DEVELOPMENT OF AN UNMANNED TRUCK PLATOON FOR LOGISTICS RESUPPLY

GAN Hao Yi, GUO Yongqiang, LIM Jun Min Leonard

ABSTRACT

This article describes an Unmanned Truck Platoon, comprising a man-driven Lead Vehicle and three Unmanned Followers (UF), and covers the objectives, design, challenges and lessons learnt through development of the system. The trucks were modified from SAF five-ton trucks using add-on actuator kits to enable drive-by-wire[1] operation. The UFs were also equipped with capabilities such as autonomous vehicle-following, obstacle avoidance and vehicle-to-vehicle[2] communication which enable the truck platoon to execute logistics resupply missions.

In addition to details on the Unmanned Truck Platoon's design and architecture, this article also captures the journey undertaken by the team in designing and developing a user-friendly and operationally robust system. The article also shares insights gleaned from the development process, and introduces concepts and technology enablers that the team is exploring in both the military and commercial domains, such as truck platoons for inter-terminal container haulage as part of PSA operations.

Keywords: truck platooning, autonomous vehicle, lean manpower, vehicle-following, unmanned logistics resupply

INTRODUCTION

Logistics resupply missions in hostile environments encounter risks and challenges. Vehicle convoys face threats from improvised explosive devices as well as other forms of attack. Operations over long distances in challenging off-road and urban terrain could also lead to accidents as a result of driver fatigue. With declining manpower resources, there is an increasing need for the Singapore Armed Forces (SAF) to reduce its logistics personnel while maintaining the ability to achieve complex and critical logistics operations.

In tandem, advances in computing, communications and sensor technologies over the past decade have also brought unmanned ground vehicles another step closer to reality. These autonomous systems will play an increasingly crucial role in the future battlefield not only to enable lean manning, but also to offer a force protection advantage by minimising personnel exposed to dangerous missions. One key concept under development is that of an Unmanned Truck Platoon which comprises a man-driven Lead Vehicle (LV) and three Unmanned Followers (UF). By integrating drive-by-wire (DBW), vehicle-following, obstacle avoidance and vehicle-to-vehicle (V2V) capabilities to existing SAF five-ton trucks, a single driver would be able to operate four trucks for logistics resupply missions. The project also serves as a stepping stone for the development of other more advanced, fully autonomous unmanned ground vehicles for the SAF.

This article is organised into seven sections. Following the introduction, Section Two summarises the design of the Unmanned Truck Platoon; Section Three describes operations of the platooning system; Section Four and Five highlight the project outcomes and lessons learnt; and Sections Six and Seven provide an overview of future technologies and further opportunities.

SYSTEM DESIGN AND DEVELOPMENT

The Unmanned Truck Platoon prototype was developed as part of an R&D project with two key objectives – manpower savings of 75% for logistics resupply missions, and robust operation even in challenging terrain. This is in contrast with commercial truck platooning projects elsewhere, where fuel efficiency[3] is the main impetus, and truck platoons are designed to function on highways and operate with drivers still 'in-the-loop' within the follower trucks. As such, in this project, the team designed the system with several factors in mind: (1) driverless follower trucks to reap manpower savings; (2) safety features and system redundancies for reduced risks; and (3) a hybrid Global Positioning System (GPS)-perception vehicle-following technique for end-to-end operations in difficult off-road terrain (e.g. under foliage with poor GPS signals).

Vehicle Platform

The Unmanned Truck Platoon is based on four of the SAF's automatic-transmission MAN 16.284 LAERC trucks, also commonly known as the five-ton truck. As the vehicles do not possess DBW capabilities, the follower trucks had to be retrofitted with add-on kits consisting of actuators to control steering, gear changes, acceleration and braking. Characterisation of the DBW-enabled UFs (e.g. different weights, braking distances, turning radiuses) proved challenging, and the team conducted many virtual simulations and physical trials to validate the vehicle-control software and algorithms. Figure 1 illustrates the placement and installation of the add-on kit within the UF cabin.

