Asia-Pacific Journal of Science and Technology: Volume: 29. Issue: 01. Article ID.: APST-29-01-01. Review Article

APST

Asia-Pacific Journal of Science and Technology

https://www.tci-thaijo.org/index.php/APST/index

Published by the Research and Graduate Studies Division,
Khon Kaen University, Thailand

Recent developments in modular unmanned ground vehicles: A review

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Received 20 July 2022
Revised 11 November 2022
Accepted 11 January 2023

Abstract

Modular Unmanned Ground Vehicles (UGVs) have extensively been used in both military and commercial applications and their demand has been increasing as the market for automation technologies continues to expand. The importance of innovation in the domain of UGV can be understood by the fact that the UGV market is projected to grow at the Compound Annual Growth Rate (CAGR) of 12.8% by 2027.The present paper discusses innovations and advancements made in the design and development of unmanned ground vehicles for 5 years i.e., 2016 to 2021. An in-depth look into the innovations made by various defence and public sector organizations depicts a clearer picture of the pressing need, that is the development of indigenous unmanned ground vehicles.

Keywords: Mobile robots, Modular UGVs, Modular robots, UGV applications, Unmanned ground vehicles, Unmanned systems

1. Introduction

In a broad sense, an unmanned ground vehicle is a mechanized machine or equipment which is capable of locomotion without the presence of a human operator. This is the most basic objective of an unmanned ground vehicle (UGV) [1]. While the earliest UGVs were designed for wartime actions, such as armed ops, carrying ammunition, and surveillance, the domain of application of UGVs has since expanded to the commercial civilian sphere.

With the onset of the global coronavirus disease starting in 2019 (COVID-19) pandemic, the market for unmanned ground vehicles has seen a remarkable expansion. Its applications have widened from military operations and have gone on to include contactless deliveries of medical kits, manufacturing payloads, domestic goods, and many more. Further to the changes in the geostrategic scenario of the world, nations across the world are seeking to stock up their inventories with technologically advanced equipment including unmanned ground, aerial, and naval vehicles.

In 2018, Gartner et al. described efficiency resulting from the synergy between modularity and autonomy in a fleet of unmanned ground and aerial vehicles during natural disaster relief operations [2]. The paper further describes a case study on integrated system design of the UGV- unmanned aerial vehicle (UAV) fleet, which incorporates modularity and autonomy in a disaster relief scenario. The proposed fleet configuration benefits from the teaming between UGVs and UAVs. While the UAVs assist with aerial reconnaissance, payload dropping, neutralizing of chemical, biological, radiological, and nuclear defense (CBRN), etc., UGVs provide ground support via mapping of contaminants, delivering payloads including first-aid kits, and rationed food to victims, as well as ground surveillance. This is just one of the many examples of the benefits of using autonomous, modular systems such as unmanned ground vehicles.

In the same year (2018), the International Federation of Robotics reported a rise of more than 10% in the UGV-specific research and publication [3]. This indicates that the growth in interest in the domain of UGVs is not merely among the defense or economic circles, but also among academics and researchers. In the preceding year (2017), Almayyahi et al. conducted experiment analyses on the navigation systems of UGVs in three different scenarios to solve the navigation challenges faced by UGVs in cluttered and dynamic environments [4]. The experimental results validated the consistency of performance shown by controllers based on a fuzzy inference system in maneuvering and route planning by the UGVs even in complex dynamic environments.

The focus on path planning for unmanned ground vehicles has been undertaken via two broad approaches: global planning methods and local planning methods [5]. The global path planning method requires the UGV to have prior knowledge about the environment. Moreover, it assumes the terrain in question to be static and unchanging. The local planning approach, on the other hand, assumes partial or no prior knowledge of the environment and holds a margin for dynamic and changing terrain [6]. The advantages of the local planning method are made clear by the resulting real-time sensory output provided by the UGV without having complete or any knowledge about the terrain.

The use of local path planning methods dates back to the 1980s. For instance, in 1986, an online collision avoidance approach was developed for a UGV or a robotic system that did not have any prior model of obstacles; the obstacles were sensed by the system during the motion execution stage [7]. However, the recent technologies used in the local path planning approach have been extended based on intelligent soft computing techniques such as fuzzy control, artificial neural networks, and hybrid intelligent techniques [8-11].

