Autonomous land vehicles

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Abstract: This paper describes the current state-of-the-art in autonomous land vehicle (ALV) systems and technology. Application of ALV systems span relatively structured domains in mining, cargo handling, and agriculture, through potential application in very unstructured tasks such as bush fire fighting, forestry, and defence. In this paper, four key functional ALV technology areas are identified and discussed. These are mobility, localization, navigation, and planning. The essential conclusion of this paper is that the necessary sensors, algorithms, and methods already exist to develop, demonstrate, and commercialize ALVs in many applications.

Keywords: autonomous land vehicles, mobility, localization, navigation, planning

1 INTRODUCTION

Around the world there are many current research and development projects aimed at developing autonomous land vehicle (ALV) technology. These range from projects in automated container handling, through applications in mining and agriculture, to large projects in military land vehicle systems. Work in ALV systems has benefited from a number of factors. Firstly, in contrast with the air or subsea domains, there are many and varied commercial applications of land vehicle systems. Secondly, there is an intrinsic demand for systems to be unmanned as many applications are either repetitive (moving containers and ploughing a field) or dangerous (mining and firefighting). Finally, in many applications the vehicle to be employed is relatively expensive and so the additional cost of the automation components is modest relative to the gains made by better utilization of the platform. Examples of a number of land vehicle systems are interspersed through this paper, with an emphasis on civilian rather than military systems.

The main focus of this paper is in surveying ALV *technology* rather than specific applications. This is done through looking at a number of functional requirements. Broadly, the functional requirements of an ALV system can be broken down into five main areas. Figure 1 shows a schematic diagram of the relationship between these different functional components.

Mobility captures the physical mechanics of the vehicle, the interaction of the vehicle with the terrain, and the effect of control of the vehicle on the terrain. Mobility is viewed simply as the effector of the overall system, the observable outcome of the system as a whole.

Position determination or *localization* provides estimates of the location, attitude, velocity, and acceleration of the vehicle. Importantly, localization is an output-only function when viewed by the rest of the system. This means that the development of a localization ability can often proceed independently from that of other system components.

Navigation on a small scale, or simply *navigation*, is concerned with the acquisition of, and response to, external sensed information. The navigation function takes input from sensors observing the operational environment. It must use this information to create an internal representation of the environment that can subsequently be used in the execution of a mission.

Navigation on a large scale, or *mission and task planning*, functionally generates trajectories, behaviours, or way points for the system as a whole. It has no direct links with either sensory input or controller output. However, it clearly must use an understanding of these, in conjunction with prior maps and defined mission objectives, to produce appropriate navigation commands.

Communication provides the link between the vehicle and any remaining elements of the global

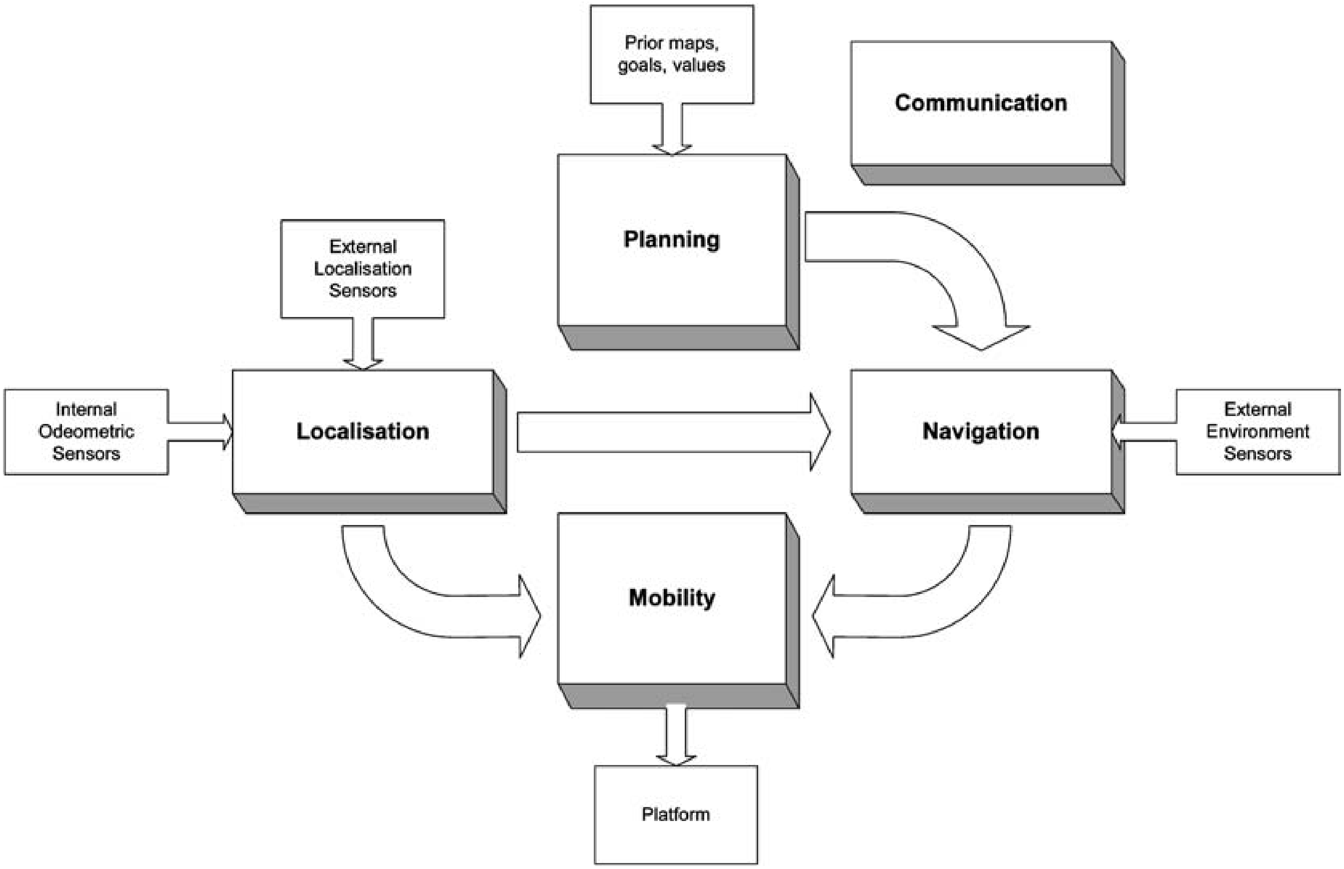

Fig. 1 The relationship between the five key functional elements of an ALV system

system, including other vehicles and operators. There is no reason to suppose that a truly autonomous ALV should not share the same communication medium with other systems and indeed be interoperable with more conventional platforms.

While the specific payload and mission to be executed must define the overall system requirement, it does not, and should not, impinge on the vehicle functional elements; the need for mobility, localization, navigation, and planning abilities remains regardless of the mission. Indeed, it is to be expected that a common realization of these four functions would serve a wide variety of payloads and missions. The structure and role of the mission and task planning function are clearly critical in enabling this degree of flexibility. The ideal mission planning system would allow a range of disparate missions to be considered with a range of operational constraints and subjective mission values accounted for.

In the following, each of the five functional technology areas is addressed separately. Of the five functional technologies identified, the areas of mobility and communication are considered to be mature and to exist in a deployable form. Localization is also mature in most domains although terrain-aiding methods for land vehicles still require some development. Mission planning methods are also considered to be mature although their application to specific missions still needs to be demonstrated. Navigation, the perception of a local environment and the use of this in motion control, is probably the least well-demonstrated area of ALV systems. Here, there are still significant issues in defining a terrain representation and identifying an appropriate methodology for fusing data in this representation to the level of integrity and robustness required by an autonomous system. However, currently demonstrated methods show considerable promise in delivering a deployable system.

2 MOBILITY

Mobility is concerned with both the design and the motion control of mobile vehicles. Design focuses on determining what kinematic and dynamic arrangement of wheels, tracks, legs, or other mechanism best achieves a particular motion. Design must be set

Fig. 2 The FRAIT 80 autonomous cargo-handling vehicle [1].

against the requirements of the environment and a task specification. In contrast, motion control is concerned with the analysis of a particular kinematic arrangement and, from this, the determination of an actuator control algorithm to achieve a required motion. The process of design synthesis, analysis, and control are closely linked.

