Team Jefferson

DARPA Grand Challenge 2005

Technical Paper

Author

Paul J. Perrone

CEO

Perrone Robotics

pperrone@perronerobotics.com

P.O. Box 4698; Charlottesville, Virginia 22905

(434) 823-2833 (Work)   (434) 823-2296 (Fax)

Abstract

Team Jefferson used Perrone Robotics, Inc. (PRI)'s Mobile Autonomous X-bot (MAX) software platform to facilitate the rapid and extremely affordable construction of their autonomous ground vehicle "Tommy" in just 10 man-months worth of software development time. PRI-MAX and the team's minimalist approach has also enabled Tommy's highly economical construction including Tommy's ability to execute all of its intelligence on a single main processor card costing less than $200 retail. This paper describes the integrated automotive, mechanical, sensory, hardware, and software architecture that has imbued Tommy with its ability to survive, drive, and navigate the DARPA Grand Challenge.

Introduction

Team Jefferson was founded by Perrone Robotics, Inc. (PRI) as a means to demonstrate how its Mobile Autonomous X-bot (MAX) software platform could be used to rapidly and affordably build and integrate highly complex robotics applications such as those considered by the DARPA Grand Challenge. Since its inception, Team Jefferson and PRI have attracted a core group of industry and university partners and volunteers to contribute time, technology, and additional support for building Team Jefferson's vehicular entry "Tommy".

Vehicle Overview

Tommy, as seen in Figure 1, is a custom-built dune buggy constructed using standard automotive components but with design consideration given to application in a rugged off-road environment. While Tommy is manually drivable, its drive-by-wire technology permits actuation of steering, throttle, brakes, and shifting. Tommy's sensory technology consists of COTS sensors for providing actuator feedback, position, orientation, and detected obstacle information. Tommy's software has permitted use of economical COTS computing hardware for main processing and micro-control. Reusable profiles of Tommy's Java-based PRI-MAX software run atop an open source operating system as well as inside the micro-controller environments. A physical architecture diagram of Tommy's hardware is depicted in Figure 2.

