Technical Paper
for DARPA Grand Challenge

Submission for the DARPA Grand Challenge

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Vehicle Name: RASCAL

1 System Description

1.A Mobility

1.A.1 Means of Ground Contact

The vehicle is a 4-wheel drive vehicle utilizing standard ATV style wheels and tires. The suspension is fully independent with coil over shocks at each corner. Diagram illustrating the vehicle dimensions are in the Appendix, Vehicle Diagrams in Figure 1 and Figure 2.

1.A.2 Challenge Vehicle Locomotion

The vehicle's method of locomotion is by way of a 4-wheel-drive drive-train. The vehicle shall be able to lock and unlock its differentials on demand providing full 4-wheel-drive when needed. Braking is accomplished by front and rear disc brakes. Steering is by the front wheels via a rack and pinion steering unit.

1.A.3 Means of Actuation

Each of the following components is in a closed feedback loop under computer control. **Steering** is actuated by an electric servo attached to the pinion shaft on the rack and pinion steering unit. The pinion shaft also has attached an absolute encoder in order to determine exact position of the steering. **Braking** is actuated by a servo attached to both front and back master cylinders via a sheathed steel cable. **Throttle** is actuated by a servo attached to the throttle pedal via a sheathed steel cable. **Gear Selection** is actuated by a servo attached to the shifter linkage.

1.B Power

1.B.1 Source of Power

The locomotion power source is from a 660 cc 4-cycle carbureted internal combustion engine built by Yamaha. Two portable power generators mounted on the vehicle will supply electrical power (4 kW) for computers, sensors, and actuators.

1.B.2 Maximum Peak Power Consumption

The maximum power consumption for the drive train is approximately 35 horsepower or approximately 26 kW. The peak electrical power consumption for the servos, actuators, and computers will be less than 4000 Watts.

1.B.3 Fuel

The vehicle will run on unleaded gasoline. The vehicle will carry a total of 32 gallons of fuel.

1.C Processing

1.C.1 Computing Systems: Number, Type, and Primary Function of each Computing System

The computing system is comprised of a set of rugged computers that are communicating through wired Ethernet (connected to a 100 T-base switch). The operating systems are Windows 2000 and INTEGRITY. The architecture as outlined in the Appendix, Figure 3, maps modular functionality on computers. For most modules, we intend to use a ruggedized laptop computer.

Here is a list of the computers and their module assignment: **Vehicle control:** embedded computer or ruggedized laptop. **Obstacle and environmental sensing:** rugged PC with PCI interface card. **Road / path finding:** ruggedized laptop, firewire frame grabber and PCMCIA interface. **Path planning:** ruggedized laptop. **RASCAL Brain:** ruggedized laptop. A number of simple microcontrollers will be used to interface the computers to sensors and actuators.

1.C.2 Sensor Data Interpretation

The system for autonomous driving uses the sensors described in section 1.E. The principal components of this system and their interconnections are shown in the system diagram in the Appendix, Figure 3.

The Path Planning module (PPM) dynamically computes the path to be followed using information from the pre-processed maps (see section 1.D.1) and GPS/IMU tracking, "corrected" by the road/trail tracking module (RTTM). The suggested path forward is passed on to the RASCAL Brain module (RBM). If no obstacles are seen by the Obstacle Detection module (ODM), the path information is passed on to the Vehicle Control module (VCM). It interfaces with the low-level vehicle control systems (throttle, brake, steering, and gear) in order to guide the vehicle along the proposed path. The ODM "interrupts" the RBM upon detecting an obstacle. It provides spatial data, indicating obstacle distance and angle relative to the forward axis. The RBM, in collaboration with the PPM, then re-computes a path that is sent to the VCM to maneuver the vehicle around the obstacle encountered. In addition, the RBM controls vehicle speed based on attitude/environment sensing and the constraints imposed by Phaseline Waypoints (provided by DARPA).

The above-mentioned control by RBM will be accomplished through a strategy-based control. Strategies for vehicle behavior are devised based on information such as terrain type, current speed, obstacles (if any), and so on. A strategy context is maintained all the time to indicate the strategy that is being executed.