The design of all-terrain vehicles is a well-understood field in many application areas. Well-established techniques exist for describing mobility and for designing vehicles with specific mobility characteristics. The commercial realization of such vehicles is pervasive: in military systems such as tanks, armoured personnel carriers (APCs), and many other vehicles, and for civilian vehicle systems in applications such as agriculture, mining, and construction. The last decade has also seen some innovative work in understanding the mobility of robotic vehicles. This has encompassed both fundamental design issues as well as the development of metrics for describing mobility. With a defined ALV requirement, it is certainly the case that a vehicle meeting any realistically achievable mobility requirements can be designed.

2.1 Motion design

Motion control of all-terrain vehicles is generally less well understood than platform design. The reason for this is simply that, until recently, vehicle control was achieved manually in all but a few cases. However, the work undertaken in modelling vehicle–terrain interaction in conventional vehicles, commercial traction, and motion control systems used on large, manually driven mining and construction equipment and the progress made in the last decade in autonomous rough-terrain vehicles has all but solved the motion control problem. With a given ALV platform, motion control at speed can be performed on any realistic and mission-enabled terrain. The arguments for this conclusion are presented in detail in section 2.3.

There are a number of viable approaches to the design of an ALV platform. The obvious approach is simply to automate an existing platform. This leverages the substantial knowledge embodied in existing manned vehicle system design. However, a key constraint, namely that the vehicle must hold a driver in reasonable comfort, does not exist in an automated system. This opens up a potentially vast range of additional design options from simply having a more compact vehicle to employing a completely different mobility mechanism. It is appropriate to review the design of existing experimental ALV platforms.

2.2 Mobility: design

The design of mobile platforms has received considerable attention in both the autonomous vehicle and the broader manned vehicle design community. The mobility design issue has been considered at two levels:

(a) the design of locomotion methodology, including the choice of wheels, tracks, legs or fins as a propulsion mechanism;
(b) the optimization of a specific propulsion method, e.g. the choice of size, number, spacing, and tractive effort of a wheeled platform.

The systematic choice of propulsion method is a considerably harder and more generic problem than simple optimization of a design.

2.2.1 Design choice

There have been two notable and quite different efforts addressing the issue of design choice in autonomous vehicles.

The first is the work of Joel Brudick [2] which develops a very general mathematical framework for the design and analysis of mobility mechanisms. The method employs geometric and kinematic methods to study the basic locomotion problem. The properties of connections lead to simplified results for both the dynamics and the controllability of locomotion systems in general. Notably the method can deal with undulatory motion generated by coupling internal shape changes to external non-holonomic constraints. This is characteristic of many all-terrain articulated vehicles.

The second, and quite different in character, is the work of John Bares at Carnegie Mellon University (CMU) in the development of a software system for the synthesis and analysis of mobility mechanisms called Darwin2K [**3**]. Darwin2K is an example of a general approach to the design of robotic mechanisms (including land vehicles). It consists of a configuration synthesizer and an analysis tool. The synthesizer, called the evolutionary synthesis engine (ESE), uses the simulation tool to evaluate the performance of each new configuration it creates. The ESEs evolutionary algorithm synthesizes robot configurations by applying genetic operators to one or more existing parent configurations. The performance of each new configuration is evaluated through simulation against a task according to a number of defined metrics. Existing metrics include power consumption, task completion time, robot mass, stability, actuator saturation, and collision measurement.

Practically, the approach taken by Darwin2K is most appropriate to the design choice and synthesis process encountered in land vehicle systems. The system has the potential to allow systematic study of platform design choices. However, the system lacks elements of more rigorous dynamic analyses that are required by land vehicle systems (see reference [**4**] for an example and possible general approaches to this problem).

2.2.2 Design optimization

Once a propulsion method has been chosen, it remains to synthesize, select, and optimize the mobility mechanism. There has been a substantial amount of work undertaken on this problem in both the robotics and the manned vehicle domains. Here the focus is only on wheel and track mobility design methods (legs, snakes, and other more exotic mobility methods are not considered further here).

The optimization of the geometry of many-wheeled vehicles has been extensively studied in the car industry. The books by Wong [**5**], Ellis [**6**], and Dixon [**7**] are the definitive texts in this area. Ellis and Dixon in particular deal with the optimization of the number, geometry, and layout of wheels for different types of road and off-road conditions. A key element of many of these analyses is the understanding of vehicle–terrain interactions through pneumatic tyres and through the effects of the terrain itself. This is particularly addressed in the books by Dixon and by Wong. The availability of commercial software packages for the detailed analysis of vehicle kinematic and dynamics is now common place. The best of these is probably ADAMS which provides modules for modelling of tyres, different terrain types, and suspension systems. ADAMS also provides performance analysis in terms of tractive efforts, speed and accelerations, forces, and handling.

The book by Wong provides the most comprehensive treatment of off-road mobility. Standard techniques for defining mobility through a 'mobility map' and 'mobility profile' are described. A mobility map consists of a standardized land area in which terrain surface composition, surface geometry and vegetation are defined. The NATO reference mobility model (NRMM) defines three terrain categories: area patch, linear feature segment (such as a stream, ditch, or embankment), and road or trail segment. The NRMM then defines mobility simulations for determining the following:

(a) maximum speeds and maximum turning of a given vehicle configuration;
(b) tractive effort available for overcoming resistive forces due to sinkage, slope, obstacles, vegetation, etc;
(c) vehicle manoeuvrability to avoid obstacles, and to accelerate and decelerate between obstacles;
(d) driver tolerance to ride discomfort (not relevant for ALVs).

These, together with the mobility map, provide a precise definition and means of computing mobility for off-road vehicles.

In the robotics community there has also been some important work in characterizing mobility. Notable is the paper by Alexander and Maddox [**8**] describing a general approach to the mobility characterization of many-wheeled vehicles using generalized coordinates, rolling, and rigid-body constraints. Also important was the work undertaken at CMU by Muir [**9**]. Together these two papers established the groundwork for much subsequent work in the design of indoor mobile robots and also path planning and control for such vehicles. However, neither of these addressed the issues of vehicle dynamics (characteristic of high-speed motion) or motion on rough terrain.

Off-road tracked vehicles have also been the subject of extensive study. Wong [**5**] again provided the most comprehensive treatment. The main interest has previously been in skid-steered tanks [**13**]. However, articulated tracked vehicles have also been studied and offer many performance advantages over skid-steered platforms. In both cases, the main defining parameters are the contact area, mass inertia, and centroid of tractive effort. Some relatively simple design rules are available for the design of track systems. The skid properties of such vehicles on a

Fig. 3 DEMETER Autonomous Harvester [**10**] (reproduced with permission). See also references [**11**] and [**12**] for other autonomous farming vehicles

variety of terrain and obstacle types are also well documented. Many of the same mobility models as used for wheeled platforms are equally as applicable to tracked vehicles.

Wong defined some basic rules for the selection of vehicle configurations for off-road operations (see reference [**14**], p. 275; see also reference [**15**]). In particular, the effects of mission requirements and terrain conditions on optimal vehicle configuration are identified. The process adopted consists of a systems analysis using mobility maps and mobility profiles on which different candidate vehicle configurations are analysed with respect to an envelope of mission characteristics. When taken together with the current tools available for synthesis (Darwin2K) and analysis (ADAMS), this approach offers a systematic means of defining and optimizing ALV mobility characteristics.

2.3 Mobility: control

The automatic or autonomous control of vehicles at speed and on rough terrain has been studied in both manned and robotic arenas. As an example in the manned vehicle domain, very large mining trucks are now normally driven 'fly-by-wire'. Trucks such as the Haulpack 930E are driven by in-hub vector a.c. drives at speeds approaching 50 km/h on rough ground with loads of over 300 t. The drives are controlled to provide appropriate traction and braking effort over a range of terrain conditions. In cars, an antilock breaking system (now standard) and newer fly-by-wire controls are increasingly being employed. In other heavy vehicle domains, electric-over-hydraulic and electric-over-diesel controls are also now standard. Detailed models of skidding, slipping, contour, and obstacle negotiation have been developed and a number of books on ground vehicles describe these as part of the standard mobility analysis methods.

In the robotics domain, vehicle mobility control is distinguished from path planning. The normal approach to mobility control is to assume a specified path and then to control the vehicle to follow this path. The path itself is normally specified by a series of way points linked by straight lines, or alternatively smooth splines joining way points [**16**]. The plan may be specified fully in advance or may be changed on a small scale by stretching or movement of way points, or changed on a large scale by addition, subtraction, or recalculation of way points. Path planning is further addressed in section 5.1. Once the path is determined, control of the path can occur either as a steering-only problem or as a complete location velocity controller. Pure pursuit controllers [**17**] in particular are widely used (e.g. Demo II) and considered to be robust to terrain and environment conditions. Pure pursuit controllers correspond to position error feedback of perpendicular path error. Increased performance can be obtained with the use of some path feedforward or through the use of full proportional–integral–derivative (PID) loops.