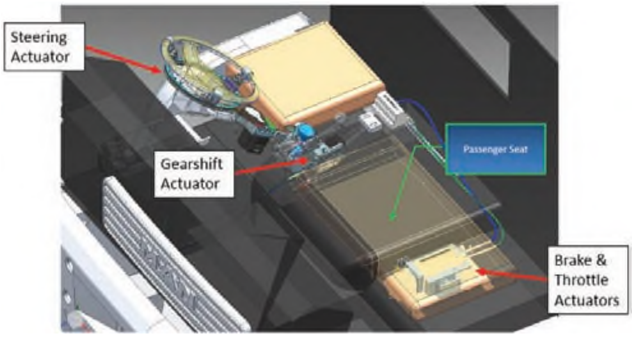

Figure 1. Placement of add-on kit in the UF
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Other Hardware Subsystems

Aside from the add-on kit, the other main hardware components that were integrated into the LV and UFs are shown in Figure 2 and Figure 3, respectively. These include cost-effective commercial-off-the-shelf (COTS) sensors such as automotive-grade radars and cameras, risk-mitigating safety equipment, and various communication and localisation subsystems. Details on the main hardware are provided in the subsequent paragraphs.

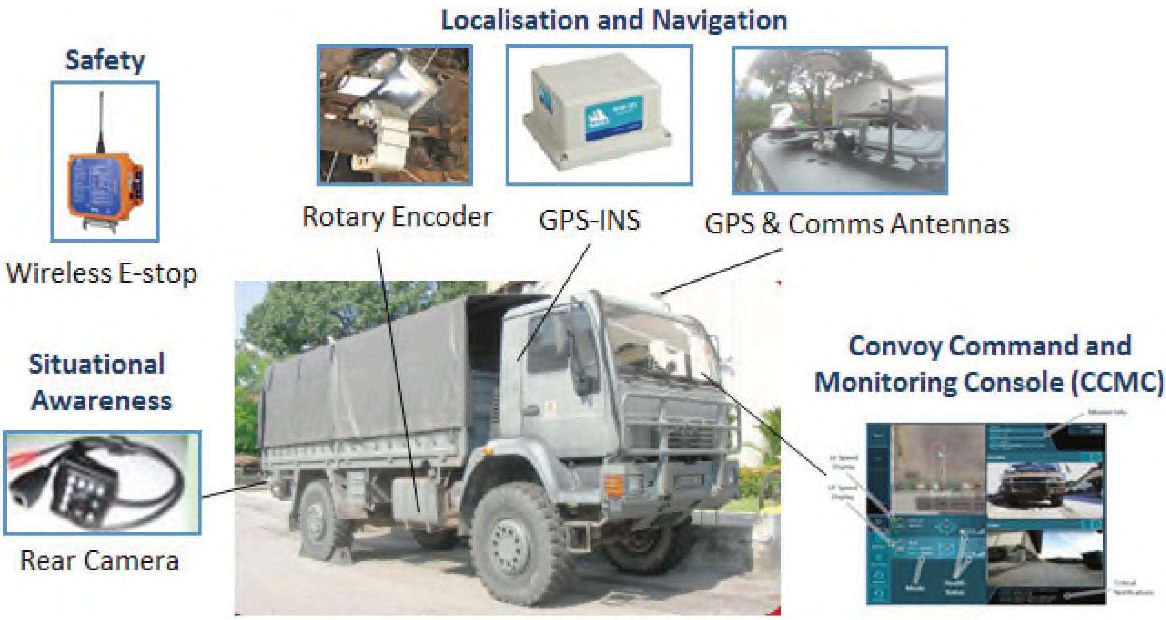

Figure 2. Main hardware subsystems installed on the Lead Vehicle
(Reprinted with permission from ST Engineering)

