Concept Development of Autonomous Multi-Purpose MHE for Logistics and Combat Service Support

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***Abstract*—Contemporary military logistics operations are commonly reliant on the use of material handling equipment (MHE). The large variety of MHE required to keep a base operational can be expensive, slow, and dangerous. A conceptual design is proposed for a networked fleet of autonomous material handling equipment to replace or augment existing logistics equipment. The proposed concept is capable of standardising existing material handling functionalities into a cohesive modular system. This system has advantages of ease of use, increased space optimisation, higher utilisation and reduced personnel-hours over traditional material handling practices. The feasibility of the concept is evaluated and predicted to be realisable within the next 10 years.**

Keywords—Autonomous Logistics, Material Handling Equipment, Warehousing, Concept Development,

I. Introduction

Autonomy and autonomous technologies have the potential to revolutionise many aspects of warfare. Apart from the technological barriers, the issue of trust in autonomous systems is a significant research topic in its own right. Logistics is seen by many as a suitable "first-cab-off-the-rank" for autonomy in more benign environments: it (mostly) avoids the more complicated ethical dilemmas that arise when considering autonomy for other warfighting functions; it provides a lower-risk environment for maturation of key enablers like effective human-robot interfaces and human-machine teaming; and, crucially, it exposes wider Army to autonomous platforms, a critical component of building trust.

One such application is in material handling. Military logistics operations are commonly reliant on the use of material handling equipment (MHE). The variety of MHE required to keep a base operational can be expensive, slow, and dangerous.

One way to mitigate these factors is to introduce a suitable autonomous material handling system. As well as addressing numerous safety concerns (e.g. removing personnel from hazardous situations, see [1,2]), such a system could capitalise on traditional areas of low efficiency: unloading, picking, and transport between nodes. The inefficiencies in logistics often occur at the points of transition from one mode to another, for example removing a pallet load from a warehouse and transferring it to a heavy forklift to be transported a short distance to the other side of an operating base. The heavy forklifts employed to move shipping containers and/or their contents to and from the warehouse are generally only in use when setting up an operating base or obtaining resupply from the National Support Base. Automation in these areas would greatly increase efficiency of operations as well as increasing equipment utilisation (less idle time – autonomy doesn't sleep).

In this paper we propose the Transport Reconfigurable Autonomous Vehicles Interactive System (TRAVIS), a system of autonomous vehicles used for transportation of goods within a warehouse, between structures in an operating base, and between bases in a deployed setting. The system is comprised of a number of modular units, which can be used individually or connected together to transport heavy material, and can be combined with various attachments to complete a variety of tasks. TRAVIS allows for storage, delivery and retrieval of materials through a coordinated network with minimal human operation, which both decreases the load on persons within logistics and increases the efficiency of operations.

The focus of this paper is on describing the TRAVIS concept itself. For a more detailed treatment of the considerations that went into the development of this concept, and more detailed discussion of its utility, please see [3].

II. Concept: Transport Reconfigurable Autonomous Vehicles Interactive System

Each unit within TRAVIS consists of a pallet-sized electric driving base and an optional attachment. The driving base contains the wheels, motors, gearboxes, battery, communication devices and processor. Each side face of the square driving base is fitted with connectors to enable the conjoining of multiple units and facilitate local communication between such units. On the top surface of the driving base is a socket for attachments, through which power and information are transmitted to actuate the attachment. All attachments are removable and reconfigurable, so a unit can change its transport function at any time.

A. Driving Base

1) Omnidirectional Base

Within warehouses, operation of MHE occurs in a relatively controlled environment, with flat, smooth ground such as concrete or packed dirt. Storage within warehouses is limited by the width of aisles between shelves, which must be

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at least as wide as is required by the largest MHE used in that warehouse. It is therefore most economical to employ MHE that is no wider than the pallets it transports, and with a small turning circle. The omnidirectional base, shown in Fig. 1, has horizontal dimensions equivalent to a standard Australian Defence Force (ADF) pallet, and is capable of planar translation in any direction as well as turning on-the-spot, minimising the required aisle space for normal operation. The size of the unit also allows for its potential use in shipping items in the place of a pallet, as items can be packed atop the driving base in the same way they would be palletised, and autonomously transported without the need of external equipment. Each TRAVIS unit is capable of coupling with other TRAVIS units on all four sides to carry larger loads.

