Abstract – Unmanned systems have experienced an era of unparalleled growth in the past decade, and current trends point to an even more vigorous growth in the future. Whilst the majority of visible developmental progress has been with unmanned aerial vehicles, progress on unmanned ground vehicles has not been as rapid, despite the rapid strides being made by various commercial companies in 2016. There are two major underlying causative factors: Firstly, the control systems for most unmanned/autonomous vehicles involve so much advanced hardware that they are expensive to the point of being impractical. Secondly, even the most elaborate systems have not had the level of reliability in obstacle recognition and reaction that is required for practical applications. The consequences are that while unmanned aerial vehicles now routinely perform complex missions, an equivalent level of performance from unmanned ground vehicles is missing. This paper provides an alternative approach featuring low-cost variable autonomous control and is partly based on the author’s participation in a DARPA demonstration of using autonomous ground vehicles for military applications. It is of direct relevance to Boeing as it seeks to expand its footprint in this rapidly growing adjacency.

Index Terms – Autonomous, unmanned, ground vehicles, DARPA Urban Challenge, UGV (Unmanned Ground Vehicle) VAGV (Variable Autonomy Ground Vehicle), ISR (Intelligence, Surveillance and Reconnaissance).

I. INTRODUCTION

Unmanned systems have experienced an era of unparalleled growth in the past decade, and all major trends point to an even more vigorous growth in the foreseeable future. Unmanned Aerial Vehicles (UAVs) such as the General Atomics Predator [1] and Boeing’s ScanEagle [2] are now in continuous service. The A160 Hummingbird [3] from Boeing is an example of an unmanned helicopter specifically engineered for greater endurance and altitude. Unmanned Ground Vehicles (UGVs) have also made considerable strides in the past decade since the three DARPA Grand Challenge competitions that were held in 2004, 2005 and 2007. The last of these was the DARPA Urban Challenge [4] and specifically focused on the ability of autonomous ground vehicles to interact with other unmanned and manned vehicles.

More recently, the U.S. National highway Traffic Safety Administration released a long-awaited policy in September 2016 to lay a regulatory foundation for widespread use of autonomous vehicles on public roads. Together, both technological and regulatory needs must be solved for practical widespread use for autonomous ground vehicles. While autonomy in ground vehicles is still not technologically capable of replacing human decision-making in all driving situations, public policy may restrict vehicles to using “highly automated” systems, as opposed to fully automated.

2016 has been a particularly productive year for the commercial implementation of autonomous ground vehicle technology. Various companies are now racing against each other to introduce autonomous transportation. Uber is embracing self-driving vehicles as an extension of its core business. Google’s self-driving vehicles continue to rack up miles on the road, although always under the vigilant eye of an on-board driver. Tesla has taken an additional leap of packaging autonomous features into some of its existing vehicles sold to consumers, which can be activated by using the “Autopilot” feature. Automotive supplier Delphi recently announced its plans of providing a fleet of self-driving cars to the city-state of Singapore. Almost all major automakers have jumped onto this bandwagon and are in the process of introducing autonomous features of various degrees of capability.

With all this excitement and activity, it is worth conducting a spot check on separating the hype from reality. In a New York Times report [N1] in mid-September 2016, a second fatality was reported to the driver of a Tesla, where the use of autonomous features was cited as the cause. This follows the first fatality back
in May 2016 when the driver of a Tesla Model S driving with autonomous features activated was killed when the vehicle was unable to detect a truck making a turn \[N2\]. Uber’s self-driving cars are reportedly already getting into minor accidents in the streets of Pittsburgh where they are being tested \[N3\]. According to Gizmodo.com \[N4\], “Uber is requiring anyone riding in one of its self-driving cars to sign a legal document that kept the company free of liabilities in case of their injury or death,” and that riders were basically “signing their lives away.”

While autonomous vehicle technology will eventually be safe and reliable, this is likely not the case in the near future. It remains to be seen how the rushed deployment of autonomous vehicles on public roads plays out, with all the risks associated with the technology and with lives at stake.

However, within the constraints imposed by the state of the art in autonomous technology, particularly in regards to reliability, there are military applications that are feasible today. This article provides a preview of such applications and their underlying technological basis, which trades complexity for reliability.

