Towards unmanned systems for dismounted operations in the Canadian Forces

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Abstract: Unmanned systems are designed to reduce risk and magnify the impact of manned forces. Expanding unmanned involvement in military operations will require greater vehicle autonomy and the adoption of new concepts of operations. This paper discusses the technical challenges of unmanned systems in support of dismounted operations and research efforts by Defence R&D Canada to support unmanned vehicles in this role. New projects have been formulated to address these technical challenges.

Keywords: autonomy; control algorithms; intelligent mobility; path planning; perception system; unmanned aerial vehicle; UAV; unmanned ground vehicle; UGV; unmanned systems; UxV; defence.

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1 Introduction

Unmanned systems are intended to reduce risk to personnel and to act as a force magnifier for dismounted soldiers, but will need new concepts of operations (CONOPS) to leverage manned/unmanned combinations and greater vehicle autonomy to keep command burdens low. Unmanned CONOPS for land warfare is an evolving target as embodied by such broad sketches as the Future Combat System (FCS) *Green Book* and similar long range forecasts (Committee on Army Unmanned Ground Vehicle Technology, 2002; Schroeder, 2005). Nevertheless, unmanned aerial vehicle (UAV) over-watch and reconnaissance and portable unmanned ground vehicle (UGV) deployment in Iraq and Afghanistan clearly indicate that UAVs and UGVs are useful in intelligence, surveillance and reconnaissance (ISR) and combat support roles. Although the addition of unmanned vehicles (UxVs) into theatre must minimise soldier workload, many important requirements remain unanswered: What kind of autonomy is necessary? How much autonomy is *enough*? How will these systems be deployed?

To expand short sensing and communication ranges, particularly for UGVs, investigators explored specific UxV combinations that share sensing, relay communications, and distribute computing (Krotkov et al., 2007). Though compelling, the impact, practicality, and sustainability of some manned/unmanned systems remain unclear and often dissociated from a mission context. This paper examines unmanned systems from the urban dismounted soldier's perspective and discusses the technical challenges of supporting infantry operations within a complex or urban context.

In the following sections, this paper will describe Defence R&D Canada's (DRDC's) approach to supporting dismounted operations. After a brief review of the dismounted role in Section 2, Section 3 examines the potential of low altitude UAVs as an asset directly supporting and under the control of dismounts. Section 4 discusses UGVs and the necessary mobility required for true dismount support. Section 5 examines world representation methods necessary for the dismount's complex, GPS-denied environment. Sections 6 and 7 examine control and dynamics aware path planning within these environments. Finally, Section 8 describes how the dismount problem has formed our immediate research projects.

2 What are dismounted operations?

Modern land warfare centres on either a mechanised or air-mobile infantry element. A dismounted infantryman has left his primary transport and moves on foot, often carrying 50–60 kg including munitions, weapons, communications gear, body armour, water, and small quantities of food. Not surprisingly, dismounts travel relatively slowly, generally through complex terrain. Soldiers will dismount for many reasons, sometimes to present a non-threatening face to the local population or to exploit the foot soldier's inherent stealth or mobility. Combat falls into a cycle of observe, orient, decide, and act. Dismounts experience this cycle at the finest scale during a wide variety of operations, including:

- position defence: e.g., perimeter defence, *5s-and-20s* perimeter vehicle inspection
- patrols: including small team excursions for security, reconnaissance and ambush often ending in enemy contact
- structure clearing: team-based search and suppression of enemy forces in urban structures
- direct fire: the use of small arms, RPGs, and shoulder launched guided weapons to suppress or destroy enemy positions
- indirect fire: the use of target designation and communications equipment to either aid artillery or guided weapons.

Not surprisingly, the large loads carried by personnel, their ability to observe surrounding terrain, and the personal risk experienced by soldiers have driven the interest in unmanned systems for dismount support, and a number of possible activities promoted as desirable for unmanned systems. Following the Canadian Forces (CF) capability model of *sense*, *sustain*, act, *shield*, and *generate* helps categorise potential unmanned roles.

Sense includes ISR and provides situational awareness to dismounted infantry through satellites and airborne manned and unmanned platforms. Mounted and dismounted patrols provide essential, yet complementary, intelligence founded on direct experience but limited to a short horizon. For the dismount, ISR products must be available quickly and in great detail. Historically, rearward analysts harvested, filtered, and forwarded imagery to dismounted units. Recent conflicts overturned this process with forward units harvesting tactical imagery through manned and unmanned aircraft flights and the one system video receiver terminals (Barnes, 2007). The demand for local imagery has driven portable systems into the field (e.g., Raven) and raised questions about the value and burden of such portable ISR (GlobalSecurity.org, 2007).

Sustain or combat service support covers logistical functions critical for infantry operations. The large load dismounts must carry remains the single greatest problem for dismount mobility. Two possible unmanned roles may reduce these loads: *mules* and convoys. The mule shifts supplies to a squad (8–10 man) load carrier that can follow the unit through the bulk of anticipated terrain (Lockheed Martin Corporation, 2006). The mule concept has many advantages including multi-purposing as a weapons/countermine vehicle, but implies a very large payload (one ton or more), range (tens of kilometres) and mobility envelope. Alternatively, patrols can also be resupplied *just-in-time* (JIT) through low cost, expendable unmanned carriers. This convoy system could perform frequent resupply missions based on a combination of mission preplanning and on-the-fly replanning with dismounts. JIT systems may provide arbitrary, flexible resupply where payloads can change based on immediate requirements.

