The SmartTer - a Vehicle for Fully Autonomous Navigation and Mapping in Outdoor Environments

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Abstract— The driving factor for the development of the vehicle presented in this paper was to construct a hardware platform that allows to perform the tasks of environment mapping and autonomous navigation in large scale outdoor environments. Our robot is based on a standard Smart car that has been equipped with five distance laser sensors, three cameras, a differential GPS, an Inertial Measurement Unit (IMU), an optical gyroscope and four computers. The car’s systems states are directly accessed through the vehicle’s CAN bus. Localization and Navigation are realized by fusing all available sensory information in a probabilistic way. This allows for high precision localization and dynamic local and global path planning. Using the 3D point clouds extracted from the rotating lasers and the omnidirectional image the smartTer is able to consistently register the 3D maps and analyse the scene for regions of interest. To control the car in both longitudinal and lateral direction we applied a couple of modifications to the car, namely providing access to the car’s power steering system, electronic gas and brake pedal.

Keywords— sensor fusion, outdoor vehicle, 3D mapping

I. INTRODUCTION

The main objective of this work was to construct a hardware platform that allows to perform the tasks of environment mapping and autonomous navigation in large scale outdoor environments. Nowadays, no commercial plateform is available for that kind of application and we had to develop a custom made vehicle. In order to avoid to start the design from scratch and to reduce the costs, a standard car was selected and modified in such a way that all the necessary characteristics for autonomous navigation and mapping are included. Substantial work has been done to accommodate an additional power generator and to enable the car with "drive by wire" capability. Moreover, the car was equipped with five distance laser sensors, two cameras, an omnidirectional camera, a differential GPS, an Inertial Measurement Unit (IMU), an optical gyroscope and four computer racks.

Using the 3D point clouds extracted from the rotating lasers and the omnidirectional images, the vehicle is able to consistently register the 3D maps and analyse the scene for regions of interest. The localization is realized by fusing data from the GPS, the IMU, the optical gyroscope and the car in a probabilistic way. This leads to an accurate and robust pose estimation that is used for autonomous navigation and to facilitate 3D scan matching.

This paper is structured as follows. Section II describes the modifications that were performed on the vehicle and the sensors chosen for perception. The autonomous operation and mission concepts are presented in section III. In particular, we present several results about vehicle localization and autonomous planning. Finally, section IV concludes the paper.

II. VEHICLE DESCRIPTION

Our vehicle, called SmartTer (Smart all Terrain), is a standard Smart car that has been enhanced for fully autonomous driving in somewhat flat outdoor environments. The model is a Smart fortwo coupé passion of year 2005, which is equipped with a 45 kW engine. This model has been chosen because it gathers several advantages:

- compact and light. Thus, the vehicle can be easily transported on a trailer to the testing area1 and fits in our lab’s mechanical workshop. Furthermore, its light weight allows for fair locomotion performance in rough terrain.
- power steering. The power steering motor has enough torque to steer the car. So, it is possible to "steer by wire" with minor modification
- auto gearshift. No additional modification is required to switch gears while the car is driving.
- easy access to the CAN bus. Important sensory information such as steering wheel angle and wheels velocities are thus directly accessible. All these features facilitate the process of converting such a vehicle for autonomous driving. The fully equipped SmartTer is depicted in Fig. 1 and 2.

A. Vehicle modifications

In order to enhance the original model for autonomous driving, several modifications have been performed on the car. This section describes the mechanical and electrical changes that were necessary.

- Wheels with better grip and larger diameter have been mounted. This allows for slightly higher ground clearance and much better traction in rough terrain.
- A 24V power generator has been installed in order to power all the electronic devices and additional actuators. The generator is driven by a belt and pulley that is directly connected to the engine output axis (which is situated under the trunk, at the rear of the car). Two batteries placed in the trunk act as an energy buffer. They have a total capacity of 48Ah and are continuously recharged when the engine is running.
- The power steering system applies a torque $M_{add}$ on the steering column that allows to minimize the effort