Figure 1: Left side, Front, and Right side (door off) views of Tommy

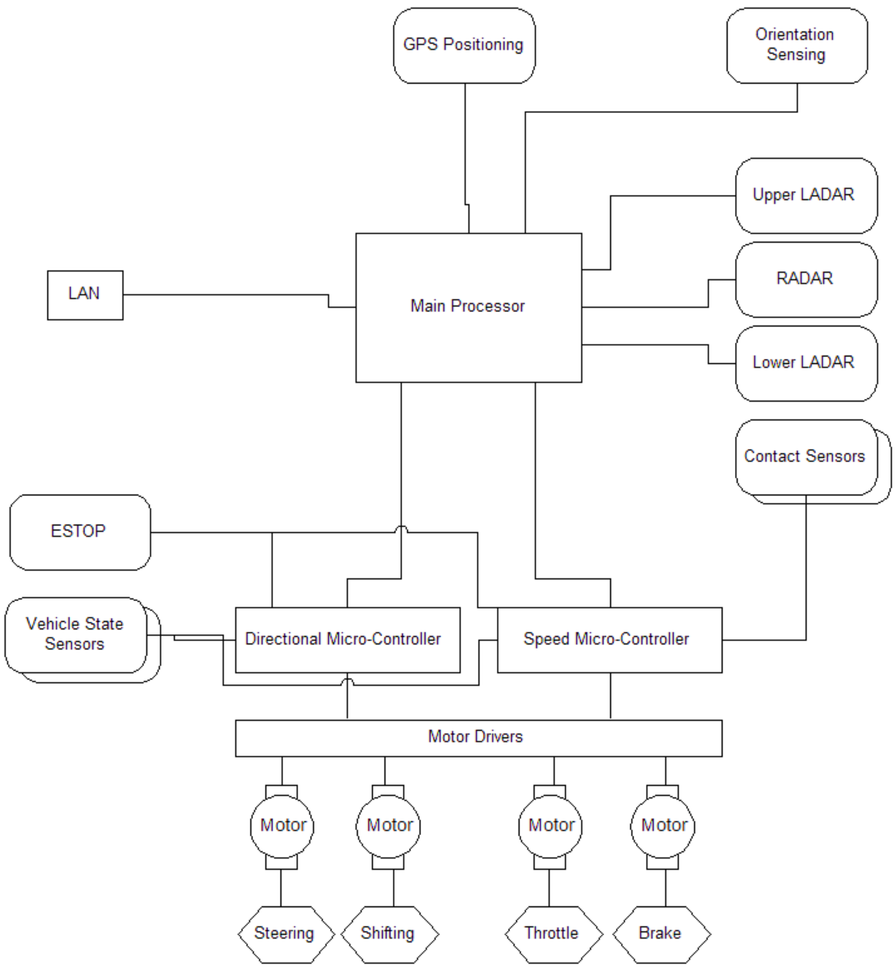

Figure 2: Tommy's physical hardware architecture

Automotive Plant

The automotive plant is a custom built dune buggy constructed by Sandtec Sandrails specifically for Team Jefferson and for the terrain in question. When considering the challenge's terrain, distance, and speed required, a standard gasoline-based automotive plant was deemed the most energy dense and reliable platform. When considering whether to modify an existing vehicle built for human drivability versus building a vehicle for computer drivability, the cost and effort needed for existing vehicle modifications was considered unnecessary. Also, since many of the features embedded into an existing human drivable vehicle add unnecessary power consumption (unless removed), and are designed with the human muscular and sensory form in mind, a vehicle built for computer drivability was considered more efficient and economical. What's more, when considering the particular off-road terrain, a dune buggy and sand rail basis was considered most appropriate for navigating and surviving in desert-like conditions.

The chassis, steel frame, and wheel shocks are built for low center of gravity and according to common dune buggy and sand rail specifications. A roll cage was constructed with a pseudo egg-shape large enough to fit one human and computing equipment inside. An aluminum shell (i.e. skin) is riveted onto the roll cage and frame. The 2.2 liter engine utilized is from a 1997 Subaru Legacy automobile and has automatic transmission. In addition to the engine's stock 12 volt alternator, a 24 volt alternator was added to charge a battery configuration that supplies 24 volt equipment. A radiator and cooling fan are rear mounted and the engine is mounted in front. The vehicle has four wheel drive and all wheel drive capability. A custom air conditioned and damped equipment box is mounted inside the vehicle to house all electronic components. One seat, steering wheel, brake pedal, gas pedal, and electronic shifting switch are also mounted inside to permit human drivability for logistical purposes. A custom 26 gallon gas tank was built and mounted in the back. The gas tank was sized to house enough fuel to power the vehicle and all equipment for more than 10 hours of desert driving time and for additional time idling in pause mode.

Actuation

A Bodine Electric rotary DC motor is directly coupled to the steering column for turning the steering wheel. Linear actuators donated by MITS Corporation are used to directly apply and release the brake pedal and to actuate the gear system for shifting between drive, neutral, reverse, and park. The engine's existing cruise control motor is used to accelerate or decelerate the vehicle via throttle adjustments. All actuation of such motors is performed through signals delivered from the vehicle's computing hardware.

A single switch is used to cut-in or cut-off signals delivered to the motors. When the control signals are cut-in, the vehicle may be computer driven. When the control signals are cut-off, the vehicle may be manually driven. A steering wheel, brake pedal, and gas pedal allow for direct human control. A single switch is used to electrically drive the shifting actuator under human control.

An emergency brake is mounted in the vehicle and is actuated via an E-stop DISABLE signal. An E-stop DISABLE signal results in actuation of the emergency brake and cut-off of the automobile's ignition source.

Sensors

CSI-Wireless' DGPS MAX system is used as the primary GPS positioning signal source. The DGPS MAX unit is configured to provide OmniSTAR corrected GPS information with sub-meter accuracy. The unit also employs CSI Wireless' COAST technology allowing the unit to provide accurate positioning information for up to 30 minutes during signal outages. As a diversely redundant positioning source, a CSI Wireless Vector Sensor PRO unit provides differentially corrected GPS information from beacon-based DGPS signals.