Shield or force protection equipment defends dismounts from many hazards including small arms fire, indirect fire, snipers, mines and improvised explosive devices (IEDs). Of these, counter sniper, counter-fire and counter-IED systems are deployed autonomous systems, but are not man-portable for dismount defence. Body armour and tactics are the dismount's main protection against injury in combat. Vehicle mounted or stationary counter-glint and counter-sniper systems detect either sniper optics or the air pressure signatures of passing rounds to locate snipers. Autonomous counter-fire systems have been proposed for artillery, mortar, and RPG projectiles based on naval close-in weapon systems (GlobalSecurity.Org, 2009). Using radar detection and kinetic counter-measures, these vehicle-mounted or stationary systems detect, track and destroy incoming rounds.

IEDs strike soldiers on frequently travelled routes, using unpredictable placement, designs, effects, and triggers to inflict casualties while undermining trust in typically safe areas. To avoid IED strikes, deployed forces have come to rely on tactics, route observation and radio jamming. Unmanned systems participate in counter-IED operations mostly after IED detection or triggering. Though some forces use specialised vehicle inspection robots (e.g., ODIN) at vehicle checkpoints, IED disposal using unexploded ordinance (UXO) robots is more widespread. However, persistent unmanned route observation or over-watch has been suggested as a possible tool for general counter-IED protocols, expanding on current UxV roles (i.e., convoy over-watch, battle damage assessment, target identification and designation).

Dismounted infantry possess many weapons and tactics in the *act* or combat role. In bringing fire onto enemy positions, the dismount has two principle methods at hand: direct and indirect fire. In direct fire, soldiers identify, track, fire, and possibly guide the weapon to the target, making direct fire both immediate yet subject to individual skill. The *shooter* has the target in sight at all times. For example, small arms, RPG, and wire-guided missiles are direct fire weapons. In indirect fire, shooting and targeting are separated, permitting infantry to direct artillery, mortars and airborne or guided weapons onto target.

Combat forces propose the use of unmanned systems in tactical roles including patrol point, weapons platform, and lone reconnaissance (Schroeder, 2005; Commitee on Army

Unmanned Ground Vehicle Technology, 2002). In practice, UAVs have been acting in the armed over-watch role in both Iraq and Afghanistan, typically as a mixture of direct and indirect fire and always with humans in the loop. Unmanned combat systems offer many potential advantages including precision direct fire, long endurance tracking, and standoff. Though some raise ethics as a barrier to robots in *autonomous combat*, reliability, cost, and logistical footprint will pose greater problems and make dismounts an essential part of any autonomous combat system.

Generate includes force training, a graduated introduction to skills from individual, company, and brigade action. Modern training mixes classroom, unopposed unit rehearsals, and realistic red-force/blue-force exercises. Unmanned *pop-up*, teleoperated systems train individuals in both small arms and sophisticated weapon systems by mimicking enemy personnel and larger moving targets.

The Autonomous Intelligent Systems Section (AISS) at DRDC – Suffield (DRDC Suffield) envisions autonomous systems contributing to decisive operations in the urban battle space. In this vision, teams of unmanned ground, air, and marine vehicles (UAVs, UGVs, and UMVs) will gather and coordinate information, formulate plans, and complete tasks, as envisioned in Figure 1. In this scenario higher altitude UAVs may supply coarse city maps to smaller more highly manoeuvrable UAVs, to construct streetscape information with sufficient information for UGVs to navigate city streets and build 3D world representations of the urban battle space. These systems must navigate unknown, highly complex environments in order to provide information with sufficient detail for tactical operations and contribute to real-time situational awareness.

Figure 1 Scenario illustrating teams of unmanned ground and air vehicles gathering and coordinating information, formulating plans, and completing tasks (see online version for colours)

The objective of this paper is to describe the research and technology at DRDC in support of the dismounted soldier. The following sections will discuss the technical challenges of supporting dismounts in a highly complex environments and DRDC's ongoing research into mission-relevant solutions.

3 UAVs for dismounted operations

The dismounted soldier encounters situations where an elevated view would improve situational awareness. A small, lightweight airborne electro-optical/infrared (EO/IR) sensor that a soldier could deploy to obtain visual information is an ideal device. CF future army plans (Department of National Defence, 2003) emphasise adaptive dispersed operations in urban environments, and DRDC has created projects in alignment with this vision. The Integrated Soldier System Project (ISSP) seeks to equip dismounted soldiers with an integrated suite of weapon accessories, electronic devices, sensors, individual equipment, operational clothing and, possibly, man-portable mini aerial vehicles (MAVs). The ARMS project (Bogner and Murphy, 2009) anticipates the use of large payload rotor craft for route surveillance to provide both mounted convoys and dismounted soldiers with high resolution surface imagery and geometry.

3.1 Supporting the integrated soldier system

Any soldier-carried airborne sensor must be capable of robust, autonomous, hovering flight. Typical fixed-wing designs are robust but cannot hover. Rotorcraft designs can hover but can be mechanically complex. Since a skilled operator can fly fixed-wing aircraft equipped with high output electrical motors like a rotorcraft using 'prop hanging' manoeuvres, DRDC investigated the costs and benefits of an alternate strategy: a slow flying fixed wing airborne sensor that might meet ISSP requirements. The next section describes research at DRDC – Valcartier that examined the technical hurdles of this potential hybrid solution.