1Because the car has been deeply modified, we are not allowed to drive in the traffic.
This task is fulfilled by the Driving Assistance unit (DA unit) which minimize the torque sensed in the steering column by applying an appropriate voltage to the power steering motor. The gain of the DA controller is set based on the car’s velocity, which is broadcasted on the Vehicle CAN bus. A specific electronic board has been designed in order to use the power steering motor for “driving by wire”. To fulfill this goal, the Vehicle CAN bus is disconnected from the DA and routed to a computer (Rack0) so that the steering angle $a_s$ can be read and used by our PID controller. An additional CAN bus, called Computer CAN, allows to feed the DA unit with the minimal set of CAN messages required for the proper operation of the unit i.e. engine on and car velocity messages. The same bus is used to send commands to a CAN to analog module which fakes the torque voltage needed by the DA unit. Finally the steering angle is controlled with a PID controller which minimizes the steering angle error $e = a_t - a_s$, where

- A system of cable and pulleys is used to activate the break pedal. The servo motor that pulls the cable is placed under the driver’s seat and is commanded using the Computer CAN.
- A specific electronic board has been developed to enable the use of a computer to set the gas command. The voltage, originally provided by a potentiometer in the gas pedal, is simply generated by a CAN to analog device. This device receives commands from the Computer CAN to analog device.
- To provide a clean interface to the vehicle, we integrated an automotive ECU (Fig. 4) designed for highly reliable realtime applications. This ECU has four CAN interfaces as well as a wide variety of analog and digital I/O. In the vehicle, it is sitting between the computation racks on the one hand and the vehicle CAN bus and our actuators on the other hand. In this ECU we implemented a state machine allowing to switch the system to the different modes of operation (STOP, PAUSE and RUN) via both wired and wireless stop buttons. Besides these emergency buttons the ECU handles timeouts in the command coming from the computation racks and ensures a safe vehicle state whenever those commands are missing. As this system is in aspects of both hardware and software a hard-realtime system and because it handles remote stop commands it allows safe autonomous driving in closed environments.
B. Sensors

The sensors used for outdoor applications must meet strong requirements such as mechanical robustness, water/dust proofness and limited sensitivity to sun light. Thus, in comparison with indoor applications, the choice is limited and the selection of optimal sensors must be done carefully. In this section, all the sensors that have been mounted on the car are described.

- **Three navigation laser scanner sensors** (SICK LMS291-S05, outdoor version, rain proof, low sensitivity to sun light) These sensors are used mainly for obstacle avoidance and local navigation. One sensor is placed at the lower front slightly looking down and the two others on the roof, looking to the sides and slightly down. This 'A' shape configuration enables a large field of view and is well adapted to all kind of terrain. The sensors are visible in Fig. 1 and Fig. 5 depicts a closer view of the sensors mounted on the roof.

![](image1)

![Fig. 5. Sensors mounted on the roof](image2)

- **Rotating 3D scanner** This is a custom made sensor that is mounted on the roof (see Fig. 6). In order to acquire 3D scans of the environment, two SICK LMS291-S05 are mounted sideways on a plate rotating around the vertical axis. A signal is triggered each time the plate performs a full turn. That way it is possible to know its angular position at each time (using the rotational velocity of the motor and the elapsed time since the last trigger). The data and power lines of the two SICK sensors go through a slip ring, which is mounted along the rotation axis. The 3D scans are mainly used to compute a consistent 3D digital terrain model of the environment.

- **Omnidirectional camera** (Sony XCD-SX910CR, focal length 12mm, with parabolic mirror and dust protection) The setup is mounted in front of the rotating scanner (see Fig. 6). It enables the acquisition of panoramic images that are used to supply texture information for the 3D digital terrain maps. The images are also exploited to detect artificial object in the scene.

- **Monocular camera** (Sony XCD-SX910CR, focal length 4.2mm) This camera is placed in the car, behind the wind shield. Like the omnidirectional camera, it is used to detect artificial object in the scene.

- **Video streaming** (Sony camera) This camera is used to have a visual feedback when the car is driving autonomously. It allows the operator to detect hazardous situations and stop the car if necessary. The transmission range can reach up to one km.

- **Differential GPS system** (Omnistar Furgo 8300HP, rain proof antenna) This system provides an accurate position estimate together with its standard deviation when satellites providing the GPS drift correction are visible from the car. When no correction is available standard GPS is provided.

- **Car sensors** The measurements taken by the car sensors are available on the Vehicle CAN bus e.g. motor RPM, temperatures, steering wheel angle, wheel velocities, gas pedal pressed, door closed etc.