The DARPA Grand Challenges were a demonstration of the feasibility of using autonomous ground vehicles for military applications. While the primary objectives were achieved, some of the limitations of present-day technology were also highlighted. One of the more significant of these limitations is best illustrated in Figure 1, which shows the autonomous vehicle from the Massachusetts Institute of Technology (MIT). The MIT team was one of the better performers in the contest, having successfully completed the designated course in the finals of the competition.

![Figure 1. A DARPA Urban Challenge vehicle, with an overhead electric generator to power various control systems.](image)

As can be seen in Figure 1, the power requirements of the vehicle’s sensor and processing hardware was so extensive that it required an independent gasoline-powered generator strapped onto the roof for providing the needed electrical power. With the interior of the vehicle also entirely filled with relevant electronics, the payload capacity of this vehicle is considerably limited. Moreover, as one can infer, the expensive control hardware on board the vehicle far exceeds the cost of the vehicle itself. This limitation is not confined to the MIT vehicle – some of the teams participating in the Urban Challenge had spent in excess of $10 million in developing their vehicles.

While this concept of “performance-at-any-price” may work in winning contests, the practical world demands much lower price points in order to enable adoption. One of the purposes of the DARPA Grand Challenge contests was to develop an autonomous supply vehicle for use in war zones. It was primarily motivated by the need to minimize coalition casualties caused by roadside bombs, which are one of the the leading causes of coalition fatalities in war zones. In this era of tight defense budgets, it would be difficult to market million-dollar autonomous vehicles as potential replacements to manned supply vehicles, even if all the capabilities are available.

The second major limitation highlighted at the DARPA Grand Challenges is in the realm of vehicle capability. It was seen repeatedly throughout the 2007 Urban Challenge that despite all the expensive hardware and elaborate software, vehicles were immobilized as a result of their inability to process a scenario that any human driver would have considered trivial. One such example was when a gate that was supposed to have been kept open unexpectedly closed, blocking a lane of the roadway. The MIT vehicle came to a complete stop when it encountered the gate blocking its lane, but would no change lanes and pass around the gate. It was only upon human intervention in the form of a crew that arrived at the scene and opened the gate that the MIT vehicle was able to continue on its mission.

A second example was at a four-road intersection where a stalled vehicle caused a backup of autonomous vehicles stuck in a seemingly permanent immobilized state. This situation was resolved only when the stalled vehicle finally moved out of the way.

In both the above cases, a human driver would have easily and quickly found a way around the obstacles. The fact that multi-million dollar vehicles were unable to solve these simple problems can explain the current situation with autonomous ground vehicles, where practical utilization has considerably lagged behind those of UAVs.

II. A LOW-COST ALTERNATIVE APPROACH

As seen in the previous section, the primary limitations to widespread use of unmanned ground vehicles are the high costs and limited capability. The first of these is considered in this section while the second limitation is deferred to the next section.

While most of the participants at the DARPA Urban Challenge 2007 comprised of vehicles with very expensive control hardware and software \([5], [6], [7]\), there were some exceptions. Most notably, a team from Kokomo, Indiana \([8]\), of which the author was a core member of, developed an autonomous vehicle for under $20,000. The key enabler was the utilization of a simplified vision and GPS sensor system that made use of commercially available off-the-shelf lowcost
hardware. Figure 2 is a photograph of the autonomous vehicle developed by this team which was a semi-finalist in the DARPA Urban Challenge 2007, and as can be seen below, many of the vision sensors were $50 webcams intended for use with personal computers.

Figure 2. A DARPA Urban Challenge vehicle, utilizing a low-cost vision system comprising mainly of personal computer webcams.

Figure 3 shows a closer view of the sensors of the two main systems. On the left is a personal computer webcam mounted on the external frame of the vehicle and being used as a side vision sensor. On the right is a commercial GPS unit, normally used on agricultural harvesting machines, which has been salvaged and used as the only GPS sensor on board the autonomous vehicle.

Figure 3. A personal computer webcam (left) used as a side vision sensor and an agricultural-grade GPS unit (right).

Details of the vision system are provided in Ref. [8] but the salient features are repeated here to illustrate its functioning. Figure 4 shows the various cameras located around the vehicle to provide near-total coverage with only very small blind spots.

Figure 4. Configuration of cameras on the vehicle to provide coverage in all directions.

