The use and integration of a novel planning approach for an all-terrain vehicle that is to navigate autonomously within an equatorial forest type terrain is described in this paper. The principles applied to the design of a global motion planner are included. The planner takes into account the kinematic and dynamic parameters of the vehicle as well as the constraints imposed by wheel-ground interactions. That is, it incorporates suitable physical models to deal with the task dynamics in the motion-planning paradigm. Data for local-tactical planning is provided by the on-board visual perception and obstacle detection modules, whilst a positioning system feeds data for global-strategic planning. A digital terrain map purveys the preliminary landmarks for planning purposes including information on the physical properties of the terrain.

The planner behaviour and vehicle responses have been validated using simulation techniques. A model of the overall system, which includes the motion planner, has been built. A digital terrain representing a typical operational scenario is used with visual information generated by the perception system used to enhance the terrain map.

By incorporating the vehicle dynamics and interaction effects between the wheels and the ground into the motion planner, it is possible to enhance motion response and to generate feasible paths whilst ensuring vehicle safety. When degradation of the visual perception system and identification of the terrain type traversed by the vehicle are detected, the motion planner launches a different visual guidance mechanism to secure that the best possible local visual information can be perceived. A purpose-built safety mechanism polls sensors on the vehicle and generates status reports that are fed into the planner as warnings or additional constraints.

1. Introduction

The deployment of an Autonomous Unmanned Ground Vehicle (AUGV) for field applications provides the means by which the risk to personnel can be minimised and operational capabilities improved. In addition to the importance of the perception system, mainly visual guidance, motion planning is a key function in preparing locomotion tasks and enhancing the capability of the AUGV to move safely toward its target position. The response of the vehicle when evolving in an unstructured or partially structured outdoor environment depends on the combination of several geometric and physical criteria. These include the mechanical structure of the vehicle, the geometric/physical features of the terrain, wheel/ground interactions, characteristics of the received commands and the applied motion control law [1].

In this project, the motion planner developed as part of the SHARP project (INRIA Rhône-Alpes, France) is applied to a vehicle operating in a real context. Results of field trials on an AUGV prototype developed by the Gintic Institute of Manufacturing Technology have shown the need to include the dynamic response of the vehicle and the effects of ground conditions as part of the decision control system. Enhancement of the visual guidance capabilities to cope with the changing conditions found in an equatorial forest is also needed [2]. The problems related to sensing and modelling the environment are beyond the scope of this paper. However, issues such as coping with incomplete knowledge of the environment and uncertainty (due to inaccurate sensing, modelling and control) merit further investigation in relationship with the planning framework discussed to make it more applicable in real contexts.

The project is motivated by the operational challenges encountered in autonomous (and/or tele-operated) outdoors-mobile robots. The results are expected to have a potential impact on civil and military applications where autonomous navigation by all-terrain mobile robots is critical (e.g. intervention in damaged sites, planetary exploration, inspection and mine counter-measures).

2. The basic problem and nature of challenges

The main locomotion task is to move a vehicle safely between particular positions in an outdoor environment. The experimental vehicle is a Jeep used in tropical forest operations. The working environment can be either unstructured or partially structured. The vehicle will move on an irregular terrain whose structure is subject to changes mainly due to tropical rain. The terrain comprises tracks or suitable surfaces on which the vehicle can travel. Various types of traversable areas...
rigid or deformable/movable relief (e.g., rocks, sandy or muddy areas, stones, etc.) are considered.

The vehicle will have three locomotion modes: autonomous, tele-operated and under operator control. In this paper, the interest resides in autonomous operation, in particular on issues related to motion planning and its inclusion into an autonomous navigation control system. The basic motion-planning problem considered is to find a trajectory (a continuous sequence of the vehicle states and wheel actuator torques) that enables the vehicle to move between arbitrary locations (and possibly at desired velocities) on the terrain. The compliant structure of the vehicle, the physical features of the terrain, and the strong interaction between the ground and the vehicle wheels exhibit new constraints and modelling/computational issues. These make motion generation and motion planning much more difficult than in the case of indoor locomotion on flat surfaces. The objective is to address the constraints arising from the vehicle dynamics and the wheel-ground interaction, in addition to the geometric/kinematic constraints (e.g. obstacle collision avoidance, evade contact between the terrain and vehicle body other than the wheels, no tip-over, etc.). These limit the effective range of vehicle motion like slippage minimisation and skidding avoidance. The premise is that incorporation of task dynamics and contact interactions is fundamental for characterising feasible motions and enhancing the planning of autonomous locomotion tasks.