In one of the more recent experiments on path planning with the use of neural network tools, De Simone et al. conducted matrix laboratory (MATLAB) trials to design an artificial neural network with supervised learning for classification and pattern recognition from the inputs received by an ultrasonic sensor [12]. In the experiment, the UGV correctly navigated and reported the types of objects encountered and their positions inside the enclosure. Another major issue to be addressed in path planning, apart from collision avoidance, is that of lateral stability. The definition of lateral stability, as given by Sforza, P. M. (2015) for spacecraft, is the stability of a spacecraft in its motion in the x-y plane or y-z plane [13]. The same definition can be extrapolated for unmanned ground vehicles with respect to motion in the yaw and roll directions. These concerns over the lateral stability of UGVs were addressed in the experiments conducted by P. Hang et al. in 2020 [14]. An integrated path planning algorithm was applied to address both collision avoidance and lateral stability issues in the motion of unmanned ground vehicles. This proposed comprehensive collision avoidance algorithm was employed under four simulation conditions for the verification of the feasibility and accuracy of the algorithm. The results indicated that the integrated algorithm could deal with static and dynamic collision avoidance, as well as maintain lateral stability of the UGV during high-speed motion.

An important parameter to consider while designing any unmanned platform, apart from path planning, is that of onboard energy storage. The two most common power systems for unmanned ground vehicles are battery-based power systems and fuel cells. The basic difference in their working principles is that while batteries store energy, fuel cells generate energy by converting the available fuel. In 2018, González et al. proposed a hybrid power system for unmanned ground vehicles [15]. In their argument for hybrid power systems, clear advantages of the hybrid system were seen over purely battery-based unmanned ground vehicles in terms of energy efficiency and an increased performance, as well as the reduced probability of energy failure due to increased power redundancy. Several other factors of UGV design, such as chassis, electronics system, control architecture, drivetrain, power system, etc. are discussed in the subsequent sections.

2. Recent trends in design parameters of UGVs

An unmanned ground vehicle, as a whole system, involves the integration of electronic components with mechanical hardware, the optimization and integration of sensors, path planning, energy, and power system design, and ruggedization for reduced probability of damage when unsupervised. All these parameters need to be met with a substantial factor of safety to ensure a robust and reliable design of the UGV. This list of prerequisites brings up two major challenges in the design of unmanned ground vehicles: operational reliability and cost of development.

Many projects have been undertaken in the domain of the design of unmanned ground vehicles, each proposing novel, or modified solutions to strike a balance between cost and reliability. One such project was undertaken in 2019 by Oyekola et al. which describes the use of Open-Source electronics to reduce cost while maintaining the traceability of the components [16]. The authors used Arduino Uno platform to drive the Direct Current (DC) and servomotors of the unmanned ground vehicle. The Pulse Width Modulation (PWM) technique was used for rotational speed control of the DC motors. Figure 1 presents a schematic of the robot’s control as described by the authors.

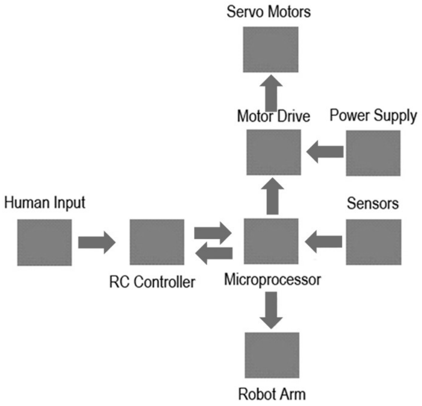

Figure 1 Schematic of Robot Controls [16].

Preceding this project, De Simone et al. (2018) designed an unmanned ground vehicle encoded on Arduino Mega 2560 board based on the ATmega 2560 processor [17]. The limitation of this design, however, was the heavyweight of the battery at 3 kg. The UGV was a three-wheeled robot with two motorized wheels driven by DC geared motors. Its chassis was made up of methyl methacrylate to reduce the overall chassis weight.