The RTTM provides its information based on computer vision methods. The 2D tracking of the trail / road border is interpreted into the spatial location of the borders of the trail / road.

1.D Internal Databases

1.D.1 Types of Maps

Using the DARPA supplied waypoint list distributed two hours prior to the start of the race, we will analyze the route and create a subset of map data along the route. These pre-processed maps will be produced through analyzing publicly available datasets from USGS such as Digital Elevation Models (DEM), Digital Line Graphs (DLG), and aerial photographs such as DOQQs in the context of the DARPA waypoints. The result of this analysis will contain micro-waypoints (additional waypoints between DARPA-provided waypoints) and information extracted from terrain features in the DEM model as to the type and gradient of the path between the micro-waypoints. These micro-waypoints and the pre-processed maps will then be uploaded to the vehicle just before the race.

1.E Environment Sensing

1.E.1 Sensors

The environmental sensors are divided into those used for sensing changes in the terrain, obstacles, roads, or other vehicles at relatively large distances and those useful at relatively short distances. The long-range sensors will be used to sense the region in front of the vehicle that is generally located in either the horizontal or vertical planes. At moderate or high speeds, the data from the long range sensors will be available in time to make changes in the heading and/or speed of the vehicle to either avoid the obstacle or to switch to a slow speed obstacle avoidance mode. The short-range sensors will be used to sense regions to the sides and rear of the vehicle as well as in front of it. They will provide input for obstacle avoidance-path planning as the vehicle moves at low speeds. The general characteristics of each of the sensors are summarized below.

Video camera – passive. A video camera (pinhole lens, NTSC video, 30 fps) will be primarily used as a long-range sensor for detecting the edges of the road/trail and other vehicles in the forward direction. Their sensing horizon depends on the visibility and how they are aimed. A maximum sensing distance of up to 100 m will be achievable on flat straight paths.

LADAR – active. The LADAR system will be primarily used for detecting obstacles at large distances in front of the vehicle. It has the capability of detecting targets at a maximum range of 80 m with a range resolution of ~ 0.3 m. An infrared laser beam is mechanically scanned over an angular range of up to 180^o in 1^o steps. The frame update time is 13 ms. At a speed of 30 mph, the vehicle will travel ~0.17 m between updates. The latency when tracking targets in successive frames may be as much as 39 ms. This sensor will provide range and azimuth data for obstacles and other vehicles that must be avoided as the vehicle moves along the corridor between waypoints. As many as four LADAR units (SICK LMS) will be used for long-range obstacle detection. In this configuration, two of the units will be used for detecting obstacles within a 180^o sector of the horizontal plane directly in front of the vehicle and two units will be mounted vertically so that the laser beam is directed forward and scanned in elevation. This will be used to obtain quantitative information about the contour of the path including both positive and negative obstacles.

RADAR – active. The RADAR system (from Epsilon Lambda) may be used, primarily for detecting obstacles at large distances in front of the vehicle. It is capable of detecting targets at a maximum range of 110 m with a range resolution of 1 m. The microwave beam is mechanically scanned horizontally over a maximum angular range of ± 20^o with an azimuth angular resolution of 1.8^o. It will also have a capability to provide target elevation data over a range of 7.6^o with a resolution of 1^o. The RADAR will be used to supplement the obstacle detection capability of the LADAR system in situations where visibility is limited by dust, fog, or rain. It will also be relied upon when the LADAR system is “dazzled” by the sun.

Ultrasonic – active. The ultrasonic range finder will be primarily used for detecting obstacles at short distances on the sides, in front of the vehicle, and to the rear of the vehicle. It will rely on the diffuse reflection of ultrasonic waves from obstacles. Its maximum usable range is estimated to be 9-10 m. There will be several ultrasonic units located around the vehicle with a fixed pointing direction for each one. Use of these sensors will assure that the vehicle can sense nearby objects, even when bright sunlight or obscurants such as fog or dust temporarily disable or confuse the optical sensors. The update time for this sensor will be 100 ms. It will be chiefly used during relatively low speed obstacle avoidance maneuvers. At a speed of 10 mph, the vehicle will travel ~0.45 m between updates.