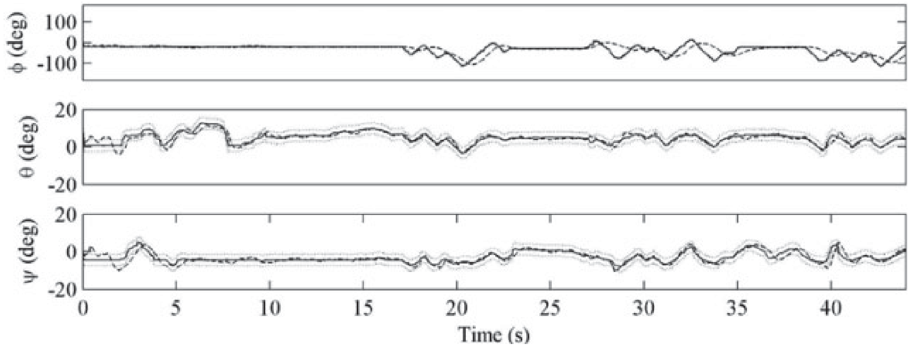
DRDC Valcartier developed MAV stabilisation algorithms using a vehicle dynamic model. Inertial measurements collected from a set of manually flown dynamic mode excitation manoeuvres were then fit to this model. Controlling a fixed-wing MAV suffering non-linear aerodynamic phenomena common to high angle-of-attack manoeuvres (e.g., hover) is possible by linearising the control around a well regulated set point (Bilodeau, 2009).

Experimental tests assessed the hover control strategy. Using a handheld controller, an operator's roll, ϕ, pitch, θ, and yaw, ψ, commands were superimposed on controller commands, permitting operators to manoeuvre the MAV and ignore hover stability.

To test this linearised control approach, DRDC Valcartier selected a commercial-off-the-shelf fixed-wing (Flatana, Great Planes) testbed based on the size and weight characteristics of a soldier-carried MAV. A brushless electric motor powered a 0.91 m wingspan, 410 g vehicle with a 10 inch propeller. A 40 g avionics package composed of a commercial autopilot, three-axis rate gyros and accelerometers and a 900 MHz radio, controlled micro-servo actuated surfaces and relayed data to the base computer.

Figure 2 depicts the attitude results. In the first 10 s, the operator translates the MAV by pitching (θ) back, and yawing (ψ) right. Later, at 15 to 25 s, the operator pitches the MAV forward with some minor yawing motions. The performance bounds show that the control algorithms kept the MAV stabilised during the operator inputs. However, the roll results (ϕ) reveal that the ailerons are near maximum deflection to counteract the propeller torque. When the operator commands set-point changes, the control surfaces often become saturated and the roll errors in Figure 2 appear.

Figure 2 Attitude test results obtained with a hovering fixed-wing MAV



Notes: Solid lines represent commanded attitudes. Dashed lines represent system response. Dotted lines represent ±3° performance bound.

3.2 *Large Scale UAVs for combat service support*

The *structured route survey* (SRS) could provide combat forces with detailed route reconnaissance. Using sensors similar to those carried by fixed-wing manned survey aircraft, low flying UAV rotorcraft could harvest high resolution EO/IR imagery without risk to personnel. A fleet of such aircraft could provide a low risk, high frequency alternative to patrols and provide a comparable disruptive effect on enemy activity. For low altitude operations in complex terrain, precise (sub-metre) localisation and obstacle avoidance will be critical and will pose significant challenges, requiring both *absolute* or geo-referenced positioning and precise *relative* positioning for close-in manoeuvres (such as flight near confined, unprepared, or moving surfaces). Position sensing could include high power/mass active ranging systems (e.g., SONAR, LIDAR, and RADAR) and lower power/mass, passive imaging techniques such as structure from motion and simultaneous localisation and mapping (SLAM),discussed in Section 5.1.2 (de Nagy Koves Hrabar, 2006).

An *autonomous resupply* (AR) system could deliver modest payloads that are either too costly, dangerous, or urgent for the traditional manned supply network. Unmanned delivery systems have been limited to either parafoils (e.g., MMIST Snowgoose) without serial pick-up/delivery capability or large optionally manned rotorcraft. Combining low cost, low speed, and high payload capabilities with autonomous navigation, rotorcraft fleets could achieve high precision, high speed delivery of small payloads to forward areas with low risk to flight crew or forward personnel.

To fulfil the common hover, payload, and endurance requirements of SRS and AR, DRDC Suffield developed the Aphid experimental platform shown in Figure 3. The Aphid, loosely based on the Mosquito Air ultralight helicopter, uses established helicopter mechanics, a twin-engine/single main rotor configuration, off-the-shelf autopilots (Cloudcap Piccolo II), and conventional ground stations to provide a modest, yet robust payload and endurance capability (100kg for ~3hr). The commercial avionics provide intrinsic waypoint following, auto-take off and auto-land capability, while the twin engine design and high stance permit large CG mounted pay loads that are easier to load and balance than outboard or pilot cabin stores on helicopter conversions. This platform, originally conceived as a research mule, has undergone a rapid evolution for both SRS and AR applications within the CF.

