mentioned earlier in this paper, generally, tracked UGVs use skid-steering. To achieve this, there can be three scenarios, the exterior track maintains constant velocity and the interior track's velocity is lowered, both tracks' velocities are lowered and raised or the exterior track's is raised and the interior one's is maintained.

Due to the skidding of the tracks, the centers of rotation are moving to the exterior of the platform, thus the interior track is skidding to the front, and the exterior one is skidding to the rear.

The slip and skid that appear as a result of steering have an important impact on the UGV's control, especially in the case of autonomous driving and require intensive studying [30-32]. For obstacle avoidance for instance, based on a preconfigured reaction, the UGV can avoid the object in a longer or shorter time and by changing its trajectory in different ways possibly making it difficult to pass through narrow spaces. This can impact the average speed that the UGV can travel between given way-points.

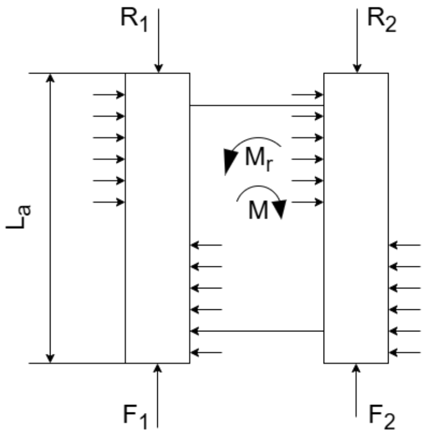

Figure 9. Tracked platform forces when performing a turn

Another particular phenomenon in tracked platforms is the *plowing* effect of the track during skid-steering. This effect means that during the rotation of the track, resistant forces from the terrain will push the edges opposing the rotation. Depending on the terrain these resistance forces will change, thus making it difficult to predict their effect. The same difficulties apply for skidding and slipping. The power needed to overcome all the resistances is known as consumed power. In extreme conditions, on lateral slopes, these resistant forces can remove the track from the wheels, making the UGV inoperative.

All these effects have a negative impact in the tracked UGVs control performance, being difficult to achieve accurate control of a tracked robot.

VI. AUTONOMOUS UGVS

As stated in the introduction to this paper, UGVs are used for easy, repetitive tasks. For these types of missions, automation is suitable. This means that the robot is able to operate on its own, making decisions based on sensor data without any human intervention. Such a process raises many challenges in a tracked UGV, especially when its missions are primarily on deformable terrain with a complex profile.

Examples of autonomous missions include supply runs (from a logistic point to the combat area), fast evacuation of wounded troops, surveillance and even *kamikaze* missions.

As described before, slip and skid naturally occur in the movement of tracked platforms. In automated UGVs they can cause inaccuracies both in controlling and positioning of the robot. In conjunction with movement on different types of terrain with different consistencies, the inaccuracies are exacerbated. In order to compensate, adaptable control systems must be developed.

The localization system is essential in an autonomous ground vehicle. There are multiple solutions such as GPS, inertial navigation systems and odometry. The GPS is limited in obstructed environments such as forests or urban areas, whereas the inertial navigation systems are prone to drift over time. Finally, odometry is highly influenced by the above-mentioned slip and skip. To solve this problem, sensor fusion techniques such as filtering are used.

Figure 10. Ripsaw M5 equipped with a small UGV and an UAV as *sensors* [33]

One other subject of interest refers to UGV-UAV cooperation and *swarming*.

UGVs face many limitations in terms of how much they can perceive, their views being often obstructed by obstacles. In many of the existing UGVs used for ISR, cameras are raised on a taller structure in order to widen their field of view. On the other hand, UAVs are superior in this matter. Furthermore, they offer better mobility and higher speed. However, they are highly limited by weight and cannot transport heavy equipment.

The two systems can complement each other [34]. One solution is to use the UGV to support the UAV's mission by transporting it, becoming a docking station or even a GNSS reference.

On the other hand, the user can take advantage of the wide field of view and the speed of the UAV to gather information (becoming a *sensor*), whereas the UGV with its capability of caring heavy equipment can be used as an *actuator*. This method of cooperation can become useful in many scenarios. For instance, in search & rescue operations, the UAV can be used to identify the victim, and the UGV can aid with evacuation.

Overall, designing autonomous tracked UGVs involves addressing the complex track-ground interaction, adapting to environment changes, and ensuring precise localization—tasks that require advanced algorithms and robust sensor integration to ensure reliable performance in real-world conditions.

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VII. Conclusions. Steps Forward

This paper presented the importance of using unmanned platforms in both civilian and military applications, for protecting humans from working in difficult or dangerous conditions, helping them in inaccessible spaces, or for replacing them in simple and repetitive tasks.

A brief comparison between the types of UGVs based on the drive system with their individual advantages and applications was made. Because of the superior mobility in difficult terrain of the tracked propulsion, this paper focused on this type of UGVs.

Next, some of the most relevant tracked ground robots were listed and their particularities were presented. The usage trends of UGVs could be seen with respect to the current technological advancements and the evolution of modern warfare in the current world conflicts. Based on this information, it can be concluded that terrestrial robots are becoming more and more important for logistics and medical purposes, but also in surveillance and even assault missions.

Another key point is that there is a clear tendency in certain countries to keep the focus on expandable UGVs rather than more complex and more expensive robots that might have yet to develop.

Another area of interest for different countries and manufacturers is the possibility of reusing outdated armored vehicles by turning them into unmanned systems.

The fourth chapter, regarding the mobility of a tracked UGV, presented a short introduction into the influence that geometric characteristics have into approaching different obstacles. It can be understood that in developing a UGV, the types of terrain on which its mission will be held needs to be thoroughly studied. Further research into track-terrain interaction is considered to be of interest, especially regarding soft grounds (e.g. mud, sand).

The steering of tracked platforms was briefly described and the main challenges that skid and slip create were presented. The effects on navigation control and path-planning were mentioned. Special interest should be given on studying the behavior on different types of terrain.

Finally, the possibility of creating fully autonomous vehicles was discussed and certain applications were listed. The cooperation between different unmanned platforms, including ground and aerial ones, brings many advantages by surpassing each system's own limitations.

It can be concluded that the study of UGVs is of high importance, being a useful system for a broad area of applications. By narrowing down, the current military needs can be found in the field of tracked robots with reduced dimensions and limited costs that can be configurable for different missions. Further research into improved mobility in difficult terrain is of interest. Also, developing interoperability between different systems is considered to be of high importance.

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