Photoelectric – active. The photoelectric sensors (Rockwell Automation types commonly used in industrial automation) may be used. They emit low duty cycle pulsed LED light beams, expanded by a lens to about 1 cm diameter unfocused beams. The majority of the approximately 24 photoelectric sensors to be used around our vehicle will be of the diffuse reflection sensing types. In a few cases, retro-reflectors will be used to allow obstacle detection by interruption of light beams. Depending on the specific methods employed for installation of the photoelectric sensors, they will provide information about the presence, approximate range and location in combination, or only about the presence of the obstacle and a rough idea of the general location around the vehicle. Time modulation of the LED light sources will allow the sensors to operate in the presence of considerable external light. Their maximum usable range is 5-6 m.

1.E.2 Locations

All sensors will be mounted on or within the roll cage protecting the interior of the vehicle. There will be no extensions from the vehicle via masts, arms, or tethers. As stated in section 1.A.1, the sensors will be located around the periphery of the vehicle so that range and image data can be obtained from an area of concern (AOC) that surrounds the vehicle. The AOC will have a generally elliptical shape that will extend more towards the forward direction than towards the sides or backward direction. The boundaries of the AOC will dynamically change as the vehicles speed changes. The sensors will operate continuously while the vehicle is moving. Range and/or image data will be supplied to the "RASCAL brain", where it will be combined with waypoint corridor information to determine if detected objects must be avoided. The sensors will be controlled from the ODM and the AES computers via analog and serial interfaces.

1.F State Sensing

1.F.1 Sensors for vehicle state

The state parameters of the vehicle that will be monitored are its global position via differential GPS, its local direction, orientation, and distance traveled, and its vertical acceleration. In addition, there will be direct sensing of the state of the vehicle's transmission (reverse, neutral, or forward), the steering angle, the throttle position, and the braking pressure.

The primary navigation will be through a Navcom Starfire SF-2050G DGPS receiver. It will be hooked up to an IMU (Rockwell Collins, GNP-10).

Differential odometer. The incremental distance traveled by the vehicle during a steering maneuver will be measured using a Hall effect sensor on the drive shaft that will provide output in pulses/revolution. This will provide input for the steering of the vehicle with the assumption that there is no significant slippage of the tires. The precise distance traveled over larger distances such as between waypoints will be obtained from the GPS/IMU system.

Speed. For steering, the speed will be obtained from the Hall effect sensor. The position information from the GPS/IMU will provide the speed of the vehicle for travel over larger distances such as between waypoints.

Accelerometer. An accelerometer capable of sensing movements in the vertical direction will be used to monitor the roughness of the terrain. It will provide input for evaluating the maximum safe speed within the overall speed limit imposed by the way point/corridor rules.

Steering rate and angle. This will be measured using an encoder on the steering servo. It will be used along with the input from the differential odometer, path planning information, and vehicle characteristics (such as maximum yaw acceleration) to provide autonomous steering.

1.F.2 Performance monitoring

Each module will provide data about its performance. If the performance is degraded, this will be considered by the RBM unit in choosing the appropriate strategy. The communication between modules is asynchronous, so that a failure of one component does not prevent the remaining system from functioning. If a module has "died", the absence of its communication is noted by the RBM module.

1.G Localization

1.G.1 Geolocation

Geolocation will consist of a two part system. The primary geo-location system will be a Navcom differential GPS StarFire. SciAutonics has chosen the StarFire SF-2050G. The output of this GPS will feed into the second navigation component, the Inertial Navigation System (INS). The INS will be supplied by Rockwell Collins. The INS will be a dual-use system. Its primary function will act as a backup for the GPS system in the event of a signal outage. The INS will maintain, using MEMS based technology, an accurate position from the last known valid GPS fix. The secondary function of the INS is to supply the vehicle control system with real-time slip, yaw, pitch, and roll information.

1.G.2 GPS – Loss of Signal

In case of short temporary loss of GPS signal, the IMU is able to determine the location of the vehicle, although with an increasing error. If the vehicle is driving on a road / pathway during a GPS outage, the road/path tracking determines the (local) travel trajectory, and the vehicle will be kept within the boundaries of the road/path. A digital compass will provide an absolute orientation clue for maintaining overall correct direction.