One of the latest projects in UGV design and development was undertaken by Zhang et al. (2022) on the integrated dynamic control of All-Wheel Independently Actuated UGV in diagonal steering. The main objective of this experimentation was to improve the overall mobility, maneuverability, and controllability of the UGV. The additional vehicle active moment generated by the active control was used to control the lateral and roll motion of the vehicle in collaboration resulting in a stable target diagonal steering performance [18].

The active dynamic control of the chassis of an unmanned ground vehicle is an innovative approach to improving the handling characteristics of the vehicle. However, it is not a novel endeavour. Substantial projects and experiments have been undertaken to deal with the problem of active handling of unmanned platforms. Ni et al. (2018) described the full X-By-Wire control architecture being deployed in various military UGVs [19]. The design of X-by-wire systems has significantly improved the configuration flexibility of unmanned platforms (ground, aerial) increasing the convenience of designing sensory, control systems and integrations. The overall mobility and maneuverability of the unmanned platforms are also improved by deploying X-by-wire.

An innovative approach in the domain of unmanned ground vehicle design is the integration of a terrain-adaptive mechanical module [20]. The terrain-adaptive module improves the UGV's ability to navigate rough terrain, climb or lift itself over large vertical obstacles, and realize omnidirectional locomotion.

While obstacle detection can be carried out via either local or global planning methods, obstacle crossing can broadly be categorized into four types based on the locomotion and drivetrain systems that have been used in UGVs across different domains of applications. The four broad types of UGVs based on obstacle crossing capabilities are the legged UGV platforms [21], the caterpillar tracked UGV platforms [22], the crawler type UGV platforms, and the wheeled UGVs [23,24]. Many obstacle-crossing UGVs have been described in the literature for the specific purpose of stair climbing [25]. The most common features or abilities of UGVs are mapping, trajectory detection and tracking, localization, detection of obstacles, obstacle crossing, and obstacle collision avoidance [26]. These capabilities of UGVs have become the basic features sought in any unmanned platform.

3. Evolution of control architecture of unmanned platforms

The control architecture of any robotic platform is an integral subsystem that influences the efficiency and overall performance of the whole system. The same holds true for unmanned ground vehicles, whose performance relies heavily on the robustness and reliability of their control architectures.

One of the earliest control architectures designed for an unmanned ground vehicle was the 4-D/RCS reference model architecture designed for the Demo III Experimental Unmanned Vehicle Programme in Figure 2 [27]. Park et al. (2010) described the failure of UGVs on three levels. Level 1 failure was wherein the UGV could still function normally, level 2 failure was the kind that restricted the speed of the UGV, and finally, level 3 failure was the kind in which the UGV lost its complete functionality [28].

Over the years, multiple control algorithms have been developed to either reduce or partially/completely negate the probability of system failure in unmanned ground vehicles. These control architectures can be classified broadly into centralized, decentralized, distributed, and hybrid control architectures [29]. The centralized control architecture makes optimization easy from the system perspective, however it has limitations in terms of system scalability. The decision-making of such a system can be made efficient by employing a dynamic data-driven adaptive multiscale (DDDAMS) based planning and control framework [30].

Earlier, most control architectures were based on technologies like Arduino and XBEE for control and wireless communication. Murtaza et al. (2014) designed a hybrid UGV based on XBEE wireless communication with an Arduino microcontroller in Figure 3 [32]. The components used in its control architecture, including global positioning system (GPS) module, XBEE module, Arduino microcontroller, ultrasonic sensors, etc., are open source and low-cost components. Several UGVs for domestic or small-to-mid-scale applications can be designed in a similar fashion, especially when the cost of development is a major constraint.

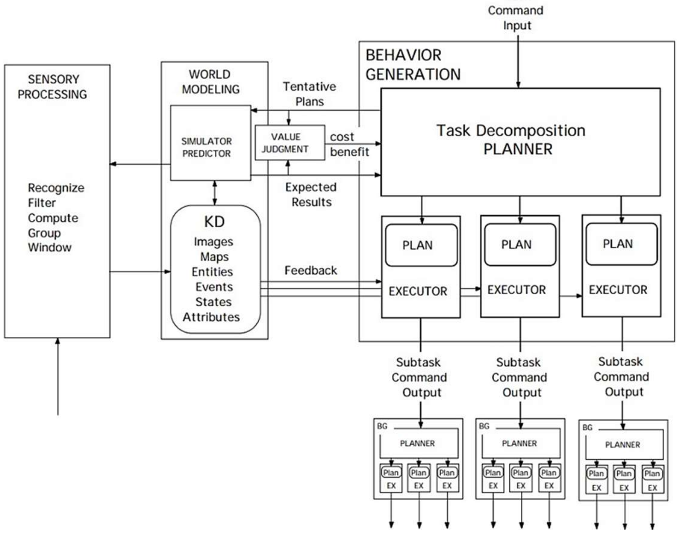

Figure 2 A typical 4D/RCS Node [27].