Today, building geometric elevation maps of the environment from sensory data is an active research area in outdoor mobile robotics, the use of appropriate models for dealing with soil mechanics is limited [3], [4]. Advanced analysis of the texture of the different surfaces may permit qualitative estimation of some of the environment physical properties (e.g., rigidity/softness and adherence). This qualitative data can be used to refine locally the environment map and to generate a description of the workspace in terms of primitives or components having different physical properties. The quantitative identification of mass, deformation, and friction parameters of these various components is, however, very difficult. This modelling problem can be overcome by incorporating uncertainty in the geometric and dynamic formulation of all-terrain motion planning and by developing appropriate algorithms for dealing with incremental contact-based sensing and model refinement. Issues that are likely to be investigated as fundamental problems in future research in motion planning for autonomous off-road mobile robots.

From the control and motion planning perspective, the key is to design and apply models, which represent the geometry and dynamics of the vehicle structure (i.e., wheels, chassis, and compliant mechanisms), under constraints. The geometric and physical features of the operational terrain must be also included. The basis for representing these characteristics and the manner in which they are applied in the motion planner and control systems are described in the next section. These are used to synthesise the behaviour of the vehicle and to characterise the feasible vehicle trajectories whilst satisfying the task constraints.

In addition to the development of modelling and motion planning tools applicable to all-terrain locomotion, other major difficulties encountered are linked to navigation-localisation, real-time constraints, robot decision-making, environmental perception and system integration [2], [5], [6].

3. Major system components and motion planner principles

The AUGV consists of four systems: Visual Guidance (VGS), Vehicle Control (VCS), Robust Communications (RCS) and Tele-operation Control (TCS). The VGS is the perception mechanism, providing information on the external environment. It consists of a set of vision modules and a 2-3D D laser ranging system. For each module a degree of confidence is estimated and accordingly data is fused. The VCS is the decision-making facility of the vehicle. It generates the driving commands to the vehicle as a function of information derived from the perception modules and operator commands. The system collects information from external and internal sensors, the operator interface, and then it infers the most appropriate actions to attain the desired goals. It comprises a digital terrain map, the navigation, positioning, vehicle control and actuation, and safety modules. The motion planner is included as part of the navigation module, it uses data from the terrain database, position module and visual guidance. A virtual model of the environment is built and correspondence with a priori knowledge fed as part of the mission planning is made. The dynamic model of the vehicle is built-in into this module. The planner output is sent to the vehicle control module. The RCS provides internal and external communications and addresses the interconnection between all modules. A proprietary messaging bus has been developed which allows for a distributed control architecture. It provides the coding for the telemetry used for the remote vehicles. Finally, the TCS allows remote driving, and tracking of the vehicle, the design is based on the man-machine collaborative metaphor. It consists of an operator console and navigational aids which apply the principles of collaborative tele-operation [7], [8].

3.1 Modelling

The operational terrain is regarded as a three dimensional workspace where a set of static objects are located and which might be subject to unexpected disturbances. The initial geometric model of the terrain surface is obtained from the digital terrain database that originates from a satellite photograph of the terrain. The model is divided into several areas, having different properties according to the estimated terrain...
characteristics (friction, rigidity/deformation, etc.). The highly deformable regions are represented by a model based on the physics of particle based compliant systems, which synthesise various phenomena arising from the wheel/soil contacts. The terrain is represented by a collection of interconnected particles obeying Newtonian dynamics. In addition a 2D hierarchical model which approximates the shape of estimated obstacles is considered [9]. As the vehicle advances, it acquires terrain images and polls the local sensors. This information is screened according to a confidence level constraint, enhancing the representation of the surveyed areas. Dead-reckoning errors as well as differences on the estimation of the terrain characteristics would introduce a certain degree of uncertainty into the model. Enhancements to the mapping of the terrain in front of the vehicle through the use of a laser ranging system and colour segmentation techniques to classify the terrain might reduce the level of uncertainty in the model [10].