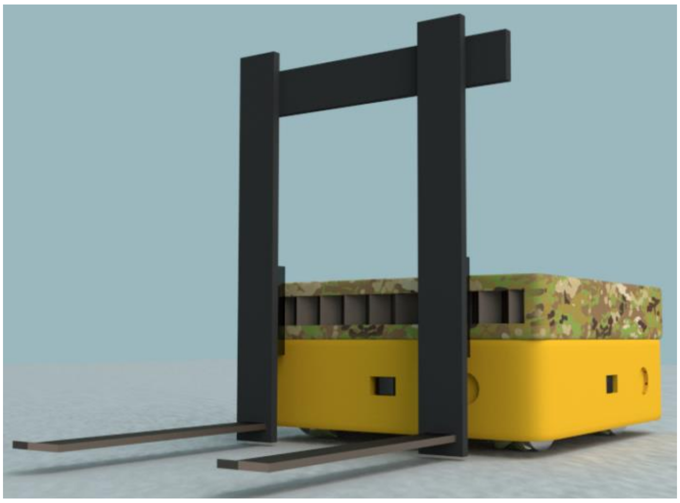

Fig. 1. Illustrstion of the omnidirectional base with a forklift attachment.

a) Mecanum Wheels

The omnidirectional base is fitted with a set of 4 30cm Mecanum wheels with a 3000kg capacity. This allows the platform to move ISO containers: an array of 12 platforms can collaborate to lift a fully laden 20-foot container, with a distributed weight of approximately 2000kg per unit. The size of the wheels means that the top surface of the base platform, without attachments, is already at least 30cm from the ground, higher than the lowest pallet racking at an average of 15cm. This means that transfer of pallets to and from racking may require some mode of lifting, such as the forklift attachment.

b) Sensors

Mounted in the relief of each side of the base is a scanning laser (lidar) and a camera. This allows the unit to locate obstacles and compute a map of its surroundings, which it uses for path planning, navigation via Simultaneous Localisation and Mapping (SLAM) and waypoint finding. The cameras are used for object recognition, such as recognition of other units, receiving areas for payloads, and detecting humans. The localisation of the robot is assisted by an Inertial Measurement Unit (IMU) and the wheel rotation information.

2) Off-Road Base

The off-road base is an alternate ground platform for use with all attachments. Shown in Fig. 2, the off-road base is intended for long-distance transportation over dirt roads, such as assisting convoys. Unlike the omnidirectional base, the off-road base is not capable of sideways movement, though it features skid-steering which allows it to turn on the spot. This base is larger than the omnidirectional base to account for the extra space needed for suspension, a larger battery, and added ruggedness to achieve reliability suitable for field operations. The front and rear of the driving base are equipped with both headlights and safety lights for night time operation and to allow the vehicle to drive with either side acting as the front of the vehicle. The off-road base is still capable of coupling with units on all four sides in order to carry larger loads.

Fig. 2. A preliminary design for the off-road base carrying two pallets, with soccer ball for scale.

a) Off-Road Wheel Choice

The off-road base must be able to traverse rough terrain but still achieve reasonable speeds, making legs unsuitable. Thus, it was decided that the off-road base should incorporate wheels and suspension. The Shweel [4] was propositioned for use in the off-road base in order to conserve space by removing this need for suspension. The Shweel, however, is designed primarily to reduce rolling resistance in order to conserve fuel, and its optimal implementation still requires traditional suspension. Additionally, the Shweel is more expensive in smaller sizes, and has a minimum diameter of 18" (457mm), which is an impractical size to implement for a small rover. Similar spoked wheel designs exist with the same drawbacks, making it more economical to consider traditional pneumatic tyres. An alternate solution could be including the suspension inside the shell of the wheel, such as the Michelin Active Wheel [5]. Unfortunately, this wheel is also available only in large diameters, making it ill-suited for application in a medium sized robot. Thus, the off-road base is conceived with traditional pneumatic tyres and suspension.

b) Wheelbase

In order to fit the wheels into the size of an ADF pallet, the wheelbase of the off-road base is comparatively short, at 687mm for 400mm tyres. A shorter wheelbase generally has advantages in manoeuvrability whilst detracting from stability. To compensate for the reduced stability of the wheelbase, the track of the driving base is made as wide as possible at 880mm. The centre of gravity of the vehicle is kept as low as possible by locating the battery at the lowest point, adding to the stability of the driving base. The result is a compact, manoeuvrable vehicle with reasonable stability.