GPS outages are handled in a series of gracefully degraded states. The DGPS MAX unit provides the highest level of positioning accuracy from OmniSTAR corrected signals. As GPS errors are introduced and outages occur, the graceful degradation plan leverages output from CSI Wireless COAST technology and beacon-based DGPS information from the Vector Sensor PRO. As the confidence in positioning information degrades, the speed of the vehicle is regulated to safer travel speeds. In the event of a complete outage, a minimum speed is utilized and the vehicle's range and touch sensors are leveraged along with dead reckoning until accurate GPS information becomes available.

The main function of the Vector Sensor PRO is to provide orientation information. A combination of moving base station RTK, gyro, magnetic compass, and tilt sensor (accelerometer) are used to provide accurate heading and pitch information with 0.1 degrees accuracy. Roll information is yielded directly from the tilt sensor.

The DGPS MAX unit is mounted inside of the equipment box whereas the Vector Sensor PRO unit is mounted in the front of the vehicle above the engine due to its need for horizontal alignment with its antennae. All antennae are mounted on the vehicle's roof and separated a safe distance from each other to reduce interface. The DGPS MAX GPS antenna is mounted on the roof directly in the middle of the vehicle and the Vector Sensor PRO DGPS antenna if mounted in the back of the vehicle. The two antennae needed by the Vector Sensor PRO for moving base station RTK functionality are mounted in front of the vehicle.

A low mounted Sick LADAR and a higher mounted Sick LADAR reside in the front of the vehicle and are used for obstacle detection. Range information of up to 80 meters is provided and used to determine if there are obstacles in the vicinity of the vehicle. In addition to positive obstacles, the upper LADAR is able to help identify any negative obstacles (e.g. ditches) that lie ahead of the vehicle. While the maximum field of view capable of the LADAR is 180 degrees, only a 100 degree field of view is utilized providing both forward looking and periphery obstacle detection.

Additionally, an Eaton Vorad RADAR unit with 150 meter maximum range and 12 degree field of view is also mounted on the front of the vehicle. The RADAR provides forward looking obstacle detection at a farther range but with less resolution than the LADARs. As such, it primarily is useful as an obstacle warning as opposed to precise location identification sensor. It is also useful as an obstacle detection backup in those scenarios of low reflectivity that affect the performance of the LADARs.

A custom bump sensor and custom feeling sensor have been mounted on front of the vehicle. The bump sensor is triggered in two different points (left or right) upon contact with a fixed obstacle. Two outward extended “feelers” (left and right) depress upon contact with a fixed surface immediately to the left or right of the vehicle. Both contact sensor types are useful as a last resort in those scenarios whereby the LADARs and RADARs were unable or are unable to detect fixed obstacles immediate to the vehicle. All contact-based sensors are designed to trigger a digital on/off signal switch.

A series of feedback sensors that sense the vehicle system state are also incorporated into the vehicle’s design. Feedback encoders that provide information on the steering angle and brake position enable precise positioning of the steering wheel and brake level, respectively. Throttle position information is used to regulate and control the throttle level during acceleration and deceleration commands. The speed of the vehicle is derived from encoders on the wheels and the drive shaft. As a redundant, but less accurate, source of speed information, the DGPS MAX receiver unit also provides speed information utilized by the onboard processor. Signals fed back directly from the transmission provide information on the gear state of the vehicle used for shifting feedback control. Run/Pause and Enable/Disable signals are also fed into the onboard electronics to detect the state of the E-stop system in order to react appropriately.

Computing Hardware

All onboard processing is achieved by a combination of two micro-controllers and a single main processing card. The micro-controllers perform all low-level motor control, feedback handling, and vehicle state monitoring. The main processor card is a low cost and low power standard COTS 1 GHz processing platform from Via Technologies and performs all of the onboard vehicle sensor fusion, planning, and decision making.