All the cameras shown in Figure 4 are capable of operating at 640x480 or 320x240 pixel resolution, except for the center forward-facing camera which is capable of higher resolutions. Each camera has a field of view of 50 degrees. The reason for operating at low resolutions such as 640x480 is to minimize the data streaming into the data processing algorithms. It has also been discovered that this resolution is sufficient for most practical obstacle detection needs.

The emphasis in the data processing algorithms is on determining the mathematical characteristics of the detected obstacle, rather than its physical attributes. These characteristics comprise of the extent of the obstacle, its position relative to the vehicle and its velocity vector. No attempt is made to further classify the obstacle into a traffic cone, edge of the roadway, another vehicle, etc. This greatly minimizes the computational load.

The process of converting camera imagery into a three-dimensional time-dependent spatial awareness of obstacles consists of two steps. Details of this process are provided in Ref. [8] and only an outline of the techniques is provided here.

In the first step, the governing algorithms of the vision system process the image field in two-dimensions, for each of the cameras being used as input. A vector field is created using detailed pixel color information as mapped in RedGreen-Blue (RGB) space. This field can be denoted by \( F_a \), where \( F_a \) is given by:

\[
F_a = F_a(u, v, t) \quad (1)
\]

In the above equation, \( u \) and \( v \) are the coordinates in the plane of the image, such as that in Figure 5, and ‘\( t \)’ denotes the time when the image was acquired. In the total absence of any obstacles or objects in the field of view, the field \( F_a \) assumes a constant vector value everywhere. However, the presence of objects alters this field. Once \( F_a \) is determined, potential obstacles are identified by the spatial gradients produced. High gradients correspond to potential obstacles when certain other conditions are satisfied. Among the conditions checked is, for example, whether the gradients are...
caused by object shadows, in which case the spatial gradient field is processed to remove shadow-generated gradients.

After this additional processing, the locations that still contain high gradients are marked in u-v space by ‘dots’, which are essentially dimensionless entities. An example of these dots superposed on a camera image for a very simple case is shown in Figure 5. This image has been obtained during testing of the 1:3 scale prototype.

Figure 5. The results of the first stage of image processing shown superposed on the original image.

In order to minimize computation, only the obstacles closest to the vehicle are marked, such as the path boundaries in Figure 5. This is sufficient for the purposes of vehicle control. Neither the pole nor the edge of the building in Figure 5 is marked as an obstacle.

The second step of the image processing stage is to convert the two-dimensional field $F_a$ into a field $F_b$, where $F_b$ corresponds to the spatial field in front of the camera. This can be denoted by:

$$F_b = F_b (x, y, z, t)$$

(2)

The transformation relating the u-v space with the x-y-z space is given by the matrix $M$, and can be denoted by the matrix equation:

$$X = M * U$$

(3)

where $X = [x, y, z]$ and $U = [u, v]$

$X$ and $U$ are the vector notations for points in the x-y-z and the u-v coordinate systems respectively. Note that this transformation does not need to be made for the entire field $F_a$, but for only those regions of the field that have ‘dots’ marked on them. Recall that these ‘dots’ were generated earlier by the spatial derivative based algorithms. Also, the projection is made on the z=0 plane (or ground plane), which simplifies the transformation.

Matrix $M$ is derived from 3-D trigonometric equations using data on camera optics and the location of the camera relative to the vehicle as input. Time dependency is not explicitly shown in equation (3) as this equation is applicable at any given instant of time during autonomous travel.

The field and transformation equations (1), (2) and (3) can best be understood by the transformation of ‘dots’ from the u-v plane of Figure 5 to the x-y-z space of Figure 6. In this figure, the Z axis is perpendicular to the plane of the paper.

Figure 6. Spatial depth perception generated from the camera image of Figure 5 using obstacle detection algorithms.

The roadway is thus projected to a distance of about 50 feet in front of the vehicle for the 1:3 scale prototype. For the full-size vehicle, this would correspond to a distance of 150 feet.

It is interesting to note that by the use of the algorithms described above, depth perception is obtained using a single camera, as opposed to the need for utilizing computationally intensive binocular vision. Moreover, data such as that in Figure 6 is generated for each of the cameras on the vehicle, thereby providing a valuable map of the obstacles in the vicinity of the vehicle. This information is constantly updated between 10 and 30 times per second, which provides the time-dependent portion of equation (2). On the basis of these data, together with secondary sensors such as short range radar, a desired trajectory is computed, along with desired velocities. This is translated by separate algorithms into steering, brake and throttle commands. More details on these algorithms will be provided later in this section.