At higher speeds and on rougher ground, however, it is essential to incorporate some understanding of the dynamics of the vehicle and knowledge of the interaction between the terrain and the wheels or tracks of the vehicle [**18**, **19**]. This issue has been considered in references [**20**] and [**21**] where dynamic models of increasing complexity were evaluated on a high-speed wheeled vehicle, in reference [**22**] where on-line slip models for tracked vehicles were developed, and in reference [**23**] in which slip models for high-speed articulated vehicles were employed in path control. It is important to note that the types of model used in guidance and control problems must be predictive, in contrast with the simulation-based models used in the synthesis and analysis of vehicle designs.

Robust path control of vehicles on outdoor rough terrains is thus a well-studied subject. Appropriate techniques exist for the control of both wheeled and tracked ALVs, at high speeds and over variable terrain.

2.4 Mobility: vehicles

By far the most common approach to ALV design is simply to automate an existing manual vehicle which has already been optimized for the required task or mission. All early ALV systems followed this route, notably Demo II [**24**] and Demo III, and the Ulysses project (an M113 APC). These cover both wheeled and tracked vehicles in a conventional arrangement. Commercial programmes in automated mining, construction, or agricultural vehicles have also taken this route. The normal mode of automation is to provide straight electric-over-hydraulic or electric-over-diesel control through proprietary hardware and controllers. A significant number of manufacturers now provide an 'automation option' on manual vehicles, notably Kalmar Industries (of Finland) who manufacture container straddle carriers and forestry-logging equipment, Komatsu-Haulpack who manufacture large mining trucks and excavators, and Vost-alpine who manufacture underground mining equipment. Fly-by-wire 'automation options' are also widely available in many manned military vehicles. A number of specialist companies now exist which provide 'off-the-shelf' retrofit automation options to any conceivable manually operated vehicle.

The next step up is the development of ALV platforms based on conventional vehicle design philosophies. Notable is the 'Modulaire' platform developed in the EEC 'Panorama' project in the early 1990s. This consisted of an all-terrain tracked vehicle approximately 3 m in length, 1.5 m in width, 0.5 m high, and capable of speeds of 6 m/s. The vehicle was demonstrated in a number of applications including agricultural spraying and soil tilling, land mine disposal, and military reconnaissance. More recently, the mobile detection, assessment and response system (MDARS) vehicle designed by RST offers a wheeled base similar to a conventional all-terrain vehicle.

The final level is to purpose-design a robotic mechanism directly from mission requirements. There is some excellent basic research going on in this area, notably as reported in references [**25**] and [**26**]. This work addresses many practical issues in the traversability of surfaces including rocks and other geoforms, in the speed and steering on different terrain types, and in mobility on different gradients. The Lunar and Mars rover communities have also developed many innovative vehicle systems, the most widely used being the Russian-designed 'Marsokhod' vehicle.

The Nomad vehicle developed at CMU stands out as one of the most innovative of all recent vehicle designs (Fig. 4). Nomad was developed as a Lunar rover and has been evaluated in trials both in the Atacama Desert and in Antarctica. Nomad's innovative locomotion design features four-wheel or all-wheel drive locomotion, a reconfigurable chassis, electronically coordinated steering, pivot-arm suspension, and body motion averaging [**28**]. Nomad also employs a unique steering system design enabling both skid and explicit steering [**27**]. Notable in the development of the Nomad vehicle has been the systematic use of mobility metrics and configuration analysis in the design and testing of the locomotion system.

Fig. 4 The Nomad platform [**27**] (reproduced with permission)

There is clearly a broad range of possible mobility systems for an operational ALV. Techniques for understanding, developing, and testing mobility metrics are established, if not yet widely used, in robotics. Once requirements for a class of ALV mission objectives are defined, the design and optimization of an appropriate platform should not be considered a technical risk.

3 LOCALIZATION

Localization is the problem of determining the position and attitude of a vehicle with respect to some fixed coordinate system. Localization is a very well-studied problem in a range of air, land, and subsea applications. Notably, reference [**29**] pp. 289–367, and subsequent citations is a particularly good development of the 'standard navigation' algorithms developed for aerospace applications during the 1960s and 1970s. Autonomous localization systems offer additional challenges in dealing with high degrees of sensor uncertainty, in interpretation of terrain and environment observations, and in the need to make robust autonomous decisions on the basis of ambiguous sensor data.

While slow in coming, the use of inertial navigation systems (INSs) in ALV applications is now well established and should serve as a basis for any localization system design. The state-of-the-art in inertial and odometric sensing is described in section 3.2.

The use of the Global Positioning System (GPS) is also now well developed for land vehicles. However, it is essential to recognize and understand that the GPS has many failure modes that make it inappropriate for stand-alone use in *autonomous* systems; in particular, the GPS may fail due to the loss of the line of sight, from the multi-path of the local terrain, and from active r.f. jamming. The GPS can be augmented through the use of pseudolites and alternative precision timing (pps) signals; however, these will have similar failure modes to conventional GPS. The state-of-the-art in GPS and GPS aiding for land vehicles is described in section 3.3.

Practically, therefore, additional terrain-aided navigation methods are required to localize a platform, both globally and with respect to the local environment. Terrain–aided localization methods are well established in robotics. Of particular importance in environments that are generally not know *a priori* is the advent of simultaneous localization and mapping (SLAM) methods. These provide an autonomous platform with the ability to build a map of the environment while simultaneously using this map to localize. SLAM methods in some form will be essential for autonomous localization in off-round and forested operations. The state-of-the-art in terrain navigation and SLAM is described in section 3.4. Finally, the range of sensors that can be used in ALV terrain aiding includes both passive EO and forward-looking infrared (FLIR), as well as active devices such as radar or laser.

The structure and operation of autonomous localization systems are generally well understood. Given requirements for localization performance, accuracy, and integrity, a composite ALV navigation system based on inertial, odometric, GPS, and terrain aiding can be assembled in an appropriative form.

3.1 Structure of localization algorithms

The generally accepted structure of most localization algorithms is shown in Fig. 5. It consists of three parts arranged in a feedback configuration. The *rate sensors* feed forward integrated estimates of vehicle position, attitude, and velocity. These estimates are also fed to an *estimation algorithm* which also takes information from a set of *external sensing devices*. The estimation algorithm produces a set of corrections which are fed back to the rate sensors. The output of the rate sensors is then corrected to reflect external sensor information and yielding a fused localization estimate. This structure embodies a number of important principles.

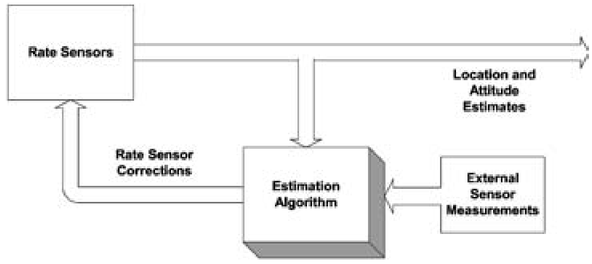

Fig. 5 Feedback structure of localization algorithms

1. *Frequency interpretation*. The estimation algorithm (often a Kalman filter) has a low-pass characteristic. Thus, external sensor measurements appear in low-pass form at the output of the structure. Conversely, the location of the rate sensors in the loop ensure that rate sensor measurements have a 'one minus filter' or high-pass characteristic. Thus, the output of the localization system is high-frequency information from rate sensors together with low-frequency information from external sensors. This accords with common experience; accelerometers and other rate sensors provide measurements of rapid motion, whereas the GPS or other external sensors provide measurements of slowly varying or fixed location. Both types of sensor are essential for successful operation of a localization system.
2. *Fault tolerance*. The structure is such that loss of external sensors or loss of corrections from the estimation algorithm causes the system to run on rate sensing only. This is a robust configuration. In general, rate sensors (such as inertial devices) are internal and not prone to failure, whereas external sensors and algorithms may fail in any number of unpredictable ways. The structure is also naturally amenable to the inclusion of varied and sporadic external correction information, from beacon observations, from terrain observations, etc. As and when external information arrives, a correction to the rate sensors is performed.
3. *Error-corrector structure*. In this feedback structure, the estimation algorithm operates on the *error* between integrated rate information and externally obtained position and attitude, feeding back corrections, rather than absolute quantities, to the rate sensors. The use of error rather than absolute value in the estimation algorithms allows more generic and accurate estimator structures to be employed.