With the advancement of technology, more and more unmanned robotic platforms are now switching to high-end sensors and modules such as 2D/3D light detection and ranging (LIDAR), Jetson Nano, etc. Saleem et al. (2015) proposed a design of an unmanned ground vehicle based on LIDAR and an image sensor unit for outdoor navigation [33]. In another project, Kaijin et al. (2019) described the design of a LiDAR-based Simultaneous Localization and Mapping (SLAM) tool for unmanned vehicles. The proposed SLAM algorithm was designed for a complex off-road environment and combined probability and feature by Expectation-Maximization (EM); the datasets for off-road scenes were obtained by LiDAR [34].

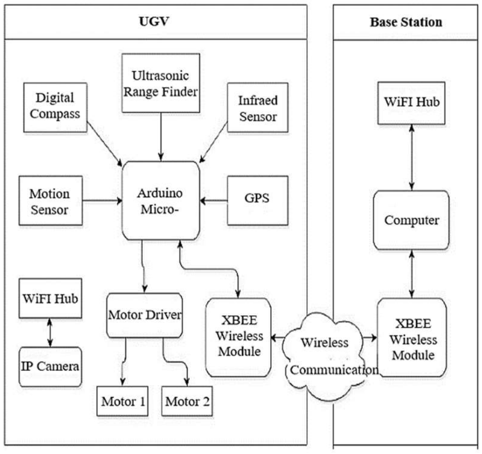

Figure 3 UGV System Architecture [32].

4. Application of UGVs

The following sections discuss the development of unmanned ground vehicles with respect to specific domains of application, such as agriculture, surveillance, and disaster relief.

4.1 Agricultural application of UGVs

With the ever-increasing population and pressing need for increased food production, agriculture as an industry is under tremendous pressure to increase its output while remaining sustainable in its production approach to preventing ecological damage in the process. Precision farming involves techniques that control the variations in the fields accurately to increase productivity, profitability, and sustainability [35].

Nguyen et al. (2020) proposed a LiDAR-based autonomous system for the measurement and selection of cultivars for high biomass yield for Australian dairy farmers. The experiment indicated that there was a strong correlation between the LiDAR-detected plant volume and biomass [36]. In another project, Quaglia et al. (2019) developed an unmanned ground vehicle “Agri.q02” with the objective of drone docking and the collection of samples with the help of a horizontal positioning system and a collaborative robotic arm. With a drone for monitoring irrigation deficits and a collaborative robotic arm for the collection of samples for crop monitoring, Agri.q02 is an example of how autonomous unmanned ground vehicles with enhanced capabilities are a solution for the precision farming needs of farms and crop management [37].

In a survey published by Bonadies et al. (2016), the increase in the use of unmanned ground vehicles for agricultural purposes was noted, citing advantages such as soil sampling, irrigation management, precision spraying, mechanical weeding, and crop harvesting [38]. Another survey published by Bonadies and Gadsden (2019) describes various navigation strategies for unmanned ground vehicles for agricultural purposes [39]. The most used methods of navigation for agricultural unmanned ground vehicles are the GPS and the geographic information system (GIS). These systems, however, rely on pre-planned routes and thus have little to no usability in new or changing terrains. An alternative to GPS navigation, as recorded in the survey, is using image sensor units like cameras, radars, and ultrasonic sensors for the detection of large obstacles or landscapes.