Use of PRI-MAX allows flexibility in easily distributing software functionality across multiple processors with the simple modification of configuration files. Having the ability to add more processor cards to distribute load was considered early on in the design process. However, algorithm efficiency and the streamlining of PRI-MAX ultimately permitted use of a single main processor card for all functionality. Not only are there cost and scalability benefits for such an approach to armies of Unmanned Ground Vehicles (UGVs), but use of a single processor platform also provides sensor fusion and reaction performance advantages. Hence, a serial port extension card was added to the main processor card facilitating the ability to receive and transmit information via standard RS-232 ports from the various obstacle detection sensors, positioning sensor, orientation sensor, and micro-controllers. Regardless, an onboard wired LAN is provided to enable expansion on demand and communication with another computer during testing and mission initiation.

The micro-controllers selected have a Java Virtual Machine (JVM) embedded in hardware. Aside from cost-effectiveness in real time design, such micro-controllers were selected to facilitate reuse of the basic PRI-MAX robotics software platform. The micro-controllers receive vehicle feedback and state information through their inputs and drive motors via their outputs. Digital outputs are converted into high power drive signals through a series of motor drivers. Low cost motor drivers were selected that are able to source the required continuous and peak amperage for the throttle, brake, and shifter as well as a special motor driver that is able to source the continuous and peak amperage required for the steering motor.

Software

Figure 3 serves as a logical architecture overview of Tommy's software environment. Tommy's software may be logically partitioned into to a standard processing environment performing all intelligent decision making and a micro processing environment performing all low-level feedback control. Because PRI-MAX is a robotics framework that is built using Sun Microsystems' Java technology, any type of underlying computing hardware and operating system may be used. As a further demonstration of Tommy's cost effectiveness and ease of integration, an open source Linux operating system, Red Hat Fedora, was selected for use on the main processor platform. Additionally, a JVM and Java libraries for enabling serial communication were installed. The generic PRI-MAX Standard profile was then installed. Additionally, a PRI-MAX-UGV framework built as a specialization atop of PRI-MAX for general purpose UGV application was also installed and evolved. Finally, specific configuration and customizations atop of PRI-MAX and PRI-MAX-UGV were made for the DARPA Grand Challenge application. All sensor fusion, planning, and decision making are performed within and atop of the PRI-MAX Standard profile and PRI-MAX-UGV framework.