Figure 3 DRDC Suffield's Aphid heavy lift rotorcraft prototype ready for transport (see online version for colours)

4 UGVs for dismounted operations

Given the evolution of combat from symmetric (direct force on force engagement) to asymmetric (unpredictable engagements with failed states) warfare, the CF anticipate increased asymmetric conflicts requiring "... increased emphasis on info ops, SA, and small, agile, dispersed units required to operate in a non-linear environment supported by instantaneous precision effects" and will "... become increasingly complex due to the asymmetric nature of the threat, the use of urban terrain, blurred operations and the expansion of the battlespace" (Department of National Defence, 2003). Since urban terrain levels the technological differences between combatants (Horn and Gizewski, 2003), a developed army's infantry should be light, fast, flexible, adaptable and mobile. These requirements drive the interest in improving UGV mobility for the dismounted infantry.

4.1 DRDC mobility research for UGV autonomy

DRDC Suffield uses large, stable, Ackermann steered vehicles to study world representation, perception, navigation and path planning. DRDC developed two drive-by-wire vehicles with proprioceptive sensing that collects raw position and orientation data from a GPS, an IMU, and odometry. The Raptor vehicle [Figure 4(a)], equipped with exteroceptive sensing, collects and generates terrain and traversability maps used to control the vehicle to waypoints while avoiding obstacles. The Canadian Forces Joint Incident Response Unit (C-JIRU) investigates chemical, biological, radiological, and nuclear events with the teleoperated multi-agent tactical sentry (MATS) [Figure 4(b)].

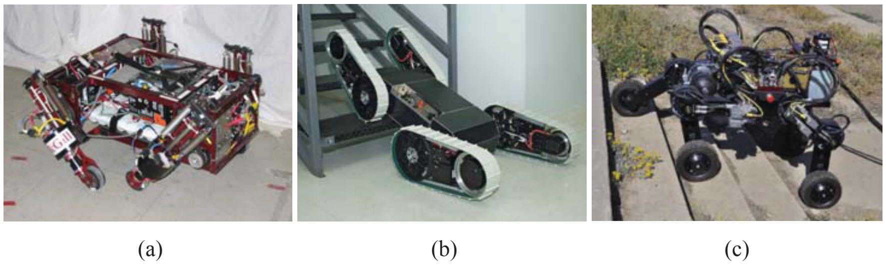
Figure 4 DRDC Suffield's Ackerman steered unmanned platforms (a) Raptor (b) MATS (see online version for colours)

(a) (b)

DRDC Suffield also conducts small-scale, soldier deployable UGV research to maximise locomotion strategies the range of a robot's traversable terrain. DRDC conceived and developed three different robots to address common forms of motion. The platform with articulating wheels (PAW), shape shifting tracked robotic vehicle (STRV), and microhydaulics toolkit (MHT) [Figures 5(a)–5(c)] illustrate a combination of wheels, tracks, and legs to provide motion. The PAW is ~0.5 m long. The leg member combines an active hip actuator with an active wheel end effector connected by a compliant leg with a pair of springs. This compliant leg allows for investigation into dynamically stable bounding gates for locomotion that uses the stored energy in the springs. The STRV is ~1.32 m long in its fully open configuration. With relatively few degrees-of-freedom (DOF), the STRV can traverse relatively complex terrain with relatively simple control. However, fewer DOF also limits the traversable terrain compared to other higher DOF platforms. The MHT has dimensions of ~0.75 m in length with 12 controllable DOF. The MHT can achieve animal-like mobility in complex environments.

Creating effective UGV systems for dismounts demands advances in perception and world representation, navigation, and learning. Beyond simple navigation, the *locomotion problem* within complex terrain need precise geometric models, while also making subtle assumptions about the environment's composition (e.g., surface stability and friction). Thus, high DOF perception systems must be capable of systematically assessing the environment and adapting according to the vehicle's capability and configuration.

Figure 5 DRDC Suffield's legged mobility platforms (a) PAW (b) STRV (c) MHT (see online version for colours)


(a) (b) (c)

5 Perception systems for UxV autonomy

Current perception systems for UxVs lack the robustness necessary to fulfil the dismounted support roles envisioned for them in Section 2. The dismounted soldier cannot afford to expend much effort in maintaining a robotic asset; it must simply work. Perception systems are particularly prone to failure, especially in battlefield conditions. Researchers must improve perception system robustness before dismounted soldier/robot teams are battle ready. Drawing from the concept of *the adaptive force*, the CF clearly value the soldier's adaptability to the full spectrum operating environment (DLCD, 2006). Perception system adaptability is also an important research area that will help to increase system robustness and speed the integration of robotics into the CF.

5.1 DRDC perception research

DRDC researchers have identified five deficiencies in state of the art perception systems, seen below, that motivate our work:

- Perception systems are designed for a specific environment with known conditions and are prone to failure when these conditions are not met.
- UxVs rely on GPS data to provide accurate position estimates. In the absence of GPS, standard pose estimation errors grow unbounded, making it impossible to map an environment accurately.
- Perception and localisation sensors are prone to failure and/or sensitive to environmental effects (dust, rain, etc.). Multi-sensor systems have not been properly exploited to handle performance degradation or sensor failure.
- Current technologies can produce accurate maps for short distances (unaided by GPS), but become inaccurate over large scales, due to errors in the pose estimate. Loop detection techniques that recognise places previously visited can be used to correct these large maps by imposing rigid constraints on a probabilistic map.
- Traditional UxV mapping systems rely on ranging devices to provide a geometric representation of the environment. Sensor accuracy and inaccurate pose estimates limit the effective range of these devices, which in turn limits the speed that the UxV can safely travel.