The motion control of unmanned ground vehicles can be done manually or by automated controls. Manual control can be obtained by synchronizing the unmanned vehicle to a wireless handheld controller and depending upon the functionality of the wireless communication set, the vehicle can be controlled either from close proximity or from a remote location. Additionally, cameras can be mounted on the vehicle to get live feed of the terrain and the surroundings of the vehicle [40]. Autonomous control can be obtained using automated control architecture with inputs of positioning and localization which can be obtained via various methods, such as dead reckoning, range sensing, reflectance sensing, and image processing [41]. Simple image processing techniques and lane detection algorithms can be employed in such farms to detect the edges of the rows of the crop. These lane detection strategies can be used for the navigation of unmanned ground vehicles.

4.2 UGVs for disaster relief operations

Relief operations during and after disasters are complicated situations exposing human lives to risk. This makes unmanned vehicles important in such relief operations for logistics, reconnaissance, payload deliveries, mapping, localization, and collaborative UAV/UGV surveillance.

Baumgärtner et al. (2017) proposed an emergency communication system between unmanned vehicles, human rescuers, and civilians using store-carry-forward technologies [42]. This proposed solution describes small islands of devices connected to each other, with limited bridges between them. These islands of small devices can then connect human rescuers with stranded civilians via clusters of unmanned vehicles. The use of unmanned vehicles for disaster relief has been an ongoing endeavor since the widespread commercialization of UGVs.

Another study by Okereafor et al. (2013) recommended the deployment of unmanned vehicles in high-risk security zones as a measure for increasing security and improving emergency response [43]. The study classifies the use of unmanned vehicles in disaster relief operations under four loose categories: (1) security agencies for bomb disposal, surveillance, and reconnaissance; (2) nuclear agencies for handling and management of radioactive materials; (3) border security; and (4) wildlife management for monitoring and prevention of poaching.

In the following year (2014), Venkatesh et al. described a solution to yet another challenge during relief operations, that of communication between unmanned ground vehicles and their base stations [44]. The paper proposed the use of stationary airborne systems for wireless control of unmanned ground vehicles in relief operations. This proposed airborne system is made up of hydrogen-filled latex balloons with a payload capacity to carry ATmega328P Microcontroller. In a more recent survey, Ding et al. (2021) have described the UGV-UAV coordination and its numerous advantages in relief operations in terms of the increased surveillance area, improved communication efficiency, and geospatial mapping in Figure 4 [45]. It describes the four main elements in UAV-UGV coordination systems, namely, UAVs, UGVs, expected tasks, and environments of operation.

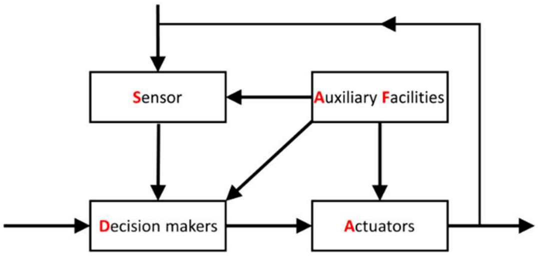

Figure 4 Functional Classification of Roles in UAV-UGV Systems [45].

4.3 UGVs for surveillance and reconnaissance

Surveillance and reconnaissance are the most widely undertaken applications of unmanned ground vehicles. One of the first tasks of surveillance and recon unmanned ground vehicles is target detection. Target detection and classification can be done in diverse ways, such as motion-based, colour-based, and shape-based methods.

Khaleghi et al. (2014) describe motion-based target detection using an optical flow algorithm [29]. The optical flow algorithm involves the detection of patterns of apparent motion between an object and a visual scene caused by the relative motion of the observer and the scene [32].

Maheswaran et al. (2020) have described remote-controlled spy robots for the purpose of surveillance over a bigger working reach [46]. Figure 5 shows the system architecture of the proposed remote-worked robots.

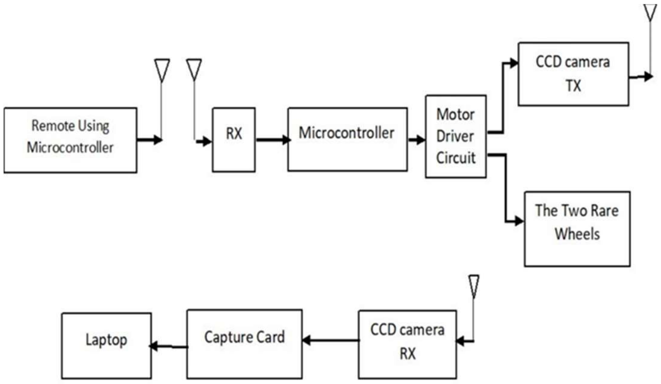

Figure 5 System Architecture of RC Spy Robots [46].