In a manner identical to the image processing that generated Figure 6 from Figure 5, an example of image processing for the full-size vehicle is shown below. Figure 7 is a typical camera image taken at any given instant during the course of autonomous operation. Processing of the data contained in this image produces Figure 8.
The system is capable of reliably detecting obstacles as small as a tennis ball at close range. It has been tested with a variety of practical obstacles. With additional processing utilizing the time dependency of equations (1) and (2), it is even possible to approximately compute the velocities of other moving vehicles. This capability is used at intersections, such as a four-way stop, to determine priority of passage through the intersection.

However, this system can, on some occasions, produce false positive results, i.e., the system detects an object that it classifies as an obstacle whereas in reality it is not of any concern. In such cases, the secondary sensor systems on board, such as the short-range automotive-grade radar system, can rapidly clarify the nature of the presumed obstacle. It should be noted that the opposite case (not detecting objects of concern) has not occurred so far in the extensive testing that has been conducted.

It should also be noted that the vision system described here, while providing a practical and effective input to the vehicle control system, is not designed to work in all lighting conditions. Performance can be degraded under very low or very bright ambient light. Under such conditions, the control system shifts to using alternate sensor input, such as GPS and short-range radar.

In addition to the unique vision system, various other innovations have been incorporated to enable reliable operation at minimal cost. One of the most important of these innovations is the creation of a virtual Inertial Measurement Unit (IMU) to replace the actual expensive hardware constituting the IMU. This has been achieved by using input from various on-board sensors and utilizing algorithms to generate the information that would have otherwise been obtained from a physical IMU.

Additional low-cost innovations include the use of simple linear actuators connected to the transmission shifter, accelerator and brake pedals of the vehicle. The brake and accelerator pedals are controlled by special algorithms employing closed-form equations to provide real-time dynamic control of the vehicle based on just the actual and desired velocities as input. These computationally lean algorithms also minimize the processing power required for any actuator-related tasks. The actuators themselves are physically positioned in a configuration that does not interfere with manual operation of the controls. This provides the benefit of rapid transitions from autonomous to manual modes and vice-versa. Moreover, it provides the added advantage of utilizing a safety driver during autonomous operation, with the ability to take control of the vehicle instantly, should the need arise.

An autonomous mission typically needs to be specified in terms of a series of GPS waypoints. These data are superposed on an internal map of the region to be traversed and an optimal route is computed utilizing a modified version of the Dijkstra’s Algorithm [9]. All potential routes are considered between the current location and the destination and then weighted penalty-functions are used to calculate the quickest route. Distinct penalty-functions are assigned for crossing four-way stop intersections, merging into through-traffic, speed limits, etc. By considering all these routes, the physically shortest route is not necessarily the quickest. The algorithm is robust enough to consider a blocked segment encountered on the way to a destination. The time to compute a new optimal route is very small (of the order of a few seconds).

Despite the full autonomous capability of the vehicle, the computing power required to handle all aspects of vehicle control is low enough to be managed by a single desktop computer powered by the vehicle’s 12 volt system. The reliance on mostly passive sensors has direct military advantages. The compact size of the sensors enables a much less vulnerable profile for military applications, as seen by contrasting the vehicles in Figures 1 and 2. More significantly, with hardware costs of only $20,000, this vehicle is only a very small fraction of the corresponding costs of most of the other vehicles participating in the DARPA Urban Challenge 2007.

As with any low-cost system, certain trade-offs have been made. Many of the vehicles at the Urban Challenge were
equipped with LIDAR (Light Detection and Ranging) systems that provide a superior obstacle detection capability as compared to the passive vision system described here. Other vehicles were packed with radar units that provide near-total coverage around the vehicle. While this certainly results in better autonomous vehicle performance, the associated costs have to be kept in mind. Additionally, from a military perspective, the use of passive sensors that have no electronic emissions has advantages. More importantly, a more reliable control system that is described in the next section negates some of the overall advantages of these expensive sensor systems once costs are factored in.

It should be noted that the vehicle used by the author’s team has logged over 1000 miles of testing which not only includes all the courses at the DARPA Urban Challenge, but also hundreds of miles of driving in regular traffic in an autonomous mode (with the presence of a safety driver to intervene in case it is needed). This includes various lighting conditions along with night-time testing, with the added hurdles of no street lighting and no headlights. This extensive validation confirms the robustness of the autonomous system as a whole.