A hybrid model that combines the mechanics of rigid-body chains with the physics of particle-based compliant systems is used to represent the dynamics of the vehicle compliant structure and to reduce the number of coupled non-linear motion equations. Rigid-body dynamics are used to represent those parts of the vehicle, which are actually controlled (driving wheels and steering), and compliant discrete physical structures are applied to model the passive joint mechanisms. This model allows a simple solution to the forward motion problem and can be applied to many types of mechanical structures. A detailed description of the planner is presented by Cherif [9]. The unknown model parameters are estimated and obtained experimentally. Whilst the response of the driving actuators on an electrical vehicle could be considered as constant, these would vary when using a combustion engine, therefore the estimated vehicle parameters could differ. When the vehicle is loaded, its model would also change, even load distribution on the vehicle chassis could introduce differences to the vehicle model. These considerations form part of the level of uncertainty that has to be introduced into the models.

Uncertainty has been addressed by some researchers in the framework of off-road navigation and path planning [11], [12], [13]. Hait and Simeon have extended the geometric planner described in [14] in order to deal with uncertainty in the terrain model by incorporating error intervals in the elevation map [12]. Kubota et al. [95] and Chen and Kumar [11] have addressed path planning aspects for a rover and a multi-legged walking robot, respectively, by incorporating “traversability” probabilities in the terrain elevation map. All these works have focused on the static behaviour of the robot and have not investigated uncertainty effects (related to geometry and contact interactions) on the kinematics and dynamics of the robot. Fraichard and Mermond have also investigated control uncertainty in the presence of non-holonomic constraints for path planning in the simple case of a mobile robot travelling on a planar surface [15]. All these techniques are relevant for future extensions of our planning framework to cope with uncertainty.

3.2 Motion planning

To tackle the intrinsic complexity of all-terrain kinodynamic motion planning, the planner is designed as an iterative algorithm that consists of two interleaving complementary reasoning levels. The high level consists of a discrete grid search that expands a tree of sub-goals within a low dimensional subset of the robot configuration space (i.e. the space of the robot position/orientation in the plane) when considering only a simplified 2D instance of the task. The 2D distance of the task is used only to guide the search and not to provide the solution. The local planner finds this when used between consecutive sub-goals provided by the global level. The sub-goals are computed assuming that the robot can move, for a coarse period of time, along a canonical non-holonomic 2D path in absence of the dynamic constraints. For each iteration, the best sub-goal (in terms of a cost function such as the distance to the final goal) is chosen and checked to determine if it is locally reachable from a sub-goal adjacent to it in the connectivity tree. This is performed by the local level reasoning, which operates continuously in the vehicle state space, and solves for effective feasible and safe smooth motions between adjacent sub-goals whilst satisfying the full set of task constraints. The task constraints considered by the planner are collision avoidance between the vehicle and obstacles and/or the ground, the distribution of soil contact, minimising slippage at the wheels, satisfying velocity bounds, and available torque and accelerations. Figure 1 shows a schematic representation of the planner structure including the sources of data used in the planning algorithm.

The hybrid model of the vehicle, the physical model of the operational terrain, and the model of the contact interactions are used extensively for predicting the forward motions and characterising feasible and safe displacements. The two levels are iteratively interleaved until the final goal is reached or no solution can be found. In the first case, the planner output is the sequence of the vehicle states and corresponding wheel control torques. In the second, a failure is detected and re-planning is performed to move the robot towards another target provided by the VCS. Figure 2 shows the connecting tree of the sub-goals and the computation of the local motions.
4. Simulation results

A system model to simulate the behaviour of the planning module and vehicle control system including the main vehicle parameters was built. The digital terrain database has been generated using a satellite image plus a surveyor’s map. The surface to be explored has been divided into zones according to the terrain characteristics, which are estimated as traversable through the observation of the maps only. The information from the Visual Guidance modules is classified and fused, then it is fed into the planner. The terrain model is enhanced using the simulated information provided by the VGS and range sensors.