1.G.3 Route Boundaries

The micro-waypoints will be calculated so that the route will stay within the given route boundaries. While driving, the system can verify that it remains within the route boundaries through its GPS and IMU. If the system realizes that it approaches the route boundary, it will slow down the vehicle. If it realizes that the chosen route would lead outside of the given route boundaries, the PPM will recalculate the route in order to stay within the boundaries.

1.H Communications

1.H.1 Wireless broadcast

Our vehicle will not broadcast any wireless transmission.

1.H.2 Wireless reception

Except receiving the E-Stop signal, GPS signals and the Starfire DGPS subscription signal, our vehicle will not receive any wireless signal.

1.I Autonomous Servicing

1.I.1 Refueling

The vehicle will not be autonomously refueled. Its fuel supply will last for the entire race.

1.I.2 Additional servicing activities

The vehicle will not be autonomously serviced.

1.J Non-Autonomous Control

1.J.1 Manual control

The vehicle can be manually driven by disengaging the autonomous control system and steering system. Operating a switch on the control panel marked "Autonomous Control" will disengage the autonomous control system. The steering can be operated as a normal car. The vehicle will not support a remote control.

2 System Performance

2.A Previous Tests

The SciAutonics team has conducted tests of sensor in the Mojave desert. We have tested hand-held laser distance measurement units and have verified detection of hills and bushes. We have acquired a SICK LADAR sensor and have verified its detection capability up to a look-ahead distance of 80 m. We have verified the ability of optical sensors to detect objects within a short distance (up to 3 m).

During field trips to the Mojave desert, we have recorded more than 7 hours of video from a vehicle-mounted camera, recording the path ahead. We have run parts of these video sequences through our path tracking software. Screenshots depicting the results of this road tracking software are in the Appendix, Figure 4 and Figure 5.

2.B Planned Tests

Our vehicle exists as being manually driven. We are in the process of installing the actuators and sensors for automated driving. Our plan calls for the first automatic driving tests at the end of October 2003.

3 Safety and Environmental Impact

3.A Top Speed of Vehicle

The top speed of the vehicle is 60MPH in 4-wheel drive.

3.B Maximum Range of Vehicle

The maximum range of the vehicle under race conditions with a full tank is approximately 300 miles.

3.C Safety Equipment on-board the Challenge Vehicle

3.C.1 Fuel Containment

Fuel is contained in a fuel cell protected by a roll cage.

3.C.2 Fire Suppression

A fire extinguisher shall be mounted externally on the vehicle in an obvious easily reached open location.

3.C.3 Audio and Visual Warning Devices

Audible alarm – An audible alarm shall be mounted on the vehicle that will meet the audible alarm specification defined by the GC rules.

Flashing Strobe – A flashing strobe shall be mounted on the vehicle that will meet the specification defined by the GC rules.

3.D E-Stops

3.D.1 Execution of Emergency Stop Commands

E-Stop Normal Mode Procedure:

This procedure can be activated either by a switch attached to the vehicle or by the E-Stop equipment. The vehicle will immediately position the throttle into the idle position and will apply brakes for an immediate stop. While in this mode the vehicle shall keep adequate brake pressure applied to prevent the vehicle from moving. The vehicle will track movement through its inertial navigation system, and drive shaft mounted odometer.

E-Stop Disable Mode Procedure:

This procedure can be activated either by the labeled red manual Disable button attached to the vehicle or by the E-Stop equipment. The vehicle will immediately position throttle into the idle position, apply brakes for an immediate stop, kill the engine providing propulsion, switch off engine main power including the electric fuel pump, and place the transmission into idle. After the engine and drive train providing propulsion has been secured the main electrical power bus will be shutdown by stopping the electrical power generator(s). The computer and micro-controller controlling the brake actuator will remain active.

3.D.2 Manual E-Stop Switches

The manual E-Stop switch will be located near the rear of the vehicle. It will be red in color and clearly marked.

3.D.3 Placing into Neutral

The vehicle's transmission can be placed in neutral by engaging the manual override switch and selecting neutral with the gear shifter switch. The linkage can also be operated by hand. With the vehicle key turned on, illuminated indicators on the dash will indicate what gear is currently selected. By moving the shifter up or down the transmission can be shifted into neutral.