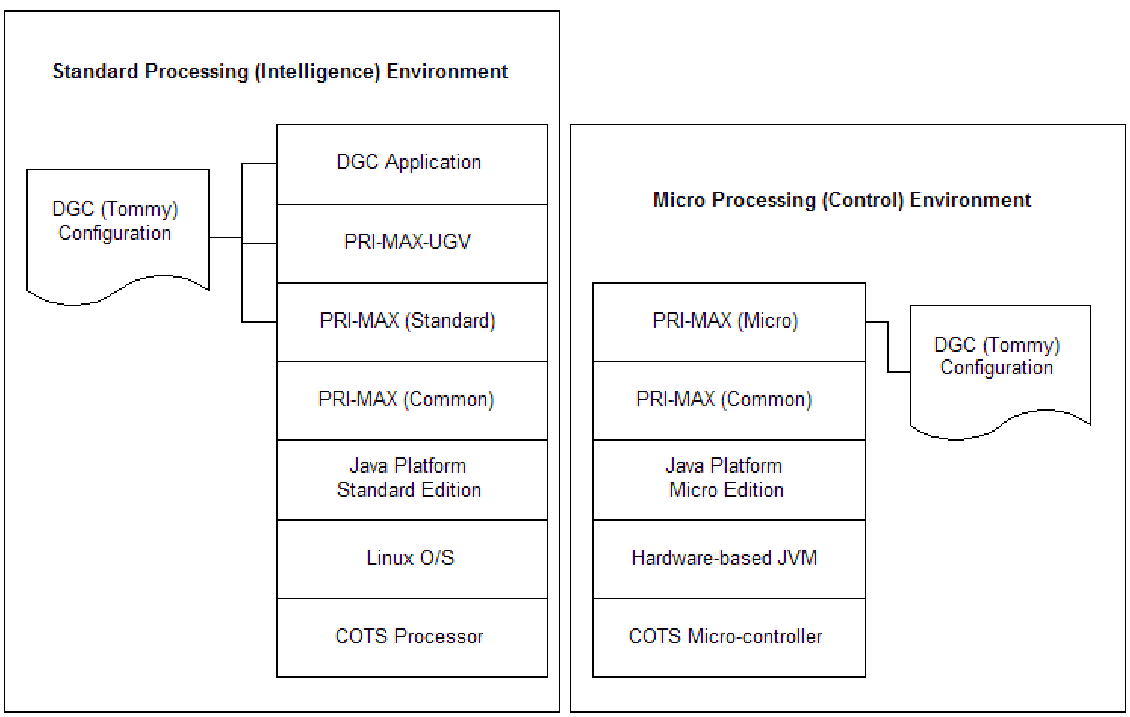

Figure 3: Tommy's logical software architecture

The PRI-MAX Micro profile was used to implement all functionality inside of the micro-controllers. Because the micro-controllers contain a JVM in hardware, the port of PRI-MAX

Standard to PRI-MAX Micro was seamless and required just 2 man-days of development effort. Hence much of the MAX platform that runs on the main processor card also runs in the micro-controller environment. The scalability, cost, and rapid development advantages follow directly from these features.

Figure 2 depicts the various sensors and computing hardware utilized inside Tommy. Within the PRI-MAX Standard profile running on the main processor, the sensory data is received and fused, a series of rules are applied to determine what plan of action should be undertaken, and then commands for actuation are issued to the micro-controllers. The micro-controllers then go through the same basic sense-plan-act approach using the PRI-MAX Micro profile. The PRI-MAX Micro profile receives commands from the main processor to actuate the drive-by-wire motors to a particular position. The command information is treated as an external sensor that directs the micro-controller. The planning component of PRI-MAX Micro on the micro-controller then employs standard feedback control algorithms to direct the motors to their desired position using information fed back via vehicle state sensors.

Whereas a typical robotic application development process would require extensive customization and software components built from the ground up for each desired function, the unique method employed by Team Jefferson was to use PRI-MAX to facilitate a rapid and cost effective application development approach. Modern object-oriented and component-based software development techniques are employed throughout given PRI-MAX' Java-based architecture. Use of PRI-MAX' basic sense-plan-act robotics platform also facilitated the reuse of common robotics framework code across the main processor and micro-control hardware. Finally, PRI-MAX' rule-based approach has enabled the easy and rapid integration of new rules of driving behavior for steering control, speed control, obstacle detection, and obstacle avoidance as Tommy was put through various test scenarios. As new rules of behavior were learned, Tommy was instantly 'trained' on the spot with new rules and unleashed to verify its newly evolved and learned behavior.

While complete independence from external human assistance during a mission has been a design requirement of Tommy from the start, consideration was given to using any intelligence derivable offline from map data prior to its mission. Such information would be used only as an added guide for Tommy's online processing and not to be interpreted as a definitive route to travel. Rather the information would serve to augment the online planning with heuristics about a particular route ahead of the vehicle. It was desired to automate this process as well rather than require or involve extensive human effort. To this end, a rule-based route planning approach was undertaken. Fair-Isaac's Blaze Advisor was used as the rule engine which serves as Tommy's pre-mission route planner. Given an RDDF file and publicly available map data, rules are automatically executed offline in just a matter of seconds to analyze this data and provide Tommy with important intelligence heuristics on projected elevation and route feature information. Tommy's online processing then uses this information for steering and speed control as it progresses along the given RDDF defined route.

The PRI-MAX platform provides generic sensor fusion capabilities that enable the identification and detection of obstacles based on range data, resolution of obstacles across multiple sources of obstacle information, and avoidance of obstacles based on such information. The result of such fusion capabilities are to output rules for steering and speed control. Such a paradigm is applicable to robotic applications that range from rat, to cat, to elephant sized. For the elephant-sized DARPA Grand Challenge application, the PRI-MAX-UGV framework augments the PRI-MAX platform with specific steering and speed control rules that are applicable for high-speed, long-distance, outdoor, and off-road or on-road conditions.