It should be clear from the structure of the localization process and from a frequency-domain understanding of the sensor noise characteristics that both rate sensors and absolute sensors are required to construct a complete localization system.

The algorithm employed in estimation is very often a Kalman filter. However, increasingly full Bayesian algorithms are also being used either in the form of particle filters, or as density function estimators.

3.2 Rate sensing

3.2.1 Inertial sensing

Inertial sensing, the use of inertial measurement units (IMUs), the development of INSs is a mature discipline. There are a number of excellent books on inertial navigation [**30–33**], although these are mainly concerned with the navigation of aircraft and missiles. Inertial sensors have a major advantage in being non-radiating non-jammable sensors which do not rely on any external information to provide estimates of position, attitude, and body rates. The main disadvantage of inertial sensors is the need to provide periodic resetting information to bound error growth. The required frequency of resetting (the rate of error growth in the IMU) is the primary measure of performance in land vehicle applications.

The use of IMUs on robotic land vehicles has been slow in coming. The main reason for this has been cost. Until the advent of low-cost solid-state IMU systems (approximately 6–8 years ago), most inertial systems, of sufficient accuracy to be useful, were far too expensive to be used in mobile robot systems. The exceptions to this employed expensive aircraft grade IMUs in a relatively blind application to provide basic dead-reckoning information (early Defense Advanced Research Project Agency ALV programmes including Demo II are examples of this).

In the last decade, however, there have been huge cost and performance improvements in solid-state inertial systems. Now, IMUs and associated navigation algorithms have been specifically developed for robotic vehicles. Two example models are as follows.

1. *ISIS-IMU*. This is a six-axis solid-state IMU weighing only 250 g and measuring only 70 mm square. The unit is capable of containing attitude drift to approximately 3° in 15 min and can maintain a less than 1 m position error for up to 3 min without external aiding.
2. *DMARS-I*. This is a six-axis IMU incorporating dynamically tuned gyroscopes and pendulous linear accelerometers. It weighs 1.7 kg and has a diameter of 120 mm. The unit is capable of maintaining attitude drift to 0.5° in 15 min and can maintain a less than 1 m position error for up to 15 min without external aiding.

Units such as the ISIS-IMU are now of sufficient precision to allow vehicles to run without any external navigation updates for several minutes. This is often enough to overcome intermittent jamming of GPS or slow acquisition of other landmark data (for example). The ISIS-IMU is currently being used in a number of commercial autonomous vehicle applications. Units such as DMARS-I are an order of magnitude better even than this and could allow high-speed all-terrain vehicle motion without external navigation updates for periods of up to 15 min. The DMARS-I unit is being used in some non-US autonomous military vehicle programmes.

Early use of inertial systems in mobile robotics focused on the use of gyroscopes. The use of low-cost solid-state gyroscopes for outdoor vehicle guidance has been described in reference [**34**]. Subsequently fibre-optic gyroscopes have become widely used; notably units from Andrew and from Hitachi have been employed in various off-road and mining applications (see reference [**35**] Ch. 13, for an excellent summary of gyroscope technology for robotics). As cost and performance have improved, low-cost gyro-compass units (north-seeking gyroscopes) have also been employed in mobile robots (notably in reference [**36**]). Now full six-axis solid-state units (providing both heading and location) have been developed for mobile robots and are being used in commercial autonomous vehicle systems for cargo handling and mining [**37**]. Further developments include redundant (more than six-axis) units for high-reliability and high-accuracy ALV and unmanned air vehicle (UAV) applications [**38**]. A particularly interesting development has been the use of vehicle geometric constraints to bound vehicle motion and thus to improve INS algorithm performance [**39**]. This is one instance of a trend to integrate IMU systems tightly both with other vehicle sensors and with knowledge of vehicle motion characteristics. This tight coupling can substantially increase the performance of a standard inertial navigation unit. An example of tight coupling with GPS and magnetometers can be found in reference [**40**].

The use of INS in ALV applications is now standard practice. Low-cost INS units now provide performance levels that can define the overall system performance for both localization and navigation functions.

3.2.2 Odometric sensing

Odometric sensing includes the use of wheel velocity sensors, ground (radar or laser) Doppler, and steering or articulation angle sensors.

The use of wheel and steer encoders is ubiquitous in robotics, both for low-level closed-loop control and for 'dead-reckoning' navigation. Simple kinematic motion models can be used to integrate velocity and heading measurements from wheel and steer encoders to provide an estimate of the location and orientation of a platform. Estimates are usually subject to substantial error due to misalignment, offsets, and slippage of wheels or tracks. This is particularly true in rough-terrain applications. It is possible to augment basic kinematic models to estimate and correct offset and slippage errors online [**23**], leading to substantially improved performance. When used in conjunction with inertial navigation units, wheel and steer encoders have a second role in making traction, slip, and other terrain characteristics observable. This is essential in guidance functions. An excellent analysis of odometric error can be found in reference [**17**].

The use of odometric Doppler sensors is not common in robotics but is widely used in racing cars and in some mining and military vehicles (see, for example, reference [**41**]). The advantage of such sensors is that they are not subject to slip in the same way as wheel and steer encoders. Doppler velocity sensors may be either r.f. or laser based. They may also be configured as a group to provide vector velocity measurements.

3.3 The GPS and related beacon navigation systems

The use of the GPS has revolutionized outdoor localization in many different domains. The GPS is widely used in the robotics community. The basic theory and methods of GPS-based navigation are well known and so will not be discussed here [**3**, **42**].

3.3.1 GPS performance

The normal GPS is now capable of accuracies of the order of 10 m. The differential GPS is capable of accuracies of better than 0.5 m, and the real-time kinematic GPS is capable of accuracies of around 2 cm. All these systems can be purchased off the shelf with update rates of 10 Hz or better for use in vehicles travelling at speed in open environments.

When more than one GPS receiver is used on a vehicle, accurate estimates of vehicle attitude (to fractions of a degree) can be obtained using a phase comparison. Although this is not yet widely used, it is employed in some air and ground robot applications.

GPS systems can fail in a number of different ways. Most common failure modes involve obstruction of the line of sight to satellites, multi-path from foliage or terrain geometry, and active jamming from other r.f. sources. Even in relatively benign conditions, the GPS will routinely fail for periods of time. In hostile environments, complete loss of the GPS is likely.

There are a number of methods for improving GPS integrity. These include tight coupling with an aiding sensor such as an INS, the use of 'pseudolites', and the use of improved narrower-band receiver designs. However, the essential physics of the GPS mean that other additional navigation sensors and methods will always be required to obtain the level of integrity necessary for deployment of an autonomous vehicle.

3.3.2 GPS aiding

The GPS was never originally envisaged as a stand-alone sensor but rather as a source of external aiding for INSs or Doppler-based navigation systems. GPS-aided INSs are widely used in military systems (see in particular the systems described in references [**43**] and [**44**]). Aiding is normally implemented in a 'loose-coupled' form in which position and velocity outputs from the GPS are fused directly with IMU measurements (in the form of Fig. 5). Many 'off-the-shelf' loose-couple GPS–INS packages are now available.

Integrated GPS–INS units are seeing growing use in ALV systems as a means of increasing navigation systems integrity [**9**, **37**]. An outstanding challenge is to perform 'tight coupling' of the GPS and IMU in the context of land vehicles. Tight coupling means that the raw pseudoranges from the GPS are employed directly in the navigation filter and IMU information can, in principle, be used to drive the GPS correlators. This has the advantage of much higher integrity for the navigation loop and the ability to use a narrower-band (and thus less jammable) GPS correlator. In land vehicle applications the goal is to also integrate other vehicle-specific information at this level to improve navigation system performance and integrity further. A number of groups are pursuing this goal for land vehicle applications.

The GPS can also be aided by other types of rate sensor including Doppler laser or radar, visual or radar odometry, or wheel and steer encoders. Generally the same principles of fusion (reference [**29**], Ch. 6, still provides one of the best design guides to aiding systems including such issues as error budgeting and integrity).