The images captured by the visual guidance unit are catalogued with the ground areas in front of the vehicle sampled and characterised. The results are compared with ground representations of the same region in the digital terrain map. If correlation between the sampled ground features and the characteristics of the digital map exists, these are used in the model. When results do not correlate, the terrain is scanned again and sample areas compared with a catalogue of images representing the type of terrain that could be found in the area to be explored. Once matching is found, the terrain model parameters are modified to consider the estimated characteristics. In addition by measuring slippage using the vehicle odometry sensors and positioning devices, the estimation of the terrain will be enhanced. The trajectory of the vehicle resulting from the simulation on
a surface that includes large obstacles and different terrain conditions is shown in Figure 3.

![Simulation example illustrating obstacle avoidance and locomotion on irregular surfaces.](image)

The resulting system is to be ported next into an outdoor wheeled vehicle and once integration completed, trials are to be run. The approach taken is demonstrated by considering the following scenarios: Traversing highly irregular relief, deformable regions (sandy areas) and areas, which include movable components (stones of different shapes).

6. Conclusions

The incorporation of the vehicle dynamics and ground physics into the planning process of an autonomous ground vehicle operating in a forest-like terrain has been described in this paper. The approach allows the system to determine whether the planned path (or trajectory) is safely executable by the vehicle and whether or not the surface where the vehicle could move can be travelled on. The principle applied is the introduction into the all-terrain motion planning module appropriate physical models, which capture the locomotion dynamics and to apply a two-level process that uses these models for characterising feasible displacements. The consideration of planning as a key function in the system permits work close to the actual behaviour of the vehicle and hence to predict and attain a better and safer vehicle response. However, the identification of ground and vehicle parameters could introduce some errors and render unfeasible trajectories or those, which make the motion of the vehicle dangerous. Another issue is the difference that might exist between the estimated position and the actual position of the vehicle with regard to the terrain model. The use of DGPS together with a high-end inertial navigational unit as part of the positioning system minimises dead-reckoning errors. The main concern is the degree of uncertainty that exists of the terrain conditions. That is, the model of the ground could differ very much from the actual field conditions, rendering the model unusable. The introduction mentioned that exact identification of certain terrain features like friction and deformation is difficult. This can be addressed by incrementally incorporating during operations some qualitative information on the nature of the regions crossed by the vehicle. An alternative solution to the modelling problem consists of incorporating uncertainty (due to modelling, sensing and control) in planning, a key issue for enhancing robustness of the planned trajectories. It also permits the reduction of the model accuracy required for planning, which is important in a real context. Past work in dynamic motion planning has somewhat dealt with the issue of uncertainty by constraining the robot to avoid the obstacles with a speed-dependent safety margin. In the planning framework presented, this safety margin can be incorporated as an additional constraint when checking collision with the static obstacles. When contact interaction constraints are important, as in the current case, planning in the presence of uncertainty is much more complex. Large discrepancies between the models and the real environment (in terms of the geometry and the physical features) may yield to important errors during execution. Because the robot...
kinematic chain is considered to be compliant, the effects of the errors in the terrain geometry may be partially reduced. Errors in friction and deformation features affect drastically the task dynamics and must be coped with in our ensuing work.

Another option could be to have a library of typical ground conditions of the operational area, with the VCS selecting which is more suitable according to the information fed by the perception mechanisms. A prospective research avenue to overcome possible discrepancies between the models and the real world will be to consider the effects of uncertainty in the dynamic behaviour of the vehicle. Fraichard has started work in this area for the 2D case; subsequent efforts will attempt to extend the obtained results to the 3D all-terrain case [15].

It is envisaged to extend the use of the presented approach as a navigational aid for tele-operated vehicles by relaxing the constraints fed into the planner according to the level of controllability the operator has on the vehicle. People confined to wheelchairs and who suffer cognitive and perceptual difficulties could also benefit of a simpler version of this system to ensure their safe displacement in known environments.

References


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