However, it should be noted that despite all the unique innovations, this vehicle is still subject to the same limitations as other autonomous vehicles. In particular, the vehicle is expected to behave no differently from other vehicles at the DARPA Urban Challenge when confronted with unprecedented situations, such as the two examples cited earlier, where autonomous vehicles went into an immobilized state, unable to resolve seemingly trivial traffic situations.

The solution to the problem mentioned above is considered in the next section.

III. VARIABLE AUTONOMY GROUND VEHICLES

The previous section dealt with the solution to one of the two main factors preventing widespread usage of autonomous ground vehicles, namely the issue of bringing down the cost associated with such vehicles low enough to render them practical.

In this section, the second of the two factors is addressed, i.e., the lack of reliability amongst autonomous vehicles. It is not sufficient from the practical perspective that autonomous vehicles are able to handle 99% of the scenarios and fail whenever the remaining 1% is encountered. As seen in the 2007 DARPA Urban Challenge and cited earlier, million-dollar autonomous vehicles were reduced to a state of immobility when encountering common traffic scenarios that would have been easily overcome by a human driver.

More recently, commercial applications have included autonomy in vehicles, and the technology is rapidly entering the public driving space. The National Highway Traffic Safety Administration has begun including autonomy technology in its regulations, safety rating procedures and future planning in its new policy. The primary focus of the policy, according to the NHTSA, is on “highly automated vehicles, or those in which the vehicle can take full control of the driving task in at least some circumstances.” [10]

The most practical means of overcoming this shortcoming is to couple autonomous ground vehicles with a remote human operator who is able to remotely intervene whenever the vehicle encounters a situation that it is not able to overcome. For optimal performance, the level of involvement of the human operator is variable and entirely situation-dependent. Moreover, the transition of control between the autonomous vehicle control system and the human operator, and vice-versa, should ideally be seamless. This type of hybrid vehicle control utilizes the best of both realms and leads to a new class of vehicle – the Variable-Autonomy Ground Vehicle (VAGV).

While it may superficially appear that the VAGV concept is a step backwards in the development of autonomous vehicles, this concept is not entirely new, as can be seen from the Predator [1] UAV control system. Although it has a limited level of autonomous operation, the remote human operator makes all the important decisions, particularly in regard to discharge of weapons. A similar control model is being extended here for autonomous ground vehicles, where remote operation through a high-bandwidth radio channel permits the human operator to manually take over control on a temporary basis until the obstacle or situation encountered is overcome.

The VAGV being considered here is ideally an all-terrain all-wheel drive vehicle, similar in configuration to a light or medium SUV, powered either directly by a conventional gasoline engine or by means of an electric hybrid propulsion system. However, the application of the VAGV control concept is not constrained by the physical size or capabilities of the vehicle.

To visualize how a VAGV would overcome the problems encountered by autonomous vehicles at the DARPA Urban Challenge, consider the first traffic scenario where a gate unexpectedly swung open and blocked a lane of traffic. This caused a million-dollar autonomous vehicle to come to a complete stop and remain self-immobilized until a crew could manually close the gate. If the vehicle was a VAGV, it would still come to a complete stop when encountering the gate, which is the right course of action. Immediately after the autonomous control systems on the VAGV conclude that it is a scenario for which an autonomous response is not available, the remote human operator is automatically alerted to the situation by the VAGV. Utilizing the images transmitted by the vision system on board the VAGV, the operator analyses the situation and realizes that the gate is only blocking the current lane and that the adjacent lane can be used to circumvent the obstacle. Using a joystick that uses the communications channel open between the operator and the VAGV, the operator, using live visual feedback from the VAGV, performs the simple maneuver of backing the VAGV, changing the lane and proceeding past the obstacle. At this point, the operator transfers full autonomous control
back to the VAGV, which is able to proceed as before in full autonomous mode.

The remote operator can be physically located at any convenient location which permits communication and control of the VAGV over a secure radio channel. This can be anywhere from the immediate proximity of the vehicle to the other side of the world, as is the case with the Predator UAV. Because the VAGV is able to maintain autonomous control most of the time, it is possible for one operator to handle multiple VAGVs in the field. The primary function of the operator is to intervene when requested by the VAGV navigations control system and to take manual control, if needed, of the VAGV’s surveillance, fire control or other additional systems, when it is so equipped.