The vehicle is towable by truck.

3.E Radiators

3.E.1 All Devices that actively radiate EM energy

The LADAR system uses a class 1 (eye safe) laser to obtain range information. The laser operates at a wavelength of 905 nm and emits a pulse having an energy of ~300 $\mu J/m^2$ and a mean power of 43.5 mW/m^2 with a minimum diameter of ~2 cm. This is less than the ANSI standard for a class I laser of <0.19 µJ to 1.2 mJ.

The RADAR system emits an FM-CW beam with a center frequency of 76.5 ± 0.2 GHz and a power of 1 mw over an area of ~100 cm^2. This is less than the ACGIH (American Congress of Government Industrial Hygienist's) safety Threshold Limit Value (TLV) of 10 mW/cm^2.

The ultrasonic sensor uses an electrostatic transducer from SensComp that operates at 50 kHz and emits ultrasonic energy with a transmitting sensitivity of 84 dB re 20 µPa/V at 1 m. This is less than the ACGIH safety TLV of 110 dB re 20 µPa.

The photoelectric sensors emit incoherent light in the near infrared (850-950 nm). They do not present an eye hazard at any distance or in any configuration.

3.E.2 Hazardous devices

Other than the vehicle itself and the fuel onboard, there are no hazardous devices.

3.E.3 Safety Measures

The maximum power radiated by the RADAR system is below the threshold limit value for the 15 GHz – 300 GHz frequency range.

3.F Environmental Impact

3.F.1 Properties

The vehicle is based on an ATV style vehicle with large floatation tires. The impact to the environment should be no greater than if a standard 4 wheel drive ATV were driving on the path.

3.F.2 Maximum physical dimensions

The maximum vehicle length will be 105", the maximum width will be 60", and the maximum height, excluding the DARPA provided E-Stop antenna, will be 65", as shown in the Appendix in Figure 1 and Figure 2. The maximum height including the E-Stop antenna will be 91". The vehicle (without human driver, but with computer systems installed) will weigh 1500 pounds.

3.F.3 Area of vehicle footprint

The tires have a chevron style tread pattern that is raised 0.75 inches. On hard surfaces where just the chevron treads are touching the surface, the ground pressure can be as high as 29 pounds per square inch. However, on softer soil where more of the tire surface is touching the ground, the ground pressure is reduced to approximately 5 pounds per square inch.

Appendix

This appendix contains additional information (diagrams, graphical illustrations) that did not fit into the primary write-up of the technical proposal.

Vehicle Dimensions

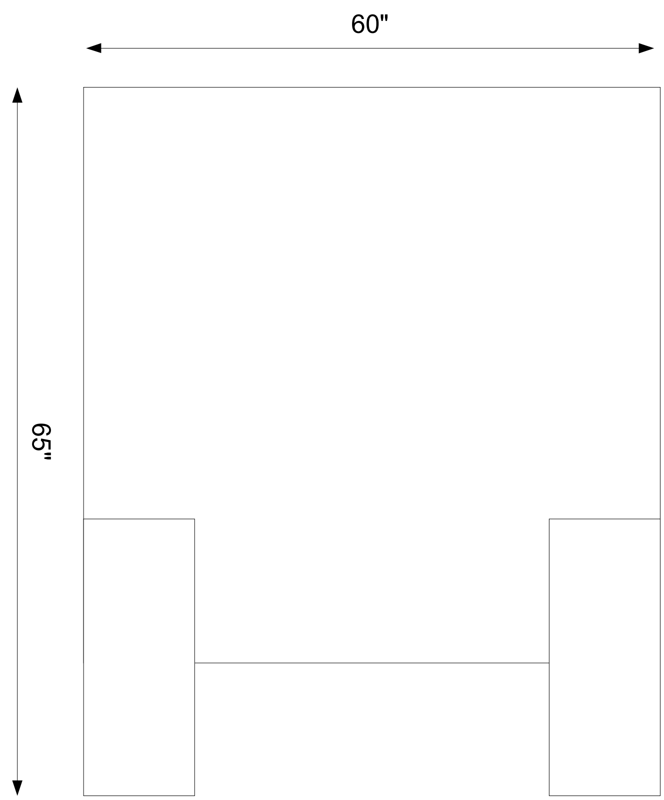

Figure 1. Front view of vehicle.