DRDC Suffield is conducting research to specifically address the deficiencies of perception systems stated above. Motivated by the desire for adaptability, AISS researchers are addressing these problems through the application of probabilistic models and learning systems to the perception system. The remainder of the section discusses current and future AISS perception research.

5.1.1 Terrain mapping

The DRDC terrain map fuses data from various range sensors with a pose estimate from DGPS and IMU data to generate a grid based map that estimates terrain height (Broten et al., 2006). This map is processed into a UxV dependant *traversability map* that encodes the ability to traverse a given cell from slope, step height, and roughness statistics (Collier et al., 2006). Path planning algorithms, such as those described in Section 7, use this map to determine the optimal path for traversal. Sensor and pose estimate inaccuracies hamper this strategy's effectiveness and limit the speed at which the UxV can travel safely. Learning algorithms that extend the terrain/traversability map beyond the sensor field of view using colour imagery are currently being investigated by AISS (Broten and Mackay, 2009).

For multiple DOF vehicles capable of changing their geometry to overcome obstacles, the aforementioned traversability map is insufficient. Instead, it is necessary to model the interactions between the robot and its environment using a dynamic physics-based modelling engine, as these interactions are impossible to compute in closed form. DRDC has developed such a world representation that models the complex physical interactions between the robot and its environment, allowing complex behaviours to be evaluated in simulation before the control signal is applied to the real robot (Li et al., 2009). Section 6.2 describes this system in more detail.

Future terrain mapping work will focus on enhancing these capabilities through the incorporation of new sensors and learning algorithms.

5.1.2 Simultaneous localisation and mapping

SLAM algorithms concurrently estimate a robot pose and a map of unique environmental landmarks using probabilistic means. This is done with a prediction step where a new vehicle pose is estimated and an update step where measurements of landmark locations from a highly accurate sensor or sensors are used to correct for the errors in the prediction step. The landmark locations and vehicle pose are part of the SLAM state vector and are estimated in each update step.

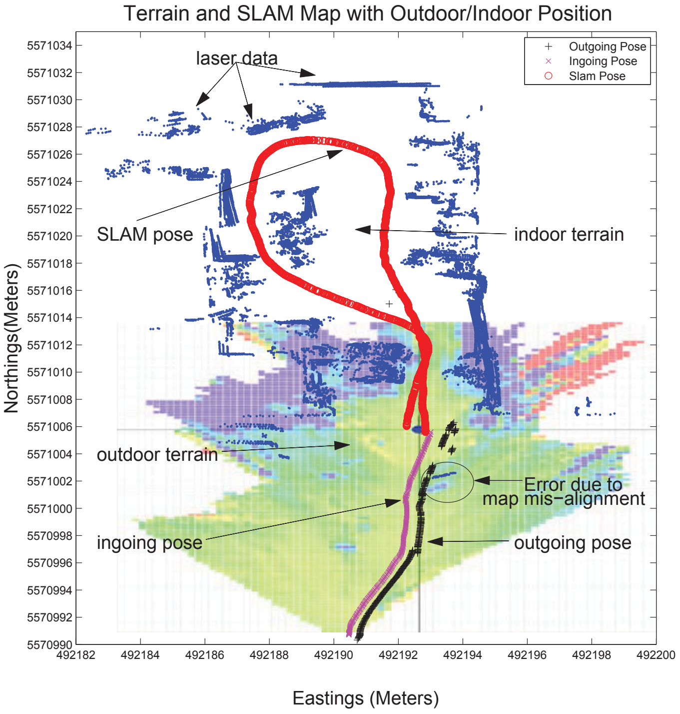
AISS developed a monocular camera-based SLAM system (MV-SLAM) that used an extended Kalman filter (EKF) to track scale-invariant-feature-transform features across video frames and estimate the camera pose and the position of the features. While the target application was aimed at UAVs, the technology is directly transferable to UGV systems. The system performed well and was able to provide an accurate estimate over small areas (tens of metres), provided there was a rich feature set and sufficient overlap between image frames. In addition, a laser-based EKF SLAM system was developed that tracked laser features providing 2D pose estimates for indoor environments. This system was integrated into an indoor/outdoor perception system discussed in Section 5.1.3.

Future work will focus on improving these technologies by combining data from multiple sensors to create a more robust system. In addition, appearance-based methods that use place recognition techniques from computer vision will be used to perform loop closing, thus improving SLAM accuracy over large areas. Learning methods will be integrated to adapt the SLAM algorithm to its changing environment and to increase system robustness. Processing constraints further hamper SLAM systems and impose a maximum velocity on the UAV. Recent advances in graphics processing unit (GPU) architectures and development environments have made GPU programming accessible. SLAM techniques could see a dramatic processing improvements through the use of GPU techniques.

5.1.3 Learning and adaptation

DRDC developed a perception system that adapted to a changing environment at run time (indoor/outdoor) through the use of vision and learning techniques, as seen in Figure 6 (Collier, 2009). The system used the terrain map described in Section 5.1.1 when operating outdoors and relied on accurate GPS and IMU sensory data for its pose. When transitioning to indoor environments, the perception system automatically switched (via a classification algorithm) to use an EKF-based SLAM algorithm. Classification was performed using a feed-forward neural network or support vector machine supervised learning system. Numerous image features and learning techniques were used to perform classification.