Figure 3. Main hardware subsystems installed in the Unmanned Follower
(Reprinted with permission from ST Engineering)

a) LV Convoy Command and Monitoring Console (CCMC) – The vehicle commander in the LV is able to monitor and control the UFs via an on-board touchscreen console known as the CCMC. The console has a 15-inch sunlight-readable display, an Intel processor and a 64 GB solid-state drive. Video feeds from the UFs can be selected for display on the CCMC to provide added situational awareness, in addition to a bird's eye view of the truck platoon.

b) UF Sensor Suite – The team integrated a COTS sensor suite (consisting of a camera and five radars) with locally developed software algorithms to enable the UF to perform vehicle-following and obstacle avoidance. The automotive-grade COTS sensors were selected based on cost and performance considerations, and were taken from production lines with stringent quality control measures in place.

c) Localisation System – The GPS-INS[4] provides the LV and UFs with information on position, orientation and velocity. For the LV, the localisation information is used to provide situational awareness regarding its position with respect to the UFs via the CCMC. For the UFs, the set of real-time data is used to plan the path ahead, and to alter their paths whenever obstacles are detected by the sensor suite.

d) Safety Features – There are manually activated emergency stop (e-stop) buttons in the cabins of the LV and UFs. When activated by a safety driver, the e-stop triggers the DBW system to apply the service brake and cease the engine, thereby bringing the UF to a stop. For redundancy, the team also designed an additional independent e-stop (IES) which does not require any electrical or pneumatic power to actuate, but is instead based on a compressed spring. Triggering conditions for the IES include critical faults, such as loss of power and failure of the add-on kit's motors.

Software Design

At the heart of the Unmanned Truck Platoon is its software. A simplified overview of the software design is provided in Figure 4 while more detailed descriptions of the UF's software modules (i.e. Computer Software Configuration Items) are given in Table 1.