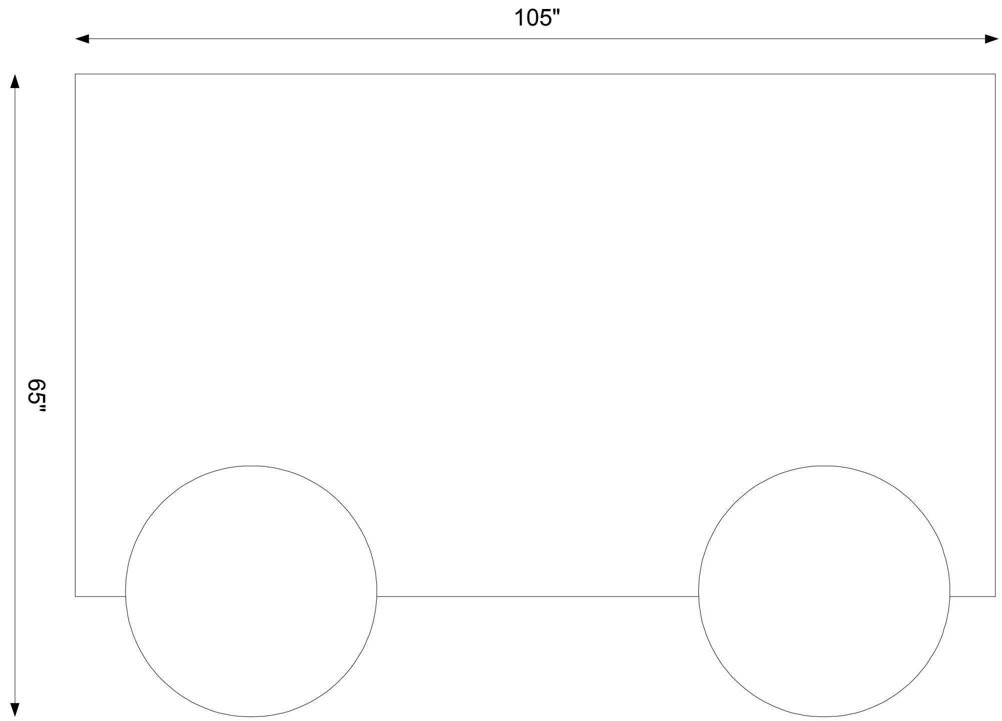

Figure 2. Side view of vehicle.