B. Attachments

Several different attachments are available for the TRAVIS units, allowing the fleet to be configured in a number of ways to serve the user. The modules are all attached in the same way atop the driving base, allowing future compatibility with new attachment designs.

1) Forklift Tines

The forklift tines attachment shown in Fig. 1 consists of a short mast and standard forklift tines. This module is designed to be used to lift pallets atop other modules such as the lifting module or onto first- or second-level racking. With a free lift of 1.2m, the forklift module can be used to pack and unpack both layers of an ISO container. The distance between the tines can be adjusted up to a maximum separation of 1m. It is possible to add a second attachment on top of the forklift attachment. If an extra counterbalance is necessary when performing high lifting manoeuvres, a payload can be loaded onto the lifting unit by another unit, or another unit can couple to the rear of the lifting unit to shift the centre of mass.

2) Lift and Convey

The lifting and conveying module uses a scissor lift to raise a load-bearing platform with built-in motorised rollers, which allows the platform to act as a conveyor belt. This allows the units to act as a reconfigurable conveyor belt with different height options, and allows the unit to unload payloads onto high racking. It is possible for the attachment to have a collapsed height of no more than 400mm, based on the Edmo TLD2000B [6] as an example, with a lift capacity of 2000kg at 1.6m and a collapsed height of only 360mm.

3) Towing

The towing module is fitted with a standard tow ball and a winch to facilitate towing of trailers and disabled vehicles, as well as clearing obstacles and hauling objects.

4) Palletising and Picking

The picking attachment is a 7-axis robotic "arm", based on the KUKA LBR iiwa 14 R820 [7] as an example. This robot is capable of picking up individual items for tasks such as palletising and picking, up to a maximum weight of 14kg. Each joint is fitted with torque sensors which enable the robot to be used safely in a collaborative environment with humans, and means that a range of items can be gripped or moved without being damaged.

C. Connecting Bases

An important factor of the design is that each homogeneous set of driving bases is able to physically link up with its neighbours, to form a chain or an array. This physical link allows the modules to carry larger loads such as shipping containers by distributing the weight. The connectors used for such linkages are able to facilitate wired communication between devices via e.g. USB, allowing a large array of connected bases to coordinate their movement without wireless communication, useful for EM signature management in field operations. A number of connector designs were conceived, but are not presented here. Please see [3] for details.

D. Control System

The control system architecture of TRAVIS must: permit autonomous and semi-autonomous operation of units, allow a scalable fleet size with no added system requirements, support user interaction with large numbers of TRAVIS units, and operate safely at all times.

To achieve this, a ‘centralised control, decentralised execution’ architecture is proposed: a central server is used to collect requests from logisticians for the movement of material; TRAVIS units connect to the server to learn of these requests (these can also be opportunistically relayed to other TRAVIS units unable to connect directly to the server); TRAVIS units then negotiate their collective responses to these requests; and a final task allocation decision is made by the central server. Negotiation and task allocation may utilise something akin to the Contract Net Protocol [8]. While currently decentralised, one could envision a distributed architecture in the future.

Individual units are responsible for local navigation via SLAM, collision detection and avoidance via Detection And Tracking of Moving Objects (DATMO), speed restriction, safety and local system monitoring. In the event that a unit needs to be shut down immediately, a command can be issued to the TRAVIS unit. If a unit is unable to receive commands, a unit should have several in-built procedures for detection of the need to shut down. If all of these methods are inadequate, each unit will have a hard-wired emergency stop.

Devising a route for multiple autonomous MHE to collect items is a variant of the NP-hard travelling salesman problem, called the Capacitated Vehicle Routing Problem (CVRP). The algorithm in [9] was designed to solve the CVRP for use by the TRAVIS system. This algorithm allows any number of TRAVIS units to quickly be assigned an efficient route within a warehouse to facilitate the collection of a number of objects, adding multiple trips where necessary. Additionally, the algorithm has the capacity to operate online, allowing new items to be requested while the TRAVIS units are collecting items. Further details are beyond the scope of this paper.