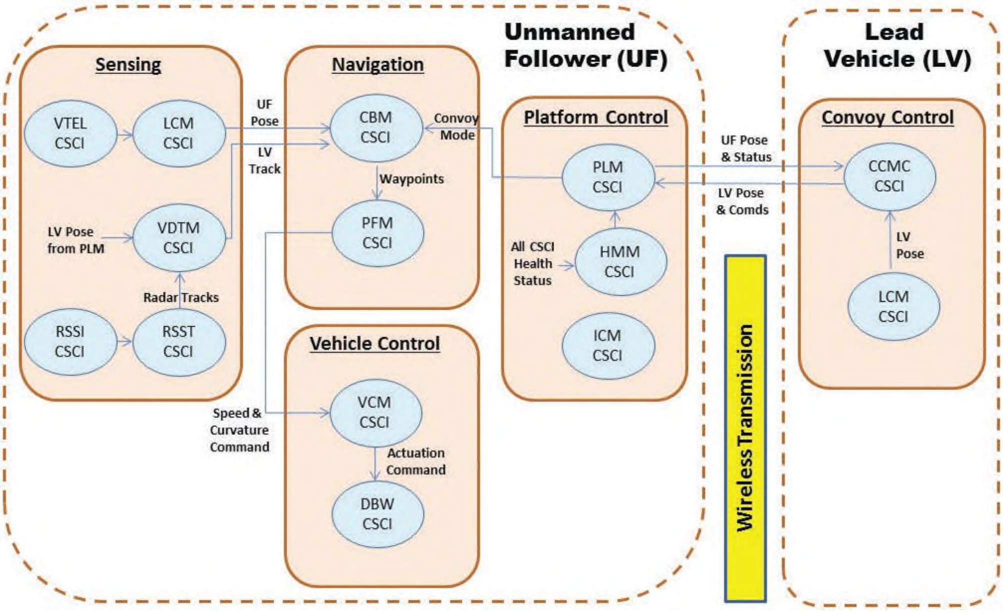

Figure 4. Software Overview of the Unmanned Truck Platoon

UF Software Module	Functionality
VTEL - Vehicle Telemetry	Provides information on speed, yaw-rate, turning signal and gear
RSSI - Radar Sensor Suite Interface	Extracts sensor data from the Radar Sensor Suite hardware
RSST - Radar Sensor Suite Tracker	Processes sensor data and provides information on objects detected by the Radar Sensor Suite
LCM – Localisation	Provides position, heading, velocity and acceleration of the UF
VDTM – Vehicle Detection and Tracking	Tracks and provides information on the position of the vehicle that is leading the UF. Also triggers the UF to come to a safe stop when a collision with an obstacle is predicted
CBM - Convoy Behaviour	Generates a path for the UF to follow
PFM - Path Follower	Generates vehicle control commands (e.g. speed and curvature) for the UF to track a path
VCM - Vehicle Control	Converts speed and curvature commands into low-level actuation commands to DBW
DBW - Drive-By-Wire	Provides control of the throttle, brake, steering and gear actuators
PLM - Platform Manager	Provides information on the system state and communicates with the LV CCMC as well as the PLM of other UFs
HMM - Health Monitoring	Monitors the health status of all the software modules residing on-board the UF
ICM - IES Control	Controls actuation of the IES hardware

Table 1. Descriptions of the UF Software Modules

OPERATION OF THE UNMANNED TRUCK PLATOON

Terrain

The Unmanned Truck Platoon was designed to be able to operate on both public roads and off-road terrain. In off-road conditions, the truck platoon is expected to traverse obstacles and rugged tracks; some examples are provided in Figure 5. In contrast with commercial truck platoons which operate on highways, such terrain posed significant challenges to the team, such as (1) the need to protect and reinforce the sensors mounted on the exterior of the trucks; (2) managing the sensor mounting positions and angles to maximise the field-of-view in various gradients and terrain; and (3) iteratively improving the navigation and vehicle-control algorithms to balance the need to operate in both public roads and off-road environments (e.g. hybrid GPS-perception vehicle-following technique that operates robustly on public roads as well as under foliage).

Figure 5. Operational Terrain

Modes of Operation

In the Unmanned Truck Platoon, each of the UFs follows the vehicle in front based on data from its on-board sensor systems, and position and orientation information (also known as pose) sent from the vehicle preceding it via V2V communications, as shown in Figure 6.

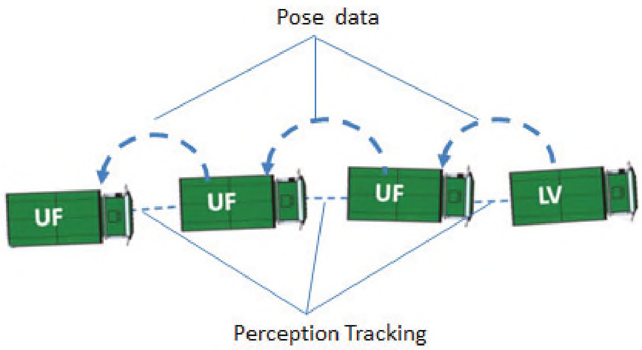

Figure 6. Operation of the Unmanned Truck Platoon

The primary mode of vehicle-following is based on the UF's perception suite. These sensors provide information on the position of the vehicle in front. With this information, the convoy behaviour module plans the path that maintains the UF at a safe distance behind the preceding vehicle. The path follower module then generates speed and curvature commands to allow the UF to manoeuvre along the planned path. These are subsequently converted into low-level DBW actuation commands for the add-on kit to control the UF accordingly.

During sharp turns and other situations, a UF may lose perception of the vehicle in front. To handle such situations, a secondary mode of vehicle-following based on GPS pose is used. At all times during the truck platoon's operation, the LV and UFs continuously broadcast their GPS pose and vehicle status via the meshed and encrypted V2V communications network. When perception is lost, the UFs will utilise the GPS pose from the preceding vehicle to plan its path instead.

The sensor suite on the UF also serves another crucial function – to detect obstacles which intrude into the path of the UF during convoy movement. Upon detection and prediction of a potential collision with an obstacle, the UF executes collision avoidance by actuating the service brake and stopping the engine, subsequently coming to a safe stop.

