Autonosys Technical Paper

DARPA Grand Challenge 2005

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W.T. Moore, CTO, Autonosys

tom.moore@autonosys.com

Abstract: *This paper describes the vehicle that Autonosys[1] has modified to participate in the 2005 Grand Challenge. The autonomous drive actuators, navigation software and obstacle avoidance systems are discussed. The vehicle's navigation decisions are based on the fusion of IMU and GPS positioning. Obstacle avoidance relies upon four lidar scanners. One lidar "camera" is an AMCW lidar that has an extremely high data-rate and a better angular resolution than the other three units. Obstacle detection is enhanced by the use of this lidar system.*

Introduction: The Autonosys team is comprised of a few full time employees and a dedicated team of volunteers with skills in mechanical engineering, optics, software and electronics. The company's goal is to develop sensor technology and control software that enables better obstacle avoidance capability. The first outcome of this work is the development of a high speed, robust lidar system with better angular resolution and higher data rates than scanners that are currently available. The vehicle and it's modification for autonomous driving is a very direct way of testing and improving the prototype lidar unit, including developing the software for terrain mapping and navigation decision making. The photograph below shows some of the members of the Autonosys team in front of the 1st generation "Autonomobile" which was used during the qualification visit in Ogdensburg, NY.

1. Vehicle Description

1.1 The 2003 GMC Z71 truck was chosen for several reasons. It is a four-wheel drive truck with an off road package (Z71). It already had skid plates in place and a tougher suspension with rear wheel locking/limited slip differential so this reduced the amount of vehicle conversion required to get it off-road ready. The short box is used to hold a large array of batteries to provide an adequate amount of backup electrical power. The batteries also serve as a counter balance to the weight of added larger bumpers on the front of the vehicle. This vehicle accommodates larger tires for the needed traction and side wall toughness. Our tire selection is an off road Good Year Wrangler MT/R, LT 305/70 R16. These have been selected for their toughness and for traction. They will also provide added cushioning during driving.

1.2 For our power distribution we have installed a 185 ampere alternator. This is more than sufficient to meet our total power requirements. We use an inverter to provide the 110V for our two main computers and use batteries for the 12V and 24V lidar scanners. The computers, radios, GPS electronics, etc. are mounted on a steel rack inside the vehicle behind the passenger seat. The hardware mounting rack is mounted with a Neoprene Pneumatic Vibration Damping Mount. This damping coupled with the vehicle's suspension and under inflated tires will prevent serious shock being transferred to our electrical systems. Our vision system consists of four lidar scanners that are mounted near the front of the vehicle and elevated to provide best vision while minimizing the dust from the front tires. The lidar scanners have sheet metal sunshades fitted to them to prevent the sun from saturating the detectors. The lidar scanners are also mounted with Neoprene Pneumatic Vibration Damping Mounts. This is to prevent shock being transmitted into the units and possibly causing damage. The rack is also where the IMU sensor is mounted so that is can monitor the pitch, roll and yaw directly at the lidar units to improve the corrections for vehicle and sensor motion. The mount is made of aluminum to minimize magnetic field effects on the gyros in the IMU. For desert conditions, the windows are covered in reflective film to reduce heat build up in the cab. The steering is controlled using a gear-reduced motor mounted under the hood of the vehicle. The brake is applied with a spring. There is an electromagnetic clutch on the actuator side that pulls against the spring. If there is a power failure, the clutch will release and the spring pulls on a cable to apply the brakes. To sense brake position a pressure sensor had been put in line with the front brakes providing force feedback when the brake is applied. The vehicle's accelerator pedal is a drive-by-wire system. We used a second pedal position sensor and are actuating it with an after market cruise control, which is mounted under the dash. A four-stage actuator drives the gear selection. This is also mounted under the dash. To use it, we simply disconnect the shifter cable from the shifter pin and connect it to the actuator drive pin and let the actuator do the work. We have mechanically placed the actuator pin in such a position that park position can never be achieved. If the vehicle needs to be in a stopped/paused position we will apply the brakes and put the vehicle in neutral. This way it is impossible for the computer to shift into park while moving.

2. Autonomous Operations

2.1 Processing

The software consists of four pieces. These pieces are:

1) Location Determination (LOC)

2) Lidar Processing Unit (LPU)

3) Navigation and Path Planning (NAV)

4) Low Level Control (LLC)

The Location Determination component is responsible for maintaining an accurate representation of where the vehicle is currently located. This includes latitude, longitude, height as well as yaw, pitch, roll and current speed. It obtains this information from OBD2, a Navcom GPS unit and a Microstrain IMU.