E. Hardware and Software Requirements

Each driving base will contain four DC motors and encoders, a battery, and the equivalent of a PC processor and motherboard. The units will also carry a GPU to analyse camera and laser data to perform tasks such as SLAM and identifying target locations. Given the considerable volume available within the driving bases, there is adequate room for sufficient battery storage to provide acceptable endurance. Units will recharge through an electrical interface (physical, or wireless) accessible from underneath the base of the unit, allowing them to self-dock in charging stations when needed.

All non-attachment members of TRAVIS are equipped with a class-1 Bluetooth transceiver, with a range of up to 100m. This allows up to 7 simultaneous connections between devices and can be used to create mobile and-hoc networks using suitable routing and transport protocols.

III. Evaluation

An autonomous material handling system like TRAVIS has many potential benefits, but may also have costs, both monetary and non-monetary. While a detailed cost/benefit or technology impacts study is beyond the scope of this paper, we can make some general statements from the outset on both advantages and disadvantages, and viability.

A. *Potential Advantages and Disadvantages*

A system like TRAVIS can have benefits for the safety, efficiency, and productivity of ADF logistics. The use of a single, unified platform for material transport has the advantage that fewer specialists are required for full functionality of the system. Further, it means that only one set of SOPs, maintenance schedules and user certifications need be issued. Operation of MHE can also be dangerous, hence the self-evident safety advantage of the use of autonomous MHE is that it removes humans from the potentially dangerous environment of a warehouse.

For some tasks it may be necessary to use more TRAVIS units than traditional MHE, a potential disadvantage. For example to move a shipping container, 12 units with forklift attachments must lift the container from the ground to allow 12 units (without attachments) to enter underneath: the platform onto which the container is then lowered. This is 22 more units than a standard crane and heavy-duty forklift. On the flip-side, the advantage of TRAVIS is that these units can also be used for other tasks, unlike the limited applications of heavy-duty MHEs like cranes. Overall, a larger heterogeneous MHE fleet has the potential to be replaced by a smaller TRAVIS fleet.

Another advantage of its large fleet size is the redundancy of the system. Several units can be disabled without affecting its material handling abilities, whereas the malfunction of a single heavy forklift can cause days' worth of delays. The driving bases also boast much greater space optimisation than manual MHE, due to their 'stack-ability' (rectangular shape and lack of cabs for operators).

In terms of efficiency, the automation of warehouses can see a marked increase in efficiency, as algorithms can process problems at a much faster rate than a human, may produce more optimal solutions, and are not susceptible to fatigue or other human failings. Due to the largely digital nature of the fleet's capabilities, the system can be readily upgraded to achieve new tasks through e.g. a simple USB data transfer, as opposed to changing hardware or altering firmware of difficult-to-access microcontrollers.

However, we must be mindful that the introduction of autonomous systems can sometimes be met with resistance, particularly if the humans impacted feel that their livelihood is threatened. A sensible suggestion is thus to progressively introduce a capability like TRAVIS through pilots and trials, so as to expose end users gradually. The idea isn't to replace humans, but to allow those humans to operate in a safer, more efficient way, freeing up effort for other logistics tasks.

Compared to current equipment, it is projected that the manufacture of TRAVIS components should be no more difficult than existing MHE. The maintenance may be more complex; however, as physical components have to be compressed and precisely located, and troubleshooting software errors may require specialists. At the end of its lifetime, a unit must be disposed of carefully due to the large proportion of electronic components, meaning that recycling of e-waste and battery disposal practices must be observed.

B. *Viability*

The above evaluation of TRAVIS suggests that it would be a valuable asset to the ADF. From a hardware perspective, the materials and equipment required to construct a single driving base or attachment could be readily acquired at the present time. Relevant autonomous software and devices currently have Technology Readiness Levels (TRLs) ranging from 5 to 7 depending on the system, making TRAVIS eminently viable.

IV. Conclusion

The TRAVIS concept is an effective replacement for several different types of MHE. Its application is also not limited to Army, as a system like TRAVIS is also ideally suited to e.g. the physical confines of the Royal Australian Navy's recent Landing Helicopter Dock (LHD) and Landing Ship, Dock (LSD) acquisitions. TRAVIS poses several advantages over current methods, including increased safety, efficiency, and redundancy. With appropriate development, autonomous MHE like TRAVIS could be realised and be deployment-ready within 10 years. We are currently developing small proof-of-concept prototypes and intend to engage with Army MHE Subject Matter Experts.

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