Notably, the team also designed the UF to allow a driver to operate the vehicle like a normal truck still, when the system is set to Manual Mode. In this mode, the back-drive of the steering actuator is minimal, and the other actuators similarly do not interfere with normal driving. This allows for ease of movement between the workshop and trial sites, and enables manual-driving of the UF without any change in hardware or software configuration.

SYSTEM PERFORMANCE AND OBSERVATIONS

The Unmanned Truck Platoon was tested on various terrain[5] to assess the system's performance in the areas of (1) Speed and Lateral Deviation; (2) Obstacle Avoidance; (3) Traversing Terrain Obstacles; and (4) Truck Platoon Reverse. The system was validated in 2016 on off-road terrain. In 2017, the system was validated through another set of trials conducted on public roads and various off-road sites within the Sungei Gedong Training Area, up to speeds of 50kph. Cumulatively, the trials added up to more than a thousand kilometres of mileage. While the performance of the system exceeded all the project requirements, the team observed several limitations and potential areas for improvement which are summarised as follows:

a) Endurance – The power supply was designed to rely on the UF's alternator and an additional bank of 12 deep-cycle batteries. Moving forward, there will be a need to increase the Truck Platoon's endurance and reduce the space taken up by the battery bank in the cargo cabin.

b) Image Recognition – With the use of a COTS camera, the image recognition database is limited to a set of objects more commonly found in urban environments, such as pedestrians, motorcycles, cars and trucks. For an expanded set of classification capabilities for off-road obstacles (e.g. potholes, trees) and military platforms (e.g. tracked vehicles), additional video analytics features should be integrated to the sensor suite. Such capabilities have been developed in other R&D projects, and can be integrated to the system in the subsequent phase of the Unmanned Truck Platoon project.

c) Add-on Kit – While an add-on kit fulfilled the need to convert the non-DBW five-ton truck into a UF, limitations of such an approach were felt by the team. These include latencies in the control of the vehicle via the mechanical actuators, reliability issues with the added components, and more complex maintenance considerations. Moving forward, as unmanned technologies become more ubiquitous, the Unmanned Truck Platoon of tomorrow should leverage DBW-enabled trucks.

LESSONS LEARNT

The team thoroughly enjoyed the opportunity to design, develop and validate the Unmanned Truck Platoon prototype over a span of three years. With the successful completion of the project, some of the key lessons learnt are documented in the subsequent paragraphs.

a) Iterative Development – Given the R&D nature of the project, the team had to be agile in all aspects of managing the project. From deep-dive and iterative design reviews to ascertain the most optimal system configuration and design, to repeated updates of software modules and algorithms to overcome surprises along the way, adopting an agile development mindset and framework was crucial in ensuring that the system was delivered within the SAF's required timeline and met all the necessary operational and technical requirements.

b) System Safety – Due to the driverless design of the UF, the system and software were subjected to rigorous safety assessments and tests. Through close cooperation with users and contractors during design reviews and system delivery, in aspects such as identification of potential hazards and implementation of mitigation measures, the system was eventually designed and tested to be robust and safe. Zero safety incidents occurred throughout the Unmanned Truck Platoon's trials and demonstrations.

c) Leveraging Modelling and Simulation (M&S) – With increasing demands on SAF resources such as manpower, support vehicles and trial sites, physical trials are both costly and difficult to execute. The team therefore pushed boundaries in the project, and used M&S tools to test and evaluate key functions including vehicle navigation and obstacle avoidance. This approach reduced the need for costly and time-consuming physical trials and allowed all stakeholders to have greater confidence in the system.

FUTURE TECHNOLOGIES

Significant investments in the autonomous vehicle domain are driving demand for better performance of sensors such as radars[6], Light Detection and Ranging (LIDAR)[7] and cameras. For example, while a LIDAR today may be expensive, rapid development in solid-state LIDARs, coupled with the increase in quantities produced, is poised to drive the prices of these sensors down. Many of these new LIDARs will also be automotive-grade with no mechanical moving parts, improving their reliability. With radars and cameras, a similar trajectory is also driving down costs and raising their performance. Many cars equipped with driver-assistance systems already come with such sensors installed, providing features such as forward collision and lane departure warnings.