3.3.3 The use of pseudolites

Pseudolites are artificial 'GPS satellites' transmitting the same timing and location information as the conventional GPS constellation but more often being ground based or occasionally air based. The purpose of pseudolites is to provide additional pseudorange information in cases where the normal constellation is either obscured or otherwise unavailable. Pseudolites are being developed primarily for use in high-integrity applications such as aircraft landing. However, they have also seen use in mining and other land vehicle applications where constellation obscuration is a problem. Stanford Telecom is one of the leading developers and suppliers of pseudolite technology.

The general principle of pseudolites is also encapsulated in the precision timing signals (pps) employed by military (Link 16 or The Joint Tactical Information Distribution System) and occasionally civilian communication systems. Here, the communication standard defines a pps signal to be transmitted in every communication package. This provides a 'pseudorange' between transmitter and receiver. In Link 16, for example, the protocol also requires the communication of transmitter location (effectively an ephemeris) which allows registration of targets across platforms. Together, each transmission site therefore defines a pseudolite as an integral part of the communications standard. In terms of ALV navigation, this provides a flexible and robust method of providing augmented positioning information. It is possible to envisage 'communication marbles', periodically dropped by an ALV, serving also as location beacons, or in a multi-vehicle configuration, many vehicles each providing location information for each other, and, in a mixed force operation, information also coming from air vehicles or indeed individual human field operatives.

General principles and use of pseudolites is well understood, even if not commonly recognized in the robotics area. It can and should be exploited in ALV localization schemes.

3.4 Terrain navigation methods

For long-duration GPS outages (and indeed as an essential adjunct to a GPS navigation loop), terrain-aided navigation methods are appropriate. Terrain-aided navigation methods use an external sensor capable of observing terrain features in the vicinity of the vehicle. By comparing observed terrain features with terrain features held in a global prior or constructed map, the navigation algorithm constructs an estimated position and attitude error which is used to correct the inertially indicated values in the form of Fig. 5.

Terrain navigation techniques are necessarily more complex than inertial-only or GPS-based navigation methods. Some of the key issues are the type of sensor employed, the type of terrain feature used as a landmark, the construction of the global map, the algorithms used for feature extraction, and the complexity of feature to map matching. These issues are briefly discussed below.

3.4.1 Map-based terrain navigation

Map-based terrain navigation systems assume the existence of an *a priori* terrain map in some form. The best known example of map-based terrain navigation are TERCOM and TERPROM. These employ a digital terrain elevation data (DTED) map sensed by a radar altimeter to provide corrections to an inertial navigation system [**45**]. TERCOM is used in Cruise missile navigation, and TERPROM is used in low-altitude aircraft navigation and collision avoidance. DTED maps are now normally constructed from high-altitude synthetic aperture radar surveys. Resolution is normally 10–25 m but maybe as high as 1 m.

The direct use of DTED maps in ALV navigation is difficult as salient features or landmarks at ground level are quite different from those viewed from the air. There have been some efforts to use DTED information in land vehicle navigation, notably in the TRACER (UK Ministry of Defence) and Ulysses (Singapore) programmes. While DTED can provide global location information at a coarse scale, local navigation is dominated by much smaller features. Fusion of local navigation landmarks with DTED data is still an open issue.

Map-based localization algorithms using local features and landmarks are commonly used in robotics. However, most algorithms have only been demonstrated in indoor environments. The Kalman filter is the most widely used map-based localization algorithm [**46**]. It has also been used in some demanding outdoor localization problems [**1**]. More recently, full Bayesian navigation methods have been demonstrated [**47**]. Bayesian methods potentially offer a number of advantages over Kalman-filter-based methods in dealing with near-field landmarks and complex sensor modelling problems. Bayesian methods are often implemented using particle filters or likelihood function estimators. Similar techniques are also now being applied in complex target tracking problems [**14**] (see also reference [**48**]). Other probabilistic landmark methods have also been developed (see reference [**49**] for a recent example).

Other more qualitative approaches to navigation have also been investigated [**44**]. These include the use of nodal topological maps that potentially avoid the need for metric localization information. However, even topological maps require some local knowledge of 'distinctive place' landmarks.

The essential problem with outdoor map-based terrain navigation methods is the requirement to obtain an *a priori* map with which to compare observations. The best practical solutions to the outdoor map-based navigation problem have been approaches that employ 'global features' and in particular the use of visual or panoramic horizons [**50**, **51**]. Although not widely used, these methods are quite innovative and appropriate to ALV applications. Further, because of the far-field nature of observations, they offer an opportunity for fusion and registration with independently acquired DTED information.

3.4.2 Map construction and SLAM

The use of trees, rocks, terrain contours, or other small-scale near-field features as landmarks for navigation is an obvious step in terrain navigation. The use of small-scale features for localization and navigation is common in indoor environments. However, navigation outdoors is substantially more complex because of the lack of well-defined structure or features in natural environments. It is not realistic to envisage the construction of an *a priori* map describing the location and geometry of rocks and vegetation. Not only does the complexity of a model on this scale seem prohibitive in anything other than small-scale demonstrations, but on this scale the environment itself is often subject to change due to variations in weather and season. Consequently, terrain navigation in outdoor natural environments invariably demands an online autonomous map building capability.

The past few years have seen considerable progress in the construction of local terrain maps for use in navigation and localization. Notable is the work at CMU and Jet Propulsion Laboratory (JPL) in stereo terrain reconstruction on grids [**29**, **52**], and more recently on triangular-tessellated terrain models [**11**, **24**]. These methods have the potential to provide quite general terrain models for both navigation and motion planning tasks. Currently, however, such methods require independent knowledge of platform location and so have limited application in localization. These methods are discussed further in section 4.2.

The SLAM problem has recently received a great deal of attention. SLAM is the process of building a map of the environment while simultaneously using this map to provide localization information. The algorithm works by generating estimates of the relative location between landmarks. It can be shown that the precision of these estimates increases monotonically and that the vehicle location estimate becomes bounded [**53**]. This means that a vehicle can start at an unknown location in an unknown environment and incrementally build a convergent map while maintaining bounds on platform error. The implications of this for outdoor autonomous navigation tasks are particularly significant.

Practical demonstrations of the SLAM algorithm in ALV applications over traverse distances of 20 km at speeds of 30 km/h have been described [**54**, **55**]. In particular, the work described in reference [**54**] uses trees and other vegetation as landmark information for a time-of-flight laser scanner. As the vehicle drives through the environment, landmarks are extracted from laser scans and placed in correspondence to a map. Subsequent observation of these landmarks are fused with measurements from an inertial navigation system and used to provide updates to vehicle and map estimates.

The complexity of the SLAM estimation problem is potentially huge (of the dimension of the number of landmarks). Further, the structure of the SLAM problem is characterized by monotonically increasing correlations between landmark estimates. Thus the state space cannot be trivially decoupled. For these reasons, there has been a significant drive to find computationally effective SLAM algorithms. This has been achieved through the development and use of the Kalman and extended Kalman filter as the estimation algorithms of choice in SLAM algorithms. In these developments, simplification in the time update step and locality in the observation update step have resulted in algorithms that can process thousands of landmarks in real time on PC level architectures [**55–57**]. However, the Kalman filter approach comes with a number of limitations, most notably the inability to represent complex environment or feature models, the difficulty of faithfully describing highly skewed or multi-modal vehicle error models, and the inherent complexity of the resulting data association problem. A parallel approach to vehicle navigation, which overcomes many of these limitations, is to consider navigation as a Bayesian estimation problem [**58**]. In this method, vehicle motion and feature observation are described directly in terms of the underlying probability density functions and Bayes theorem is used to fuse observation and motion information. Practically, these methods are implemented using a combination of grid-based environment modelling and particle filtering techniques. These Bayesian methods have demonstrated considerable success in some challenging environments [**59**].

Other applications in both airborne and subsea environments have also been demonstrated [**60**, **61**]. An interesting application is in navigation of an autonomous surveillance vehicle for use in jungle warfare, being developed by Gintic and DSTA in Singapore. In this case, there is no possibility of using GPS because of foliage cover, nor is it reasonable to expect any kind of local terrain map to be available as the terrain is dominated by seasonal vegetation. Consequently, SLAM algorithms are essentially the only means of providing localization information. The sensors used in this case include millimetre-wave radar (MMWR) and infrared (IR) imaging [**62**].

4 NAVIGATION

Navigation is taken here to mean the guidance and control of a vehicle in response to information from sensors concerning the state of the environment in the local neighbourhood of the vehicle. This involves both reactive response to immediate situations such as collisions, as well as local path planning to avoid or negotiate objects. Higher-level 'mission planning' is discussed in section 5; lower level motion control is discussed in section 2.3.