- **Optical gyroscope** (KVH DSP3000) This fibre optic gyroscope can measure very low rotation rates (it is able to measure the earth rotation). Thus, it is possible to use it as a heading sensor for a relatively long period of time (several minutes) by integrating the angular rate. Contrary to compasses, the integrated heading it is not sensitive to earth magnetic field disturbances. Finally, this unit offers much better accuracy than mechanical gyro and is not sensitive to shocks because it contains no moving parts.

- **Inertial measurement unit** (Crossbow NAV420, water proof) This unit contains 3 accelerometers, 3 gyroscopes, a 3D magnetic field sensor and a GPS receiver. The embedded digital signal processor of the unit combines the internal sensors to provide the filtered attitude of the vehicle (roll, pitch, heading to true north) and the position (latitude, longitude and altitude). However, this sensor is not well adapted for ground vehicle at low speed because of a bad signal/noise ratio of the inertial sensors. Furthermore, the earth magnetic field can be strongly distorted when the vehicle drives next to iron structures. This causes large error on the esti-
mated heading. For better accuracy and robustness, we finally implemented our own localization. The sensor fusion algorithm combines the car odometry, the attitude angles, the integrated angle of the optical gyro and the position and heading information from the GPS.

C. Computational power and software architecture

The system consists of four compact PCI computer racks communicating through a gigabit Ethernet link. All the racks have the same core architecture i.e. a Pentium M @ 2GHz, 1.5G of RAM, Gigabit and Fast Ethernet, two RS232 serial ports, USB ports and a 30G hard disk. Each rack is dedicated to specific tasks and acquires measurement from different sensors as it is depicted in Fig. 7.

![Architecture of the system](image)

Fig. 7. Architecture of the system

All computer racks run the Linux operating system and the software architecture is based on both GenoM\(^2\) and Carmen\(^3\) robotic software architectures. The functional modules running on different computers exchange data using the Inter Process Communication (IPC\(^4\)). To guarantee that the time stamp associated to each data packet is globally consistent, the cpu clocks are synchronised using the Network Time Protocol Daemon (NTPD). In order to reduce communication delays, the architecture has been designed in such a way that it minimizes the amount of transmitted data. Finally, the modular architecture together with the IPC based communication enables the system to be flexible and reconfigurable.

The Vehicle rack is endowed with a CAN interface that is used to access the vehicle CAN bus. The measurements of the car sensors are continuously read and the car commands such as the vehicle velocity and steering angle are passed to the ECU. The other sensor i.e. the DGPS, the IMU and the optical gyro are connected to the rack through RS232 serial ports. The main tasks of the Vehicle rack are to keep track of the vehicle position and to control its motion (steering, breaking, velocity control, etc.).

The Navigation rack acquires range data from the three navigation scanners through high speed RS422 serial ports. It is endowed with a firewire interface (IEEE 1394) which allows to grab images from the navigation camera. The main task of this computer is to plan a safe path to the goal using the sensor measurements (images and range data) and to provide the motion commands to the Vehicle rack.

A 3D map of the traversed environment is updated on the 3D Mapping rack using the measurements acquired by the rotating 3D scanner (RS422 board). Like on the Navigation rack, the scanner data is acquired through RS422 ports. The index signal is detected using a multi-purpose IO board and the motor speed is set using an RS232 interface. For more realistic rendering, the texture information acquired by the omnidirectional camera is mapped on the 3D model as it is depicted in Fig. 8.

![3D scan with texture](image)

Fig. 8. 3D scan with texture. One recognize a tree on the left hand side, yellow street markings (-x-shape), a pink box (next to the street markings) and persons (on the right, with arms extended)

Finally, the scene analysis is performed on the Scene interpretation rack. The artificial objects are extracted from the textured 3D maps and raw omnicam images and their representation and location are stored in memory as the vehicle moves along the path.

III. AUTONOMOUS OPERATION AND MISSION CONCEPT

The SmartTer is intended to establish a consistent 3D digital terrain map and detect artificial objects in the scene while autonomously driving along a specified route. The main tasks for accomplishing this mission are: Localization, Navigation, 3D Mapping and Scene analysis. The current results related to these tasks are discussed in this section.