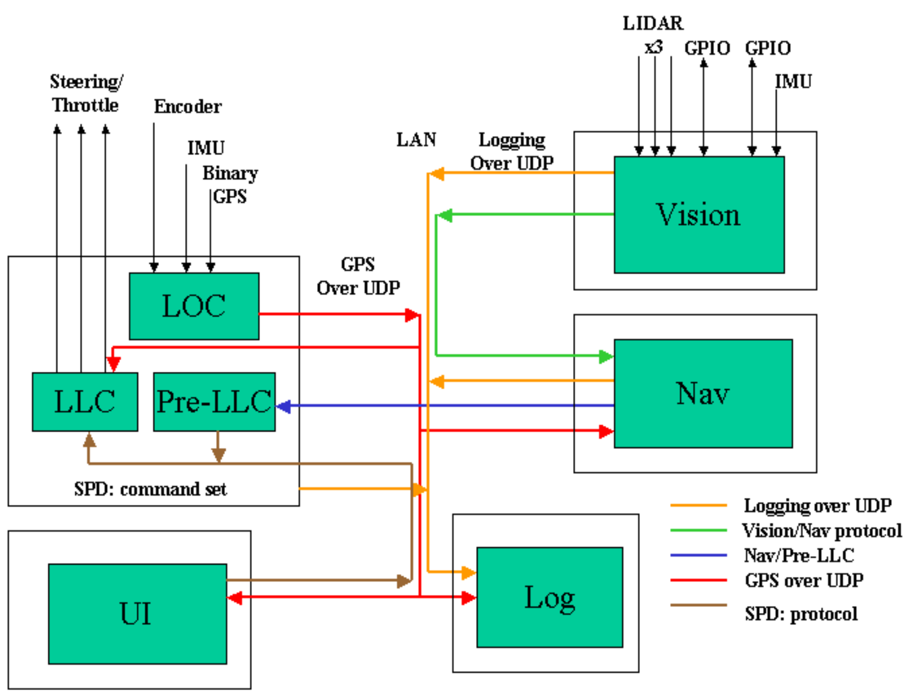
The Lidar Processing Unit is responsible for taking in the input from the Sick lidars and generating a 3D map of the world. It uses the currently known position of the vehicle from LOC as well as the fixed position and angles of the lidars with respect to the vehicle. It produces a constantly evolving "point cloud" of the world. In addition, the data from the AMCW lidar is used to detect obstacles that are not seen by the lower resolution scanners and acts as an early warning for vehicle path decisions.

The Navigation and Path Planner is responsible for taking the current position of the vehicle, the waypoint data for the route, and the LPU derived map of the world and to evaluate all of this data to determine the preferred path. For each choice, it first evaluates the terrain to determine if the path is drivable based on the terrain map. For each drivable path, it then evaluates the paths based on waypoint information including lateral boundary offsets and path distance from the waypoint-to-waypoint track. The Navigation unit's output is to provide the Low Level Control module the setpoints for throttle, brakes and steering.

The Low Level Control is responsible for setting and maintaining the drive systems at the desired setpoints. Feedback from different sensors for speed, steering angle and brake pressure is used to close the control loops.

The different components communicate via Ethernet for high-bandwidth, low-latency, reliable communication.

2.1.2 The system architecture is as shown in the figure below.



2.1.3 During the development of the navigation software, a simulation program was created that uses USGS topographical data and simulated vehicle dynamics in order to evaluate different algorithms for path selection. Either real lidar data or simulated lidar data can be used so that various types of terrain and different sizes of obstacles can be used to test the navigation decisions. Simulations of both positive and negative obstacles as well as noisy lidar data can be done.

2.2 Localization

2.2.1 The GPS system is a Starfire subscribed NAVCOM 2050G[2] which is specified to have a resolution of 0.1 meters and an update rate of 25Hz. The IMU is a Microstrain MEMS based unit 3DM-GX1-SK[3], which is a gyro enhanced position sensor. The GPS and IMU data are integrated using a Kalman filter[4] approach that is robust enough to allow for the LOC software unit to keep running for several seconds using just IMU data without serious errors in position. The GPS bearing readings are ignored when the vehicle speed is below a threshold speed as the errors can be significant. The discontinuity in position when the GPS data is re-acquired after an outage due to tunnels or trees is manageable as long as the data “downtime” is not too long. In the event of a sufficiently long period of time without GPS data, the vehicle will stop for safety reasons and wait until new data is acquired as well as completing a full lidar scan of the terrain in front of the vehicle.

2.2.2 No map data is used in the navigation system except for simulation purposes. Only the publicly available 10m resolution USGS data is used for this purpose, which allows us to simulate terrain with different topographies.

2.3 Sensing

2.3.1 The GPS unit is mounted directly on the roof of the cab and the IMU is mounted outside the vehicle with the lidar scanners. All the lidar systems are mounted on an air shock isolated external roll cage above the front wheels. At this time, all the lidar units do simple line-scans but with provision to change the pitch angle for the centrally mounted lidars. The two side viewing lidars are SICK LMS 291-S14 units that have 90 degree field of view. These are mounted at a fixed angle and are used in tight turns and in tunnels or roads with obstacles on the sides of the roads. Generally, the front viewing SICK LMS 291-S14 is looking 15-20 meters down the road and the pitch is adjusted upward with increasing vehicle speed and downward to examine negative obstacles at higher pitch angle. The high-speed AMCW lidar examines a 40 degree field of view with a higher frame rate and a higher resolution than the SICK units.