Essentially there are two main approaches to the navigation problem. The first is to consider navigation as purely reactive: 'avoid holes' or 'don't hit anything', for example. This approach has been particularly popular over the last decade for the 'behavioural' control of indoor vehicles [**63**]. The approach seems less applicable in outdoor environments where some forward view of terrain type or possible manoeuvres is often essential. The second approach to navigation has been to build up a local model of the environment in the neighbourhood of the vehicle and then to undertake a degree of path planning with this local model. This approach has been most successful in current outdoor vehicle projects.

The navigation of an ALV requires a suite of sensors that can look forward and build up a picture of the environment in front of the platform. Such sensors must minimally be able to determine the geometry of the environment and to distinguish obstacles, ditches, or other obstructions from traversable terrain. The ability to classify different terrain types is also likely to be advantageous. Sensors must also be capable of operating at speed in a range of environment conditions. A number of different passive and active sensors have been employed for ALV and

Fig. 6 GPS–laser-based positioning system for a large mining haul truck

vehicle navigation. More than enough choice exists to satisfy the most demanding mission applications. These sensors are discussed in detail in section 4.3.

While navigation sensors are generally well advanced, methods for fusing information from these sensors to build up an environment picture are generally less well developed. The use of active ranging information in reactive collision avoidance has been developed in a number of ways for indoor vehicle applications. Outdoor applications are less widely known but are used in areas such as automotive cruise control and for autonomous mining trucks. The use of passive collision detection sensors in outdoor applications is possible but generally less robust than the use of active systems. Reactive navigation and collision detection are discussed in detail in section 4.1.

The construction of terrain pictures for local path planning and navigation is probably the most complex problem remaining in enabling operational ALV systems. While many good sensors exist, fusing and processing information to provide an accurate and reliable description of terrain geometry and type are complex operations. Making this information available in real time and being able to undertake local planning and to reason about possible trajectories while a vehicle is on the move are significant challenges. However, a number of techniques are emerging for constructing local navigation maps in a form that allows robust fusion of relevant sensor information. Such maps can also incorporate statistical terrain information in a form enabling local trajectory planning. Terrain picture compilation is discussed in detail in section 4.2.

As a general problem in perception, navigation is not yet entirely solved. However, currently available sensor technology together with new methods in terrain reconstruction offer a viable development path for the majority of envisaged ALV missions.

4.1 Collision avoidance and reactive control

4.1.1 Reactive methods

The classic reactive approach to collision avoidance is the use of potential fields [**64**]. These have been successfully employed in a number of different outdoor navigation systems (see, for example, reference [**65**]). The system described in reference [**66**] is particularly valuable and relevant to the ALV missions. It describes a reactive potential field method for navigation in lightly cluttered cross-country environments. The system uses stereo vision in conjunction with a probabilistic cell-based model of the local terrain to generate platform motion corrections. The work particularly addresses the issue of the fusion of successive visual frames without recourse to a complete terrain model. The use of potential field models as immediate collision avoidance methods will almost certainly be a component of any ALV navigation system.

A second approach to collision avoidance is the use of certainty grids [**67**]. Certainty grids offer the ability to build local probabilistic models of the surrounding environment and then to use these in local path planning for collision avoidance. The idea of local probabilistic certainty grids has been extended to the use of evidential reasoning methods [**2**]. These have the advantage of additionally encoding 'ignorance' about areas of the environment and consequently are far more robust in path planning. The vector histogram approach described in reference [**68**] has also been widely used in obstacle avoidance.

4.1.2 Local modelling methods

Both potential field and certainty grid methods are commonly applied to two-dimensional navigation problems (locally flat worlds). The extension to undulatory 2.5-dimensional outdoor environments, with gradients and dips, requires some additional understanding of the world. The most successful approach to reactive control, and hazard and obstacle avoidance in outdoor environments has been to couple either potential field or certainty grid methods with a simple 'freeway' model of traversable regions. Here, the intended or possible paths for the vehicle are used to define 'regions of interest' and used to clip (restrict the view) of the collision sensor data (see, for example, reference [**69**]). Within the clipped window, the local geometric structure is computed, generally consisting of a piecewise planar model of the near-field area. This model is qualified with a statistical measure of the quality of the model and with additional derived measures of terrain quality including a measure of texture (rock or particle size) and vegetation type. The information about gradient and terrain is then combined into a traversability index in the form of a local grid. Minimization or optimization of the path on this grid then provides the local vehicle trajectory. Some of the best work in this area has been undertaken at the Laboratoire d'Automatique et d'Analyse des Systèmes (LAAS), Centre National de la Recherche Scientifique [**70**, **71**]. This work explores a number of key ideas: multi-level planning, the use of distinct terrain representations, the classification of terrain areas into classes (unknown, uneven, flat, or obstacle), and the use of these in generating a traversability index. The work described in reference [**24**] also addresses a number of these issues. In particular, reference [**20**] provides traversability measures based on uncertainty, slopes and perceived obstacles (and also describes an interesting 'virtual sensor scrolling' idea), and reference [**72**] considers the issue of hazard arbitration.

4.2 The construction and use of local terrain models

The use of reactive navigation methods is not always enough. For longer-term planning, it is necessary to build a representation of the local environment which can be used for both local and more global planning. This is evidenced by the work at both LAAS [**65**, **71**] and CMU [**24**]. The terrain representation must allow information from different sensors to be fused over many time frames and from different locations along the vehicle trajectory. It should also be possible to use the representation to reason about local structure, to measure traversability, to identify obstacles such as rocks or vegetation, and to locate traps or ditches.

4.2.1 Elevation grids

Initial work in terrain modelling made substantial use of elevation grids [**52**, **73**]. The work of Matthies *et al.* [**29**] is of particular interest for its use of stereo, IR, and laser imaging for building off-road terrain models. There are a number of disadvantages with grid-based terrain modelling methods. In particular, they do not provide any direct (statistical) means of managing uncertainty or errors in sensor observation, they do not provide an obvious means of combining or fusing terrain models, and they do not scale well in large environments. Nevertheless, grid-based models form the basis for a number of local navigation methods [**72**, **73**]. Grid-based methods are also a feature of the work at LAAS [**20**], although these are supplemented with other techniques for fusion and registration of data.

4.2.2 Tessellated terrain models

More recently, triangular-tessellated terrain models [or triangular irregular networks (TINs)] have come into use [**20**, **74**] (Fig. 7). These resemble the finite-element grids common in engineering computing. TIN terrain models naturally lend themselves to being updated with variable resolution sensor data. On arrival of new data, the TIN can be retessellated as a local operation using a Delauny triangulation. As a consequence of this, TINs also allow a variable-resolution representation of the terrain. This can be used either to model near and distant terrain at different levels of detail or indeed to describe the same terrain at different sensor resolutions. Finally, new particle filtering ideas can be used to coherently represent uncertainty on TINs through the use of sample densities and information measures. In reference [**20**], TIN models are used to fuse vision and range data. A mechanism is described which allows a particle-based measure of uncertainty to be incorporated into the terrain measure. The application of TIN methods to the reconstruction and recognition of a ditch (for the Demo III programme) has been described in reference [**75**]. The last 3 years have seen the use of TINs established as the primary means of representing natural terrains.

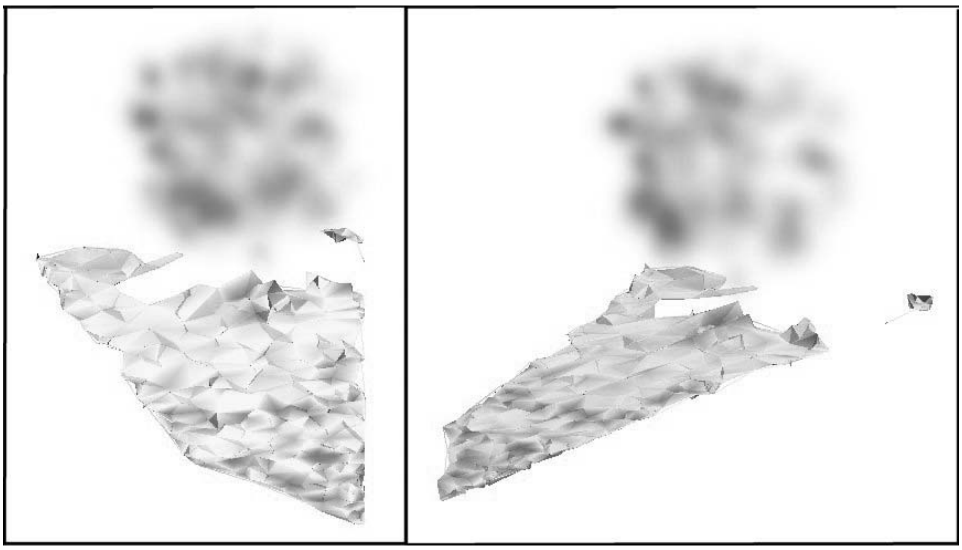

Fig. 7 A model of a terrain (triangular tessellation) and a tree (probability density cloud) generated from combined radar and laser imagery

4.2.3 Other terrain representation methods

A slightly different approach to terrain reconstruction using wavelet models has been described in reference [**76**]. The use of wavelets and related functionals provides a natural means of describing geometric texture at different scales. The use of a multi-scale functional description of the terrain also allows direct planning of vehicle motions.