A. Localization

The proposed localization algorithm is based on the information form of the Kalman filter i.e. the Informa-

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\(^{2}\)http://softs.laas.fr/openrobots/tools/genom.php

\(^{3}\)http://www.cs.cmu.edu/~carmen/links.html

\(^{4}\)http://www.cs.cmu.edu/asl/cs/project/TCA/www/ipc/index.html
tion filter. This filter has the property of summing information contributions from different sources in the update stage. This characteristic is very interesting when many sensors are involved, which is the case in our system. Our sensor fusion scheme is based on [2][3] and [4]. To accurately localize the vehicle, four different sensors are used: DGPS, IMU, optical gyro and vehicle sensors (wheel encoders and steering angle sensor). The combination of their measurements allows the estimation of the vehicle's 6 degrees of freedom i.e. the 3D position (x, y, z) and the attitude (roll, pitch, heading). For outdoor applications, the following situations are the most difficult to handle:

- the vehicle goes on a covered area, underground or in a tunnel: the GPS signal is not available and therefore absolute position is not available
- the vehicle drives next to large structures: GPS reflexion can occur, this is the worst case because GPS is available but provides wrong measurements
- when traversing rough terrain: the wheel encoders provides wrong measurements when wheels are slipping
- the vehicle drives next to iron structures: the earth magnetic field is locally distorted and the compass provides erroneous measurements

Thus, each sensor has its own advantages and drawbacks depending on the situation and sensor fusion is crucial to compute robust position estimates. In Fig. 9, the raw GPS data is plotted to illustrate the difficulty to handle noisy and sometimes erroneous data. One can see that the DGPS signal is not always available along the path. The outages occur mainly when the vehicle drives close to the buildings or underground (Fig. 10). On the other hand, the standard GPS is available more often because it does not rely on the visibility of geostationary satellites providing the DGPS correction. Indeed, these communication satellites are low above the horizon at our latitude and are often occluded. However, standard GPS is much more noisy and less accurate than DGPS.

The filtered trajectory combining the vehicle model, the inertial measurement unit, the odometry, the DGPS and the optical gyro is depicted in Fig. 10. The plot in

Fig. 9. Raw GPS measurements. The altitude measured by the GPS can jump up to several meters

Fig. 11 depicts the evolution of the standard deviation of the position over time. The uncertainty increases when GPS is not available because the system relies only on dead reckoning. On the other hand, when GPS is available the position is reset and the uncertainty decreases.

B. Navigation

Our approach to autonomous navigation combines a global planner with a local planning capability.

Local planning

We use the information from our laser range finders to construct a local grid-based cost map specifying the
nearby obstacles and difficult areas to traverse for the vehicle. Each cell in the grid is a square of width 20 cm. Cells containing obstacles are assigned an infinite cost, representing untraversable areas, with cells corresponding to less difficult terrain assigned less-expensive cost values. We perform a configuration space expansion on this map, which has the effect of ‘growing’ the obstacles and other expensive areas out by the width of the vehicle. This allows us to treat the vehicle as a single point during planning. Given this local map and the current vehicle position and orientation within this map, we can then project potential vehicle actions onto the map and check the cost of these actions. We use a discrete set of variable-length arcs for our vehicle actions, corresponding to different steering angles and vehicle speeds [1] [5]. Each of these arcs represents an action that is feasible from the current vehicle position, orientation, and velocity. We then choose the best of these arcs according to their costs and perhaps also some general objective, such as the amount of distance the arc takes us in our desired direction of travel. This arc can then be directly executed by the vehicle.

Global planning

Our global planner is based on the Field D* algorithm, which has been incorporated into several fielded robotic systems [8][6]. This algorithm provides very low-cost paths through grid-based representations of an environment. These paths do not take into account the heading restrictions of the vehicle and instead approximate the least-cost path to the goal for a vehicle that can turn in place. Because Field D* does not encode the mobility constraints of the vehicle, it cannot be used alone for accurate trajectory planning for the vehicle. Consequently, we combine it with our local, vehicle-specific arc-based planner to provide feasible paths. Our combined system maintains a global map of the environment containing all the observed obstacles and high-cost areas. Then, every planning cycle, the vehicle projects out its set of available arcs into this map and computes the cost of each arc based on its distance and the cost of the cells it travels through. This gives the cost of traversing the arc itself. To this value we then add the cost of a global path from the end of the arc to the goal. This cost is provided by our global Field D* planner. Then, the arc with the minimum combined cost is selected and executed by the vehicle.