In order to shield the sensors from dusty or rainy conditions, we had designs for positive airflow or continuous replacement of windows, but have settled for extensive sun, dust and heat shields that we feel should be sufficient for the conditions encountered during the Grand Challenge.

2.3.2 The lidar data is used to generate an x,y,z map of the terrain immediately in front of the vehicle. The raw lidar data is corrected using the data from the LOC software module. At this stage, terrain discontinuities due to poor data from either incorrect lidar ranges or position corrections are treated as potential obstacles. In the event that terrain data is physically impossible, the vehicle will slow to a stop and re-acquire a complete terrain map using the lidar and the lidar pitch and rotation actuators on the central lidar unit.

2.3.3 The vehicle state is monitored by the use of feedback sensors on brake, steering and throttle as well as accessing the OBD2 data. Generally, only the speed is acquired from OBD2 and compared with the GPS, IMU fusion data from LOC. In the paused state, the vehicle is in neutral and RPM is monitored instead of vehicle speed.

2.3.4 Each of the control loops for braking, throttle, and steering is run by the low-level control module and relies on closing a feedback loop using the appropriate sensor.

The control loops are PI, PID, or fuzzy logic control algorithms depending on the system involved. The Navigation module examines the terrain map for drivability by looking at topography, positive obstacles and then negative obstacles. The extent of negative obstacles, the vehicle speed and present and proposed steering angles are evaluated for path selection. Limitations on maximum throttle, steering angle have been built into the control algorithms. Braking force can be modulated to slow down the vehicle on steep inclines in order to maintain the desired vehicle speed. In addition, there are several instances of emergency braking where full braking force is applied.

2.4 Vehicle Control

2.4.1 The NAV control module is responsible for all path-finding decisions. There are also checks on whether the vehicle is responding in a way that suggests it is not slipping, stuck or not maintaining the speed setpoint. If the system senses the vehicle is not moving forward although the forward transmission is selected and the throttle has been increased, the vehicle can be reversed and driven back several meters and stopped while the terrain is re-scanned for obstacles. For vehicle paths that extend outside the lateral boundary offsets, a software warning will cause the vehicle to stop and re-examine the terrain and reset the position data. For obstacle avoidance, the navigation code only allows path selection where no obstacles are detected. In the event of a dead-end, the vehicle will reverse its GPS path and re-acquire lidar data for an alternate path.

2.4.2 In general, there are checks to make sure the brakes and throttle are not applied simultaneously except during hill starting. There are two modes of operation for the braking system, one using the brake pressure feedback sensor and the other the emergency braking system which releases the electromagnetic clutch. This system is also fail-safe so that in the event of a power failure, the brakes will be applied. The steering angles have both hardware and software limits and in the event that a tighter turn is required, a three point turn using reverse could be done.

2.4.3 Navigation decisions are done by minimizing the deviations from the intended waypoint path but only driving on “driveable” terrain that is not too steep and does not contain obstacles large enough to stop the vehicle.

2.4.4 All the modifications to the vehicle have been done so that they are easily mechanically disconnected and the vehicle can be controlled normally. The total time to disconnect brakes, throttle and steering actuators is much less than 10 minutes.

2.5 System Tests

2.5.1 Our testing strategy was meant to ensure that the systems were ready for the DGC but our decision to change our vehicle to a more rugged vehicle has left much less time than desired to properly test the vehicle. Since we also decided to change the software systems to have a real time operating system for the lidar processing unit and LOC modules, our total test time on the completed vehicle will be minimal before the qualifying trials in Fontana. The high bandwidth lidar system is going due to be completed for installation in the September, 2005 timeframe so that the control systems will only use this data as additional obstacle detection capability, rather than for the primary terrain mapping. From our earlier vehicle, we have improved both the actuator ruggedness and the ease of swapping to/from autonomous operation.

2.5.2 In addition to the concerns outlined above about the lack of time; data latency and bad data has been our biggest challenges in order to get our vehicle ready for the 2005 DGC. We have improved these issues considerably by having better screening software for the identification of suspect data and by re-writing some of the data acquisition routines. A continuing problem for improving our system has been the lack of suitable training areas and problems with getting liability insurance for system testing of an autonomous vehicle. A lack of funding and the resultant use of part time volunteer designers hampered the development of our AMCW lidar. A second generation AMCW lidar system with even higher bandwidth and that is smaller, lighter and more robust is under development.

References:

[1] www.autonosys.com

[2] www.navcom.com for details, specifications on the 2050G

[3] www.microstrain.com for details, specifications on the 3DM-GX1-SK

[4] Kalman, Rudolph, Emil, A New Approach to Linear Filtering and Prediction Problems, Transactions of the ASME--Journal of Basic Engineering, 82, Series D, 35-45, 1960