The main mode of communication from the VAGV to the operator is in the form of a live video feed from various onboard cameras. These can also include infrared imaging cameras for night-time use. This feed need not be continuous and can be activated only when needed to conserve bandwidth. This can also include a corresponding live audio feed to enhance situational awareness for the operator. Additional information transferred includes various operational parameters such as the vehicle speed, heading, location (in the form of GPS coordinates), vehicle status information (such as engine temperature, fuel reserves, battery condition, etc.). Depending on the nature of the mission, the corresponding hardware (such as ISR equipment, fire control system, etc) would provide additional feedback to the operator, either continuously or on-demand.

All these data will be visually presented to the remote operator in the form of one or more display screens. Utilizing this flow of information, the operator is able to take control over one or more of the systems on board the VAGV as and when needed. For example, during an ISR mission, the operator can selectively control the video imaging cameras associated with ISR while the vehicle simultaneously navigates in a full autonomous mode.

Operator control over the physical movement of the vehicle can be in the form of a simple joystick control or more advanced vehicle-type controls with a corresponding steering wheel, brake and throttle pedals. Utilizing these controls and the live video feedback from the vehicle’s navigational cameras, the remote operator is able to manually guide the vehicle whenever it is required.

While not essential for most missions, a Virtual-Reality helmet utilized by the remote operator, in which all the visual information streaming from the VAGV is appropriately projected inside the helmet, would provide a level of situational awareness that is second to only being present in the vehicle. Such a helmet-mounted visual display would track the movement of the operator and project video imagery relevant only to the particular direction that the operator’s head is pointed at. Various other data being received from the vehicle can be either numerically or graphically superposed on the virtual reality displays within the operator’s helmet visor. Physical controls, such as the steering wheel, accelerator and brake pedals, switches, etc., can be identical in layout to those in an actual manned vehicle. The use of a Virtual-Reality helmet is particularly suitable for controlling multiple VAGVs in the field.

IV. PRACTICAL APPLICATIONS OF THE VAGV

The capabilities described in the two previous sections lead to many interesting applications, some of which are described in this section.

The VAGV can be readily configured to serve as a low-cost unmanned supply vehicle in war zones. This is of particular relevance today, with the mounting casualties due to roadside bombs. The desired and alternative supply routes connecting the base station with the forward outpost needing supplies can either be obtained from high-resolution satellite imagery, or by actually traversing the route and recording detailed waypoints. Alternative routes can be digitized in a similar manner. A virtual road network is created in the control system memory which can then be followed, as described in an earlier section, utilizing the most optimal route determined by the modified Dijkstra’s algorithm. Any blockages in the primary route can easily be handled by re-routing. With infrared imaging and high-resolution GPS, missions can even be conducted in extreme darkness without the need for headlights. This is a major advantage from the perspective of avoiding detection. Moreover, if equipped with a hybrid powertrain, the VAGV can run silently on electric power alone in regions where audio emissions need to be curtailed.

An interesting variant of an unmanned supply vehicle is a casualty extraction vehicle for use in high risk situations that may preclude extraction by helicopter. The decision to use a VAGV in this scenario would have to be made on a case-by-case basis after weighing all the risks and benefits of a given situation.

A VAGV can either operate alone or in tandem with other VAGVs forming a convoy or acting in an independent manner. The ability to communicate automatically between VAGVs will considerably enhance their effectiveness. For example, if one of the VAGVs discovers that a particular segment of a road is blocked, it can immediately and automatically alert all other VAGVs in the area to update their internal maps accordingly, thereby optimizing the routes to their destinations. Concept of this system is detailed in a U.S. patent issued to Boeing in 2015, Unmanned multi-purpose ground vehicle with different levels of control. [11]

Communications between VAGVs at short ranges can be made with encrypted laser, radio, or even Wi-Fi. A communication protocol for such short range communications would need to be used. Information exchanged would include map data, obstacle updates, etc., using SMS-style text messages to minimize data transfer. Large data transfers, such as imagery and videos, are not intended for transfer from vehicle-to-vehicle using these methods.