Fig 12 shows an illustrative example of this combined approach. The set of available arcs are shown in red/gray, with the best arc shown in blue/black. Here, the best arc was selected based on a combination of the cost of the arc itself and the cost of a global path from the end of the arc to the goal (the goal is shown as a filled circle at the right of the figure). The global path from the end of the best arc to the goal is also shown in blue/black. In this example, a purely local planner would have selected the straight arc leading directly to the right, as this brings it closest to the goal in terms of straight line distance. However, such an arc could cause it to get stuck behind the clump of obstacles in the middle of the map.

Motion Control

The control of a passenger car is twofold. As a human driver an autonomous driving system has to control the system by means of both speed and direction of travel. As for human driver the means of fulfilling this control task are gas and brake for the speed and the steering wheel for the direction of travel. The underlying systems allowing this control are described in section II-A. While the steering angle is controlled using a standard PID controller, the control of the vehicle speed is more complex and usually done using a whole set of control regimes for the different gears used when travelling in different velocity ranges. In the system described here we use a fuzzy logic controller (FLC) allowing a consistent control of the vehicle’s throttle and brake system over a whole range of velocities from under 10 km/h up to 100 km/h covering most common travel speeds.

C. 3D Mapping

The 3D Mapping unit creates consistent global 3D point clouds using the inputs of the rotating scanner and the localization module. In parallel, a local traversability map is created on-line that is used for local planning. We use multi-level probabilistic surface map (MLS maps), which can be regarded as an extension to elevation maps. This allows to compactly represent multiple surfaces in the environment as well as vertical structures. It enables a mobile robot to cor-
rectly deal with multiple traversable surfaces in the environment as they, for example, occur in the context of bridges. In order to register single MLS maps into one global map we first extract features from the local maps and then apply map matching based on the iterative closest point algorithm (ICP) to these features (vertical objects, flat surface, rough terrain). To further improve the maps, we apply a loop-closing technique based on a constraint network whenever a loop is detected. The resulting MLS maps are especially useful to distinguish between traversable and non-traversable regions of the environment. In Fig. 13, green areas represent traversable map cells, whereas red and blue are non-traversable. A detailed presentation of this approach can be found in [11].

D. Scene analysis

The coloured 3D point-cloud map is further used for scene analyses. This module is using the inherent properties of artificial objects in order to extract it from the environment map. The question arising is what an artificial object looks like. Our definition considers an artificial object to be composed of a sufficiently smooth surface and a sufficiently extended area, which has distinctive color with respect to the surrounding world. The artificial object detection task is accomplished without human supervision or any trained object database through three steps, in a quasi real-time. In the first step (called laser layer), linked smooth surfaces with sufficient area extension are extracted from the 3D map. In the second step (called camera layer), a complex image color segmentation is performed in order to identify useful color blobs. Finally, in the third step, the laser and camera layers are fused together in a probabilistic and unsupervised way, where every instance has a given confidence of being an artificial object or not using a particular defined untrained neural network. In this way, it is possible to manage the uncertainty of false positives or the partial and noisy information coming from the two sensors. The results are shown in Fig. 14.

![Fig. 13. MLS map of an outdoor terrain. Traversable and not traversable are easily identified.](image)

![Fig. 14. Artificial object detected in the scene.](image)

IV. Conclusion

In this paper, we presented the development of a hardware platform that allows to perform the tasks of environment mapping and autonomous navigation in large scale outdoor environments. A standard smart car has been modified to accommodate sensors and to enable its control using a computer i.e. steering, breaking and velocity control. The system is fully functional and allowed to produce good results such as accurate localization, autonomous navigation and textured 3D mapping. The next step of the project is to investigate the problem of autonomous navigation and mapping in dynamic environment such as found in cities. The first step will consist in developing algorithms for robustly construct 3D textured maps of cities. Then the focus will be on autonomous driving. The challenge will be to handle a highly complex scene in real-time and have a system which is reactive enough to account for many hazardous situations e.g. a pedestrian suddenly crossing the road.

References