Another potential method of describing terrain information is through the use of probability density functions. In indoor environments, this approach has been pioneered by Thrun [**58**]. Here, particle models of density functions are used to represent walls and other objects in typical indoor environments. The sum of Gaussian and other density models is also possible. The information represented in this way can be used for both navigation and localization.

Terrain representation methods have matured greatly in the past 5 years. The TIN representation together with some measure of uncertainty would seem to be the preferred approach. It provides a multi-resolution basis on which to fuse data, a mechanism for describing uncertainty, and the richness to encapsulate most natural terrain information.

4.3 Terrain navigation sensors

A wide range of appropriate sensor technologies have been applied to the terrain-aided navigation problem. These different sensor technologies can be placed in three broad categories: passive imaging devices, active point ranging sensors, and range imaging systems. These are briefly discussed below. There are many good books on different types of sensing technology, and far more information than can be reviewed here. As a broad rule, the use of sensors in the robotics community tends to follow and benefit from the huge military and civilian sensors industry. However, of specific interest to robotics is the book by Everett [**35**], which describes a great many relevant sensor technology areas, albeit at a rather low technical level. In addition the review paper by Herbert [**74**] provides a good recent survey in the area of passive and active imaging.

4.3.1 Passive sensing

Passive sensing includes conventional computer vision, stereo vision, other EO sensors, and IR and FLIR imaging. Passive sensing is almost always image focused; a two-dimensional array of receptor devices measures ambient energy amplitude reflected from objects in the environment. Vision, stereo, and other EO sensors are ubiquitous in robotics. The great advantage of visual sensing is the low-cost high data rate. The great illusion in visual sensing is the anthropomorphic appeal. In reality, processing of visual data is extremely complex and visual image interpretation is prone to high levels of uncertainty, ambiguity, and error. The use of visual sensing in outdoor unstructured environments is the most demanding of all applications. The only real way of ensuring that a stand-alone vision system will work with sufficient integrity is to limit the domain of operation to either a specific environment, specific feature types, or specific illumination constraints.

IR and FLIR sensors have similar operating characteristics to vision except that, of course, they operate in different wavebands. FLIR systems have seen a huge decrease in price and increase in accuracy and sensitivity in the past few years (see, for example, reference [**77**]). Many commercial systems are now available. FLIR and EO systems are now used in a number of autonomous underwater vehicle (AUV) projects including, for example, the RST MDARS vehicle. A notable application of IR to an AUV operating in complex jungle environments has been described in reference [**62**]. The main advantage of FLIR over conventional vision is the use of thermal wavebands. Together with conventional EO wavebands, this potentially provides reduced ambiguity in image interpretation. Extending this principle, multi-spectral vehicle-based imagers are also now making an appearance.

4.3.2 Active sensing

Active sensing includes the use of time-of-flight or phase delay lasers, the use of radars at different frequencies, and the use of sonar. Active sensors transmit energy and irradiate the environment with specific types of energy. The key advantage of active sensors is that knowledge of the transmitted energy pattern usually allows accurate and unambiguous interpretation of return signals in a broad range of environment conditions. The clear disadvantages of active sensors are that they require energy, are not stealthy, and generally cost more than passive sensors.

In the past decade, low-cost time-of-flight lasers have become commercially available and are now widely used in robotics. Notable are the LM series of lasers manufactured by Erwin Sick; these lasers provide 10 cm accurate two-dimensional range scans to a distance of 50 m. They are now ubiquitous on indoor robots and have also been used in a number of challenging outdoor robot applications in surface and underground mining, bulk cargo handling, and agriculture. Longer range lasers, to 400 m, are produced by Riegel. The Sick lasers can run up to 20 Hz, producing 200 samples per scan. Some Riegel units run at sample rates of 20 000 Hz. Riegel also produce a novel 'last-return' laser. This provides a range measurement from the *last object* detected, allowing the laser to 'see through' rain and dust. Riegel lasers coupled with two-dimensional and three-dimensional scanners are used in a number of ALV projects. Also of note in laser scanning is the work being undertaken on 'urban' robots by JPL and CMU (see in particular http://telerobotics.jpl.nasa.gov/tasks/tmr/homepage.html).

Over a similar time period, MMWR for outdoor vehicles and robots has also become affordable. MMWR (typically 77 or 94 GHz) provides an all-weather all-environment performance often lacking in laser and EO sensor systems, while providing the directivity, accuracy, and compactness lacking in lower-frequency radars. A great deal of development has been undertaken in MMW collision detection or cruise-control radars and these are now appearing on automobiles. Such radars are usually of limited bandwidth and with range accuracy of around 1 m. Beam widths and shapes vary but can be as wide as 15° (although this is often quite suitable for the application). The technology employed uses surface-printed (MIC) antennae and beams are often electronically scanned. A number of higher-performance MMWR have also been produced for field robotic applications (see, for example, reference [**78**]). These have relatively high bandwidth (12 cm accuracy) and narrow beams (1–2°). These radars are normally mechanically scanned. However, unlike lasers, full coherent amplitude signals are normally obtained which provide an 'image' of the terrain seen in the beam of a single sample. These radars can also be used over far longer ranges (2 km) than lasers.

4.3.3 Range imaging

Range image sensors employ a complex imaging intensity array to sample time-of-flight or phase information from an actively illuminated scene [**35**]. Illumination is normally from a laser, in which case the sensors are referred to as Lidar. Such sensors are capable of providing an 'image' of range points in real time [**77**]. Lidar sensors are commonly deployed in military helicopters in a number of different roles.

Clearly range image sensors can be of considerable advantage in ALV applications, and indeed a number of Lidar-type systems have been used in recent ALV designs (notably the German DVLR system, and in Demo III [**79**]). However, a major limitation is that typical Lidar systems are very expensive. This has restricted their development and effective use in ALV systems.

4.3.4 Multiple sensors

Combining active and passive sensor data makes considerable sense in ALV applications. Passive image-based sensing provides a detailed forward picture of the environment. However, this picture carries little direct depth or three-dimensional information, and the picture alone can often be difficult to interpret in terms of the geometry and structure of the local terrain. Spatially sparse range information can substantially aid the process of interpretation and make construction of terrain pictures much more robust [**9**].

While the fusion of passive and active sensor data is largely an algorithmic issue (and is discussed in section 4.2), there are a number of efforts to construct so-called 'common mode' sensors which physically integrate both passive and active devices into a single unit. This approach is commonly accepted in military aerospace applications (e.g. integrated targeting pods) but has yet to be seen in ALV or field robotics applications. Of note, however, would be the fusion of a passive FLIR imager with a beam-imaging MMWR as a common-mode ALV sensor. This would offer unprecedented all-environment capability to an ALV navigation system.

5 MISSION AND TASK PLANNING

Mission and task planning is concerned with the construction of trajectories and other vehicle actions, typically over a long time horizon and beyond sensing range. Functionally, planning resides above the processes of navigation and mobility. In the scenarios envisaged in general outdoor missions, planning is focused on the deployment of a payload along a trajectory or at a specified location. While there may be many constraints that need to be accounted for in the planning process, the essential output of planning is a series of way points or trajectories through which the vehicle must pass. Trajectory generation methods are described in section 5.1.

Mission planning must also incorporate additional tactical information including, e.g. the ability to communicate, the need for stealth, or cooperation with other vehicles. Within this, a broad scope of 'intelligent' control ideas can be considered. While such issues are important in the context of a real mission and of robotics intelligence in general, they are beyond the scope intended by this paper. Section 5.2 briefly examines the problem of mission specification and optimization.