To form a convoy, the remote operator(s) sequentially changes the control mode of each VAGV to a ‘follower’ mode, where an operator-designated vehicle in front is tracked by vision or radar and the VAGV maintains a certain...
distance (depending on vehicle speed) behind this lead vehicle. This lead vehicle can be manually driven or be a VAGV itself. Any number of VAGVs can be added to a convoy in this manner.

As mentioned in an earlier section, due to the high level of autonomy in a VAGV, a single remote operator will be able to control multiple VAGVs. Moreover, if any of these VAGVs requires additional assistance, the operator is available to take temporary control and guide the vehicle. The number of vehicles that a single operator can realistically control would depend on the nature of the mission and the terrain on which it operates. While it is theoretical possible for a single operator to control a dozen or more vehicles, the practical limit may be significantly lower.

The VAGV also serves as a versatile tool in the realm of Intelligence, Surveillance and Reconnaissance (ISR). With its long range and endurance, relatively low noise emissions, utilizing mostly passive sensing and able to operate in near-total darkness, the VAGV will find many uses on the modern battlefield. In this role, the VAGV shares many features in common with the autonomous supply vehicle role described earlier. Additionally, armed with high-resolution visible and infrared telephoto cameras capable of transmitting live video and capable of being controlled by the remote operator, the VAGV can be used to stake live-value targets for extended durations. ISR integration in a VAGV shares many aspects in common with proven ISR technology currently used in UAVs, which considerably reduces the complexity of the integration process.

To extend operating range, the VAGV can be delivered as well as recovered by helicopter. With its ability to traverse long distances, the VAGV provides the flexibility of utilizing multiple potential drop and recovery points.

Currently some Boeing rotorcraft have demonstrated the capability of being equipped with Unmanned Aerial Systems LOI (Level of Interoperability) 3 and 4, which enables command and control of certain autonomous aerial vehicles. While currently in the experimental stage, this capability, when implemented, will enable an Apache pilot to view the live video feed from an unmanned aerial vehicle that is performing ISR over a target area, and, if needed, command the UAV to provide imagery of a specific target. A similar level of command and control can be extended to the VAGV. This would be of particular importance in specific situations, such as when the enemy’s aerial defenses are sophisticated enough to prevent the deployment of UAVs. Additionally, it is possible for UAVs and VAGVs to work in tandem, with each providing a piece of the ISR picture that complements the other. Current unmanned vehicle control standards such as STANAG 4586 and JAUS (Joint Architecture for Unmanned Systems) can be extended to include VAGVs.

An interesting application of ISR capability in the nonmilitary arena is the case of border security. A fleet of VAGVs can be assigned to traverse remote border areas on patrol. An operator can gain a much higher level of situational awareness than what would have been possible with only stationery remote surveillance. A single operator would be able to cover a very large area, thereby freeing up more border security personnel to focus on incident response.

A more advanced application of the VAGV is in the form of an armed vehicle that is able to perform assault missions. In this role, the VAGV can be viewed as the land equivalent of the Predator UAV, where the remote operator uses the ISR data collected to make targeting decisions and then actually carry out the attack.

It should be noted that little mention has been made here of utilizing VAGVs in civilian applications such as sharing city streets with regular traffic. Despite the considerably enhanced reliability of VAGVs as compared to even the best purely autonomous vehicles, the safety issue is paramount. A remote operator will not have the same situational awareness as a driver of a manned vehicle using highly autonomous systems. This makes the risks associated with utilizing VAGVs in such environments significantly higher than the potential benefits. Trade-off decisions weighing these risks and benefits will always need to be made prior to any VAGV usage.

V. CONCLUSION

As described in this paper, utilizing the combination of a proven low-cost approach coupled with a variable level of autonomous control appears to be the most practical means of delivering reliable unmanned ground vehicles capable of filling a variety of roles. Among the possible applications are autonomous supply vehicles in war zones, as casualty extraction vehicles in certain circumstances, as ISR platforms with long range and endurance capability, as border patrol surveillance tools and even as assault vehicles capable of carrying a variety of armaments. Moreover, with the additional functionality of interoperability with other unmanned and manned air and ground systems, a significant enhancement in overall capability is achieved.

From Boeing’s perspective, with its proven expertise in unmanned aerial systems, a rapid expansion into the adjacent area of unmanned/autonomous ground vehicles, particularly for the applications described in this paper, is well within its technological reach and resources.

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