Figure 6 Indoor/outdoor mapping using learning to switch the perception system when the vehicle moves from outdoor to indoor (see online version for colours)



Researchers are currently developing a fault-tolerant state-estimation framework based on multiple ranging techniques (e.g., stereo, scanning LIDAR; stereo SLAM; monocular SLAM; structure from motion), an inertial measurement system and GPS. The goal is to produce a fused estimate of the vehicle and surface positions in the presence of sensor or algorithmic failures. Range data is used to produce a six-DOF ego motion-based state estimate in realtime that is fused with the IMU and GPS state estimates. Active fault-recovery algorithms are an essential element of this work.

6 Control for UxV autonomy

The control problem for UxVs operating autonomously in complex environments is best described by two requirements. First, is the well understood requirement for robust stability and performance of an individual robot operating in a world free of constraints or obstacles. The requirement implies that the control algorithm provides vehicle stability and performance according to specified performance criteria, despite changes in environmental operating conditions such as temperature, external disturbances such as wind gusts, degradation of vehicle actuators and sensor information, and changing vehicle parameters during operation such as weight due to fuel or payload considerations.

The second requirement is the successful operation of a robot in a complex environment cluttered with obstacles and walls, an especially challenging requirement where a collision or hanging the vehicle on an obstacle can lead to mission failure. It is this second requirement that extends the traditional control problem definition to address UxV autonomy for dismount operations. The following section discusses the challenges and trade-offs of UxV control for UAVs and UGVs.

6.1 Control synthesis and analysis: robust stability and performance

Control system synthesis and analysis tools are well established for UAVs, but much less so for UGVs. Automatic control systems play a critical role in numerous industrial applications. Specifically, in aerospace applications, control systems are used for flight controls of inherently unstable aircraft. These and numerous other examples of success exist as a result of R&D activities that have yielded a theory and tools that handle many inputs, many outputs, complex uncertain dynamic behaviour, difficult disturbance environments, and ambitious performance goals. One might expect to apply existing control strategies used for UAVs directly to the mobility problem for UGVs. However, it is important to note that:

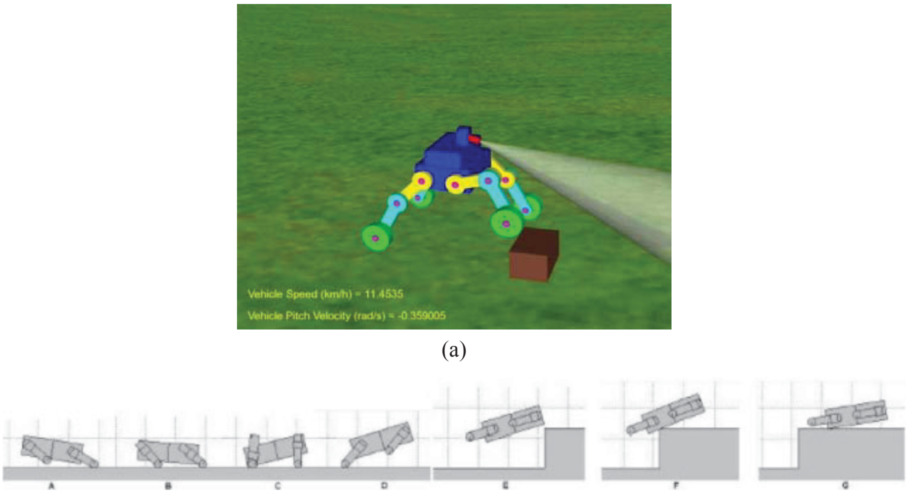
> "the control needs of some engineered systems today and those of many in the future outstrip the power of current tools and theories. This is so because our current tools and theories apply directly to problems whose dynamic behaviours are smooth and continuous, governed by underlying laws of physics and represented mathematically by (usually large) systems of differential equations. Most of the generality and the rigorously provable features of our methods can be traced to this nature of the underlying dynamics." [Murray, (2003), p.30]

The requirement for UGVs to operate in highly complex unstructured environments suggests skilful interaction and contact with obstacles to successfully negotiate difficult terrain. However, much of non-linear control theory relies upon differentiation. This assumption translates well to UAV control where the underlying motion of the aircraft is smooth and continuous. Unfortunately, where contacts are made and/or broken with robotic vehicles that walk, gallop, jump, or change shape to interact with their world, the governing equations of motion become discontinuous. Thus, the assumption of differentiability of the equations of motion is no longer valid, which explains the limited success in application of non-linear control theory to the UGV control problem.

6.2 Sensing, control, and motion in complex environments

To fulfil the second requirement of the UxV control problem, algorithms to control vehicle dynamics and behaviours must be mated with relevant perceptual information allowing the UxV to interact intimately with its surroundings and produce meaningful motion. For the most part, use of open-loop behaviours, which do not close the control loop with world representation information, are unable to meaningfully manoeuvre UxVs in the world. For a closed-loop system, perceptual information must be made available to the controller. This is most certainly the case for UGVs, whereas UAVs only require a simplified world representation to operate meaningfully in the real world. UAVs can be more reactive in their behaviour whose performance specification can be reduced to obstacle avoidance along a GPS waypoint path. Thus, the focus of this section is the world representation required for UGV locomotion. However, it is important to note that additional perceptual information may be required to aid in achieving UxV mission objectives and provide soldier situational awareness.