New civilian vehicles today are also increasingly designed and produced with DBW capabilities, where the steering, throttle, gear change and brakes can be controlled electronically via an on-board electronic control unit. This allows an autonomy kit to control the vehicle directly without the need for add-on actuators. The removal of the additional electro-mechanical interface reduces lash in the system, thereby allowing for tighter control and improved performance. The reduction in complexities associated with the design, installation and calibration of such electro-mechanical interface further improves the reliability of the autonomous vehicle and facilitates the scaling up for wide-spread deployment. While complete DBW capabilities are currently limited to light vehicles (e.g. cars), commercial heavy vehicles are expected to adopt them eventually as these DBW capabilities provide advantages such as improved safety and lower fuel consumption, even for non-autonomous vehicles.

With computers exercising direct control of physical systems within an unmanned vehicle, often with little human supervision, cybersecurity is a crucial area of growing concern. The networking of individual platforms into cooperative fleets further increases the associated threat vectors and requires a systems engineering approach when looking more in depth into cybersecurity.

FURTHER OPPORTUNITIES

Beyond logistics, truck platooning technology can also be used in other mission sets as a means to insert unmanned assets efficiently into the area of operations. One example would be to have unmanned combat engineering vehicles follow manned vehicles via platooning during the movement phase, and upon reaching the designated location, be tele-operated to conduct the mission. As platooning features are now more mature than fully autonomous capabilities, the combined use of platooning and tele-operation allows for stand-off operation of combat engineering equipment in the short to medium term, reducing the risk of exposure for soldiers.

In the commercial sphere, truck platooning technology has a host of applications. Within Singapore, a truck platooning system will be trialled for inter-terminal haulage of containers between Brani Terminal and Pasir Panjang Terminals. The ability to control four trucks using only a single driver will address the expected shortage of truck drivers in the future, and allow more freight movement to be conducted at night to ease traffic congestion. Moving forward, platooning technologies can also be used to reap efficiencies for other logistics operations such as the movement of goods between warehouses and stores across the country.

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ENDNOTES

[1] Drive-by-wire technology involves the use of electrical or electro-mechanical systems to perform vehicle functions traditionally achieved by mechanical linkages, such as control of braking and acceleration.

[2] Vehicle-to-vehicle communication refers to the wireless transmission of data between two or more connected vehicles.

[3] Truck platooning improves fuel efficiency by allowing the trucks to drive more closely together than in conventional situations. This reduces aerodynamics drag on the rear vehicles in the platoon, leading to lowered fuel consumption.

4 Global Positioning System (GPS) is a satellite-based navigation system that provides geolocation and time information to a GPS receiver. An Inertial Navigation System (INS) is a navigation aid that uses a computer, motion sensors and rotation sensors to calculate position, orientation and velocity of an object without the need for external references.

5 The Unmanned Truck Platoon was tested on various terrain, such as tarmac roads, sandy and uneven ground in off-road training areas, and obstacle courses within Mandai Cross-Country Driving Circuit.

6 Radar (Radio Detection and Ranging) is an active detection system which emits radio waves, receiving and processing the waves reflected off an object to determine the object's range, angle and velocity.

7 LIDAR (Light Detection and Ranging) is an active detection system which determines the distance to an object by measuring the time it takes for emitted pulses of light to travel to the object and back.

BIOGRAPHY

GAN Hao Yi is a Programme Manager (Land Systems) overseeing the development of an Army C3 system, and is concurrently a Senior Systems Architect (DSTA Masterplanning and Systems Architecting). He was involved in various Unmanned Ground Vehicle projects for both WOG and the SAF, and was formerly a Member of Technical Staff in DSO National Laboratories (DSO). Hao Yi graduated with a Bachelor of Engineering (Electrical & Electronic Engineering) degree from Imperial College London (UK) and a Master of Science (Management Science & Engineering) degree from Stanford University (USA), in 2012 and 2013 respectively.

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