Xin et al. [47] reviewed and described the trends of technological advancement in military-specific unmanned ground vehicles. Unmanned ground vehicles designed for military purposes are not a new invention and can be traced back to the 1930s. Two of the earliest unmanned ground vehicles to be designed were the British radio-controlled tank called “Black Prince” and the German remote-controlled tracked vehicle called “Goliath”. These were World War 2 era remote-controlled unmanned vehicles. There was a large number of military unmanned vehicles in history, some of them being Squad Mission Support System (SMSS), Atlas Bipedal Humanoid Robot, Legged Squad Support System, and Guardium Unmanned Combat Vehicle [48].

5. Technological advancements

Technological advancements have been cutting across domains and fields, influencing every aspect of the marketplace with concepts such as Artificial Intelligence, Machine Learning, and Blockchain. The market for unmanned ground vehicles is not untouched by the advancements made in technologies. The operation of UGVs has gone from being teleoperated to computer-aided driving and autonomous control.

The automation of unmanned ground vehicles has further been classified into six levels: level 0 - no driving automation; level 1 - driver assistance; level 2 - partial driving automation; level 3 - conditional driving automation; level 4 - high driving automation; and finally, level 5 - full driving automation.

The technological advancements in the UGV-specific areas have revolved around perception and are based on sensors and mobility software with an objective of improved situational awareness of the unmanned robotic system. Important advancements have been made in the domain of navigation and path planning by the integration of the vehicle’s perception, situational awareness, and communication. An up-and-coming domain of interest for research and development in the field of unmanned ground vehicles is that of human-robot interactions. With developments in artificial neural networks and other artificial intelligence (AI) and machine learning (ML) algorithms, tactical behaviour and learning in unstructured environments have become more accessible. However, more experimentation and research are needed in this area.

Some of the technological challenges faced by unmanned ground vehicles currently revolve around terrain behaviour. Navigation, sensing, mapping, localization, etc. are still a challenge for unmanned ground vehicles in terrains that are either unknown or changing/dynamic. Figure 6 summarizes the overview of the UGV, which are generally adapted in all the systems.

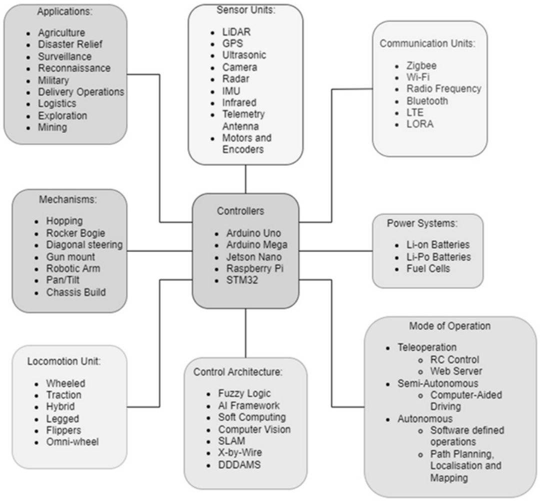

Figure 6 Overview of UGV Subsystems.

Table 1 and Figure 7 show the projected growth trend of the unmanned ground vehicle global market in the coming decade (2020-2030). The global market share of unmanned ground vehicles is projected to grow from USD 2.12 billion in 2019 to USD 6.04 billion in 2030 [49,50].

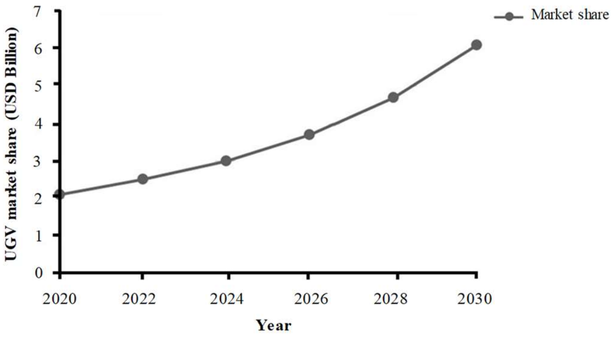

Figure 7 UGV expected market share in 2020-2030.