5.1 Path planning methods

There are a great many path-planning systems described in the literature. Most of these are concerned with the construction of trajectories optimized for a specific purpose. Trajectory generation can be through the use of straight lines between way points, spline curves, clothoids, or other appropriately smooth geometric structure. The book by Latombe [**16**] is generally regarded as the definitive text on classical path planning issues. Classical path planning generally assumes complete knowledge of the world and in return provides useful properties of correctness and completeness.

In contrast, most outdoor vehicle missions do not have complete knowledge of the world. Rather, sensor information is acquired during mission execution and path planning proceeds incrementally. Heuristic planners, such as the subsumption architecture, track arbitration schemes [**80**], or way-point-type algorithms are more appropriate to outdoor environments. They are better able to accommodate new sensor data than classical planners are. However, such path-planning algorithms do not provide any guarantee of completeness [**32**].

Generally, sensor-based motion planners are incremental. The robot senses its immediate environment and determines the 'best' local path segment based upon these measurements. After moving along the local path, the robot begins the cycle again. There are two main approaches to the sensor-based path-planning problem: the use of 'freeways' and the use of cell or grid methods. Freeway methods include the TangentBug algorithm in which a visibility polygon is generated and a path constructed, like an elastic band, around obstacles and other traversability constraints [**32**, **81**]. Grid-based methods are best represented by the D* algorithm [**82**]. The D* algorithm uses an approximate cell decomposition, filling in a grid-based world model incrementally with sensor information. The algorithm has the advantage of being well developed and of being particularly suited to rough terrain navigation.

Once a process for incorporating new sensor information is established, and once a representation (either freeways or grids is defined), then way points or trajectories can be computed. Most often, trajectories are computed using splines or other smooth curves. The use of 'energy minimization' or the 'elastic band' principle is both common and intuitively appealing. In essence, a path is laid out which minimizes some potential function, constructed from the initial grid or freeway and incorporating any other relevant optimization criteria [**23**, **28**, **36**]. The advantage of such a representation is that it can be easily stretched or modified by new incoming sensor information.

5.2 Mission planning methods

Mission planning is little studied in robotics although a number of methods available in other domains could be applied to this problem. At one extreme, rule-based methods implementing a conventional doctrine could be employed. The disadvantage with such methods is the need to respond to unforeseen circumstances in an autonomous manner. At the other extreme would be to employ unsupervised learning methods (e.g. reinforcement learning) to develop strategies in the face of different situations. Practically, these methods are beyond what is required for most missions.

Most valuable are mission-planning algorithms solely focused on trajectory and way-point generation. The mission-planning problem described in reference [**70**] is a good example of a possible approach to this problem. This consists of the optimization of a spline-based trajectory. As terrain information is acquired in front of the vehicle, the spline is extended and modified on the basis of measures of traversability for the perceived terrain (see section 4.2). Modification is undertaken as a constrained optimization problem. The costs of various paths are evaluated in terms of the perceived nature of the terrain, modification from the initial trajectory, distance from the goal, and consumed energy. It is not hard to imagine other constraints being incorporated including maintenance of communication line of sight, availability of localization information, or stealth. In effect, these enter in to the problem simply as cost functions in a multi-objective optimization task.

A final point to consider in mission planning is the generation of system-level control objectives. This problem is characterized by the need to fuse or sequence single controller actions into complete system missions. This is currently an active area of research in robotics. The 'meta-control' modelling methods developed by Burridge *et al.* (see, for example, reference [**83**]), provides one of the few general methods for tackling this issue. In this work, a 'funnel model' of control action is developed, describing the effect of a controller in transferring the system from one state to another. Compositions of funnels feeding funnels allow behaviours to be combined with *predictable* outcomes.

6 COMMUNICATIONS

ALV operations require communication between vehicle and base station, and potentially between vehicles and field operatives. Radio communication technology for this type of system has made huge advances in the past decade and many options for communication exist. A detailed exposition of communication technology in this context is beyond the scope of this paper; however, a number of key points can be made.

Radio Ethernet is commonly used in indoor robotics projects. It has the advantage of high bandwidth and low cost, but the disadvantage of requiring line of sight and having very low range capabilities. Radio Ethernet is not likely to be appropriate for ALV applications by itself. However, the implementation of transmission control protocol (TCP) and internet protocol (IP) on other tactical radio systems may well have a significant impact on operations.

Off-the-shelf spread spectrum (1–2 GHz) radio systems with a bandwidth of over 1 Mbit and a range of up to 20 km are readily available. Some units also include transmission of a GPS timing signal that can be used in localization. A number of current ALV research and development projects use spread spectrum systems. The advantage of these systems is relatively high bandwidth, long range, and immunity to jamming and interference. The disadvantages include the need for line-of-sight operation.

Live video feed is also possible, but generally undesirable, in ALV missions. Video can be fed, with appropriate compression, over TCP, IP or spread-spectrum networks. Over short ranges, a number of commercial off-the-shelf broad-band video systems are also available. Over longer ranges, directional antennae are normally used (common for UAVs). This is generally considered undesirable for ALV missions. Autonomous missions are generally taken to exclude live video feed.

A range of military tactical radio systems exist in the ultrahigh-frequency and very-high-frequency bands (The Joint Tactical Radio System is the current embodiment.). The lower frequency provides far greater range than the systems described above and does not generally require line of sight, although lower frequencies generally means lower data rates. Tactical radio systems have substantial built-in immunity to jamming, interference, and interception. Details of such systems are, for obvious reasons, not widely available.

At the tactical level, the Link 11, Link 16, and future Link 22 communication standards are of relevance to ALV applications. These standards define a communication layer between the physical communication system and a tracking or data fusion function. Together they are elements of the developing joint data network. Link 16 and future Link 22 embody a number of features which are of considerable importance to autonomous systems. These include the following:

(a) a standard global coordinate system (WGS-84) for fusion of data;
(b) a standard timing signal to allow communication of real-time data between platforms;
(c) a precision timing signal that can be used as a pseudorange to provide self-localization between a number of receivers;
(d) the incorporation of receiver location information as an integral part of message packets;
(e) a measure of uncertainty (a single measure in Link 16; a covariance proposed in Link 22) in track data that can be used in the fusion process.

Whatever communication system is developed for ALV applications, it would seem essential that it too would include all these elements.

At the tactical level, the use of ‘communication marbles’ is appealing in allowing networking between vehicles, operators, and other systems. The principle is that low-cost communication modules could be dropped by an ALV, from a UAV, or by a field operative and used to relay information otherwise restricted by line-of-sight, jamming, or stealth considerations. A high-frequency high-gain point-to-point communication network is the most likely physical implementation for such systems. Incorporating parts of the Link 16 protocol as part of a communication marble would substantially increase their value. The use of timing signals would allow marbles to self-register in a global coordinate frame and to double as pseudolites to provide precision location information.

In addition to tactical systems, there are a number of strategic communication options. These may include the use of a satellite up-link. Commercially available up-links such as Iridium are used in a number of projects. Military up-links provide sufficient bandwidth for live video feed. In tactical situations, up-links to a UAV could provide direct and high-bandwidth communication relays at modest cost.

Unsurprisingly, there are a range of different remote communications options appropriate to ALV operations. A possible approach is to use two or more different options in combination, e.g. spread-spectrum plus an up-link, or point-to-point marbles plus a tactical radio. This provides a degree of robustness to variations in operational circumstance.

Whatever physical communication mechanism is chosen, a protocol that provides similar functionality to Link 16 is desirable.

7 CONCLUSIONS

This paper has reviewed the current state-of-the-art in ALV systems and technology. The key conclusion is that the technology currently exists to develop and deploy an operational ALV system. Of the functional elements identified, mobility, localization, and communication are well-understood and well-developed areas that can offer immediate solutions to ALV technology needs. The remaining two areas, navigation and planning, are less mature but are, regardless, deployable in a broad range of mission scenarios.

A second conclusion is that the successful development of an operational ALV system will rely on an effective approach to systems engineering. A precise description of mission requirements and a clear definition of component functionality seems essential. This is particularly important in the areas of navigation and planning where a finite definition of mission objectives and vehicle functionality will make the whole problem tractable. Too many ALV programmes have ended up chasing an elusive 'intelligent and autonomous' target. It is appropriate to quote Patrick Winston's (a former director of the Artificial Intelligence (AI) Laboratory at the Massachusetts Institute of Technology) definition of AI in the context of ALVs: 'AI is whatever we cannot currently do. When we know how to do it, it is called an algorithm'.

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