Figure 7 (a) MHT model stepping onto an obstacle in a physic-based representation of its environment based on relevant geometric features (b) simulation of PAW behaviour used to jump onto a similar sized obstacle (see online version for colours)



(a)

(b)

There is currently a disconnect between the information provided by perception systems and that which is required by the locomotion system for controller synthesis. Mathematical models are essential in the analysis and design of traditional control systems and are indispensable tools to the controls engineer. A logical extension would be to embed a mathematical modeller in an autonomous system. To this end, AISS is using Vortex by CMLabs Simulations Inc., a physics-based engine, to act as an onboard modelling tool. To fill the gap between the real world and the controller, geometric environmental features are extracted into a world representation, whose coordinates are passed to the mathematical modeller. A UGV model that includes its dynamics, is positioned into this world model (Figure 7). This model now contains sufficient information represented in a meaningful mathematical framework such that it can be used by intelligent mobility algorithms (Trentini et al., 2007).

6.2.1 Intelligent mobility algorithms

Intelligent mobility algorithms seek to exploit available world representations of the environment and the inherent dexterity of the platform, allowing the UGV to interact with its surroundings and produce locomotion in complex terrain. Intelligent mobility uses control, sensing, and learning algorithms to control vehicle dynamics, extract measured variables from the world, and learn by experience. A framework for reasoning and planning in these unstructured environments requires new mathematical concepts that combine dynamics, logic, and geometry in ways that are currently unavailable (Murray, 2003).

6.2.2 Measured variables from complex environments for locomotion

In the practical application of control theory, determination of the controllable and measured variables is performed to make the system behave in a desired manner. For traditional control problems, these relationships are fairly intuitive, but become more abstract where higher levels of control are needed to produce improved mobility characteristics.

Here, intelligent mobility algorithms must select the variables that should be measured from the world in an effort to move the UGV successfully through its environment. The measured environmental variables change depending on the specific UGV, the vehicle speed, modes of locomotion, and mobility objectives. Specific examples of measured variables include footfall distances for galloping, gap crossings for jumping, hill grades for energy management, or clearances for shape-shifting manoeuvres. For example, during the course of its approach (Figure 7), the MHT must calculate the step height to raise its leg to step onto and over an obstacle. For a similar sized step and the much smaller PAW vehicle, also in Figure 7, the PAW must be made to calculate the footfalls necessary to store and release the required energy at just the right time and place to enable it to jump onto the ledge (Harmat et al., 2008).

7 Dynamic path planning

For UxVs to provide credible dismount support, they must be capable of executing robust manoeuvres. The previous sections expressed the need for enhanced mobility and stressed the importance of meaningful motion control through an interaction with relevant perceptual information from the environment. Any level of planning for these more capable UxVs must somehow exploit the dynamics of the vehicle in order to generate paths that incorporate more robust manoeuvres. The following describes DRDC Suffield's current approach to path planning and places in context the technical challenges that must be overcome to achieve this end.

7.1 Current path planning

DRDC Suffield's Raptor vehicle controller implements an event-based publish/subscribe paradigm using the architecture for autonomy (AFA), an hierarchical collection of modules built upon the Miro framework and CORBA notification services (Broten et al., 2006). Two AFA modules embody vehicle path planning, FindPath and GlobalTraverseMap. The FindPath planner adapts of Koenig's D*Lite planner, an efficient replanner that combines aspects of A*, the classic AI heuristic search method, and incremental search to plan near-optimal paths in partially known environments (Koenig and Likhachev, 2002). Initially, D*Lite finds an A* path through the environment using *a priori* information. As the vehicle attempts to follow the planned path, D*Lite discovers obstacles and must replan; a process at least ~2 orders of magnitude faster than repeated A* searches and at least as efficient as D* (measured by the number of nodes interrogated to find a goal path). In order to replan efficiently, D*Lite maps the traversal cost for each visited grid cell. In the AFA implementation, the GlobalTraverseMap maintains this traversability information. The FindPath module polls the GlobalTraverseMap for the vehicle's position and the traversal metric contained in cells neighbouring the vehicle's current position. Splitting the implementation of the D*Lite planner into the GlobalTraverseMap and FindPath modules, running in separate multithreaded processes, allows the GlobalTraverseMap to receive update events while enabling FindPath time to plan.

7.2 Sensing issues

The Raptor uses a sick laser rangefinder as its primary range sensor. Given the mounting geometry on the Raptor and the intrinsic limitations of the laser rangefinder, the maximum sensing distance is ~20 to 25m, too myopic to enable the planner to identify obstacles in the far field and replan a path around them while travelling at anything other than low speed (Broten and Collier, 2006). For this reason the Raptor's current speed of operation is ~2.8 m/s. At this speed, our system works plausibly well, but this is too slow to be militarily relevant. How fast can an autonomous vehicle drive? Two conditions combine to dictate the maximum speed at which a UGV can travel (Kelly, 1995):

- the maximum range at which obstacles can be identified
- the distance required to panic stop.