System Diagram

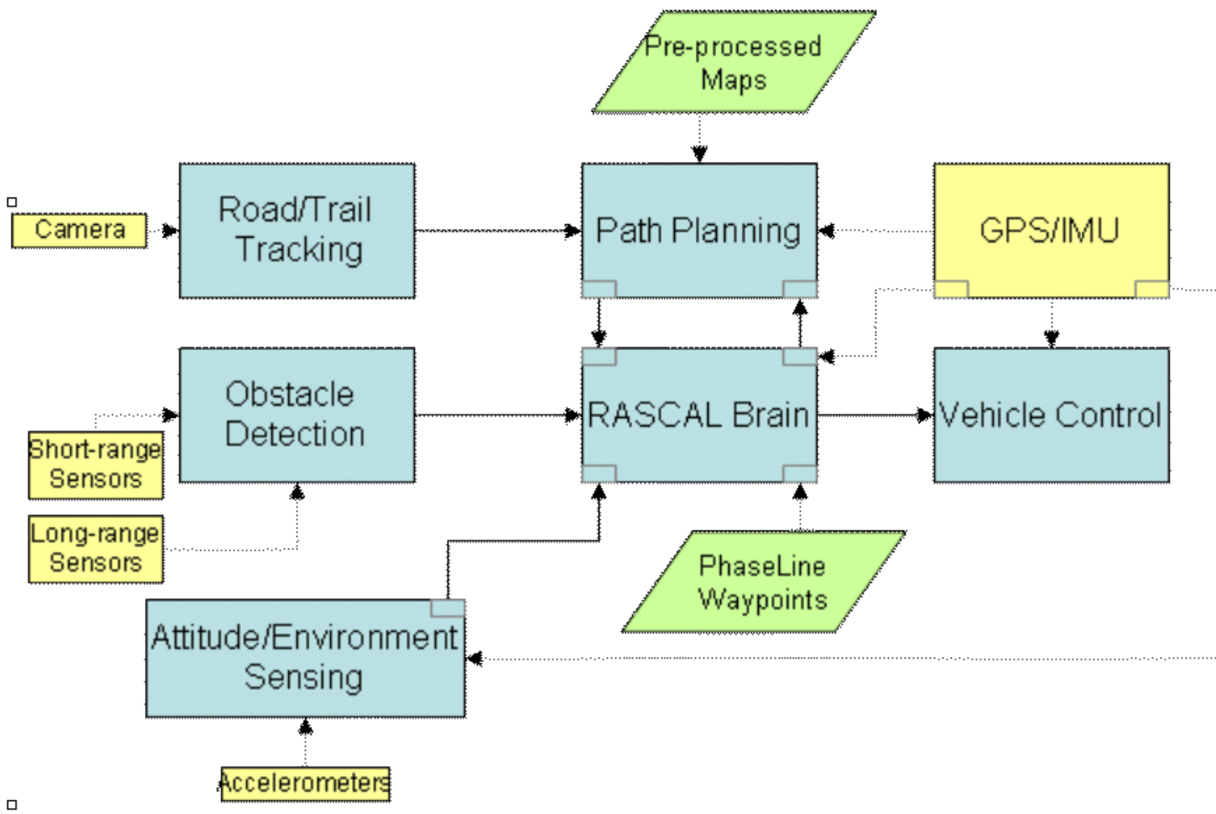

Figure 3. System diagram of the RASAL control system.

Results of Video Processing for Path/Route Detection

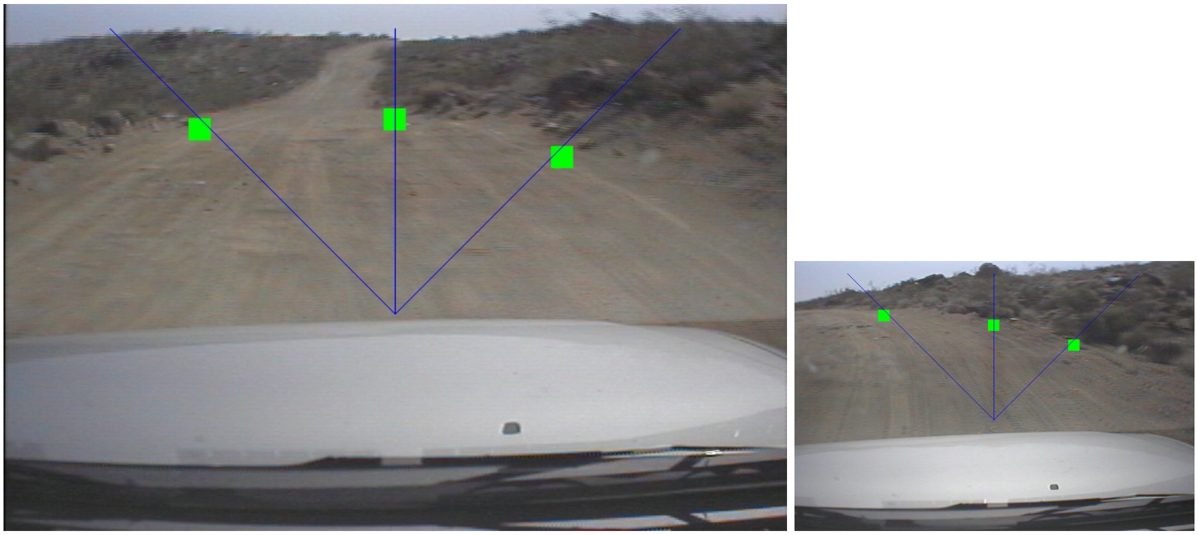

Figure 4. Screenshot of automated path searching. The green squares mark the detected border of the dirt road on the recorded video scene.

Figure 5. Screenshot of road tracking software. The detected lane markings are shown with small green vertical line segments.