Table 1 Comparative analysis of market share of UGVs in future according to its applications.

Applications	Market share of UGVs till 2020 (%)	Market share of UGVs till 2020 (USD Billion)	Market share growth till 2030 (%)	Application segment
Military	66.64	1.785	+11.4	Combat Operations
Commercial	20.01	0.536	+8.5	Autonomous Robots, Mapping and Agriculture
Enforcement	13.35	0.357	+5.9	Rescue Robots, Bomb Disposal and Surveillance

6. Summary

The market for unmanned ground vehicles is bound to continue growing in the coming years. With advancements in technologies of sensors, electronics, and mechatronics, the designs of unmanned ground vehicles are further bound to become more sophisticated and accurate in terms of navigation, image processing, sensing real-time inputs, mapping, localization, and other functionalities. While significant success has been obtained in obstacle detection and obstacle crossing via various algorithms, the path planning and navigation of unmanned vehicles in complex unknown or dynamic terrains remains a challenge. The use of high-end sensors such as LiDAR and image sensory units have improved the situational awareness of unmanned robotic platforms. It has also, however, tipped the scale towards the high cost of development and a high risk of component failure.

The domain of application of unmanned ground vehicles has expanded from being just military equipment to being deployed in the case of natural disasters, as well as in commercial establishments for inventory management, payload transport, crop monitoring, and farm management.

With the growing uncertainty in the global geopolitical scenario, countries are bound to channel the flow of investments into growing their defense capabilities. This increased flow of cash from governments to their respective defense research and development arms, along with the increasing technological advancements in the market, is bound to only increase the market scope of unmanned ground vehicles in the coming years. The five major growth drivers for the unmanned ground vehicle market are: (1) reducing casualty and collateral damage; (2) investments from governments to dedicated UGV research and development (R&D) sectors; (3) automation under Industry 4.0; (4) instability in geopolitical strata; and (5) memorandum of understanding (MoUs) between governments and Defense Public Sector Undertakings (DPSUs).

One of the fundamental purposes and advantages of deploying UGVs is the drastic reduction in the number of casualties and collateral damage. UGVs provide troops with an ability to adopt an offensive strategy without crossing enemy lines. Moreover, with surveillance and logistics being automated, UGVs also reduce the overall risk of collateral damage during recce by avoiding ambush or guerilla attacks. Unmanned ground vehicles are more likely to be an auxiliary addendum rather than a complete replacement or substitute for manual patrolling. However, even as an addition to a troop, the UGV adds value in ways such as making remote places accessible for surveillance and carrying faulty equipment back to the ground station without requiring the troops to leave their post.

Governments are in a bid to increase their expenditure on automation and technological advancements, and unmanned ground vehicles are an enticing opportunity in the domain. From their obvious military applications to even commercial uses such as disaster relief, no-contact delivery, and inventory management: unmanned ground vehicles have a wide scope of use, and thus provide a very profitable venture for investments. Owing to this versatility in applications and the growing trend of automation, more and more governments are channeling a flow of liquid, capital, and material investments in the manufacturing and large-scale production of unmanned ground vehicles.

As is widely known and accepted, this phase of the industrial revolution is called Industry 4.0 - and it is all about automation. From artificial intelligence-powered self-driving cars to the use of neural networks for mapping and prediction models - automation is rising rapidly. Amidst this increasing trend of reducing manual labour, unmanned ground vehicles are a primary candidate for many industries: manufacturing, medical, retail, welfare, and military - UGVs have a strong need in many domains. This has channeled private defense sectors' interests in developing and producing unmanned ground vehicles for militaries of different countries. Moreover, many tech startups are looking into UGV technology for construction site inspection, disaster relief, agricultural optimization, etc.

The growing instability in the global geopolitical strata has given an accelerated push to the domain of defense advancements. Every country wants its armory stocked up with the latest advances in weapon technology. And this has, as a natural consequence, increased the inflow of resources in the production of UGV. While the government sectors are investing heavily in their own defense arms for the production of unmanned ground vehicles, there has been a trend of MoUs between governments and DPSUs. This amalgamation of resources accelerates production, fosters innovation, and creates channels for a faster time to market.

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