For onboard sensors, the limiting distance on obstacle identification is a function of the sensor's mounting geometry and the intrinsic properties of the sensor. Assuming that an obstacle can be perceived at a distance d in front of the vehicle and that the vehicle is travelling at a constant speed v then the vehicle will reach the obstacle in time $t_d = d/v$. This is a lower bound on the time available to either plan a new path manoeuvring around the obstacle or come to a stop to avoid collision with it. Clearly, the time required to panic stop, t_s, will be a function of the vehicle's speed, the terrain, and the vehicle's intrinsic (tyres, brakes, suspension, inertia, etc.) characteristics. However, we can say with absolute certainty that if the vehicle is heading towards an extended obstacle and $t_s > t_d$, then it will crash. We have shown previously that for DRDC's Raptor vehicle, at even moderate speeds of ~10m/s, stopping distance alone can easily exceed the maximum range of the SICK laser range finder guaranteeing collision (Broten et al., 2008).

The preceding arguments with respect to sensing are an over simplification of the problem, as there are other delays involved in DRDC's AFA. Any delay contributes to an overall shortening of the time window between the sensing of a potential obstacle and the classification of that obstacle in the GlobalTraverseMap, and only at that point can a replanning episode be triggered. At present, we do not know how significant these delays are. However, the most significant delay between the sensing of a potential obstacle and the generation of a steering command designed to avoid collision with the obstacle is likely the delay that planning incurs.

7.3 *Increasing vehicle speed*

To safely increase the vehicle's speed or enable more aggressive manoeuvre in general, the planning horizon must be increased. The sensing range must be increased to identify obstacles farther out, thus giving the vehicle more time to manoeuvre, and/or the planning time must be decreased. How can this be achieved? In the context of onboard sensing, the terrain map can be extended using another sensing modality that sees into the far field to map terrain elevation data in the near field into the far field. Colour information from an onboard camera has been used to map near field terrain elevation data into the far field, beyond the range of the LRF (Broten and Mackay, 2009). This technique is not without problems, principally, the sparseness of data in the far field due to the non-uniform coverage of the ground plane. Another approach to increase the planning horizon is to use UAV over-watch to extend look ahead (Thrun et al., 2003).

A tighter coupling between sensing and planning could decrease the time devoted to planning. The GlobalTraverseMap and FindPath modules are candidates for collocation under CORBA. Essentially, they would reside on the same node, in the same address space, and communicate as if using shared memory. This would effectively remove the overhead incurred between modules communicating via an event channel.

Finally, planning incorporating vehicle dynamics has the potential to reduce planning time and produce plans that are physically realisable. Even in a quasi-static case, there are areas of the GlobalTraverseMap to the immediate right and left of the vehicle location that are not reachable; the vehicle simply can not turn sharply enough or translate sideways. Increasing the vehicle's speed exacerbates the situation; less of GlobalTraverseMap is physically reachable. Since a large fraction of grid cells in the GlobalTraverseMap are not physically reachable, why include them in the planning space? It would make sense to use a model of the vehicle's dynamics to reduce the number of grid cells that need to be examined by the planner. Planning in *manoeuvre space* seems to be a promising approach amenable to both UGVs and UAVs (Frazzoli, 2001).

8 DRDC vision

The following section discusses recent and successful proposals for Advanced Research Projects (ARPs) that are funded by DRDC and approved by military sponsorship and review.

8.1 Emerging robotics for protection

A focus of UGV research at DRDC Suffield is to improve the mobility performance for human-scale robots operating in complex urban terrain. The current MHT prototype, equipped with basic mobility behaviours, will communicate with a leader. The objective is to increase the survivability of dismounted soldiers during urban operations through the use of standoff robotic technologies including CBRNE detection, ISR, weapons, supplies, etc. The robust MHT prototype capable of untethered long endurance operations will follow a leader on smooth terrain. The MHT robot is capable of traversing linear step features under teleoperation, as shown in Figure 5(c), which is a topic of future research.

8.2 Adaptive SLAM

Improved SLAM techniques will extend the range and robustness of UxV perception systems particularly in GPS denied environments. The project will develop adaptive SLAM techniques allowing perception systems to operate in a changing environment by modifying algorithm parameters and performing large loop-closing using appearance-based methods. Multi-sensor fusion and fault detection techniques will be incorporated into SLAM algorithms to improve robustness and decrease the incidence of failure.

8.3 mUAV over-watch

Mini-UAVs (mUAVs) have the capability to provide low cost surveillance, without adding personnel, in areas where medium altitude UAVs cannot operate. This project will develop methods enabling mUAVs to navigate in GPS denied areas while avoiding obstacles. Reduced operator workload and increased situational awareness will be achieved through returned stabilised imagery. The technical solution will exploit the advances being made in mapping and path planning algorithms designed to guide a vehicle through environments littered with obstacles. This requires construction of a limited model of the environment and may be further exploited to provide autonomous behaviours such as *return to me*. Obstacle avoidance behaviours require a compromise between flight performance, available onboard processing power, and intelligent reactive behaviour.

9 Conclusions

In this paper, in the context of the CF capability model (*sense*, *sustain*, *act*, *shield* and *generate*), putative roles for UxVs in support of dismounted soldiers have been introduced. A number of technical challenges that must be overcome before UxVs can credibly support dismounts have been examined in detail. Researchers at DRDC understand these challenges and are directing their efforts to address these problems. Three new projects have been approved looking at the mobility of legged vehicles for dismount support, adaptive SLAM technologies for large scale mapping, and man-packable mUAV technologies for ISR. While separate programs, these technologies are complementary and will push the state of the art in dismount/UxV teamwork for future CF capabilities.

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