The PRI-MAX-UGV framework also augment's PRI-MAX' generic navigation framework by directing the robot to Geo-based latitude and longitude waypoints. The route of the vehicle is thus dynamically and constantly updated with new and intermediate Geo-based latitude and longitude waypoints derived from offline and online desired route information. An optimal path through available openings on the path are dynamically and constantly computed. The vehicle derives a steering plan to reach the dynamically established waypoints computed for the optimal path based on a set of easily configured steering control rules. The vehicle also derives a speed control plan based on closeness to obstacles, upcoming turns, maximum track speed, and other easily configured speed control rules.

A simple and core set of rules have been developed over time for steering and speed control. Such codified rules were mapped from human describable rules of driving behavior. As Tommy was placed into various navigation and obstacle detection scenarios and as we learned new desired rules of behavior, Tommy's rules of engagement were quickly updated. A more evolved Tommy is then taken out for testing of his newly imbued and learned behavior.

Various exception scenario and contingency rules have also been codified into Tommy as they were considered or discovered. For example, in the event that a path impasse is reached, the vehicle is stopped. If it is unknown whether or not the entire path is blocked, then the vehicle will back up and search for another path opening. Other exception rules that limit steering and speed have also been codified such as consideration of maximum allowed steering angle and speed on an incline to prevent tipping.

While such an infrastructure has enabled rapid codification of learned exception scenarios and behaviors, certain known 'instinctual' behaviors form the core of the PRI-MAX-UGV framework. For one, calculated and configurable maximum speeds for handling turns are built in. A novel waypoint following algorithm which dynamically computes the next waypoint toward which the vehicle should steer considers upcoming turns either known as part of the route or as dynamically computed by the obstacle avoidance and route planning components. The waypoint algorithm helps ensure that the vehicle stays within the course boundaries, reaches the next desired track segment, and takes turns as smoothly as possible. The speed control algorithm governs an increase in throttle for climbing a hill, throttle decrease when going down a hill, potentially braking when going down hill if the hill is steep, and slowing down the vehicle as its roll orientation becomes more severe.

Integration and Test

The testing mantra of Team Jefferson is to attempt immediate testing of any new feature and to continue testing it over time. That is, as a new hardware component is installed or a new behavioral rule is considered or discovered, Tommy is rolled out of the workshop doors into its dedicated proving grounds and immediately tested. Often, software modifications and new rules may also be implemented and deployed immediately while on the proving grounds. The reliability of the PRI-MAX platform alleviated us from having to worry about much of the basic robotics infrastructure since that was largely already existing, tested, and ready to apply in our application.

As new hardware and software components are added to provide desired functionality and are determined functional, a second pass was often taken to 'ruggedize' such components either by ensuring all hardware interfaces are secured or all software interfaces perform as desired under all conditions. Reliable, but cost-effective, hardware components were selected and tested against their specifications. As an example of lessons learned during testing, a point of failure discovered was an occasional excessive amount of current destroying motor drivers during certain tests. The source of such over-current was addressed and solved, software limits put in place, hardware protection circuits implemented, and on one occasion a new motor driver type was selected.

In addition to short run tests of functionality, endurance tests were also performed. Via a configuration variable setting, the vehicle can be told to follow an RDDF route for a certain number of laps. Running the vehicle for an extended period of time has helped identify potential hardware endurance and software feedback drift problems that can arise during extended missions.

All of our testing has been performed on rugged terrain. Just outside of our workshop doors, we have a proving grounds with bumpy fields, steep inclines and declines, trees, and plenty of natural positive and negative obstacles. All testing was performed under such conditions to reveal and correct problems with navigation and obstacle detection on such a terrain.

Conclusions

In one year's time, Team Jefferson has gone from having no vehicular entry to having Tommy built and ready to compete in the 2005 DARPA Grand Challenge. In just 10 man-months of software development time, Team Jefferson has gone from having a shell of a vehicle to Tommy, able to see, rationalize, and react to complete autonomous ground vehicle missions. The idea from the start was to demonstrate that this could be done more rapidly and cheaply by using PRI-MAX along with well integrated COTS software and hardware components. Finally, using such a software approach, the ability to reuse and extend such technology for use in multi-bot configurations with robots of all shapes and sizes is an economical and immediate reality.