AI Motorvators

Technical Paper

DARPA Grand Challenge 2005

Team name: AI Motorvators
Team Leader: Chris "C.J." Pedersen
chris@cjpedersen.com
www.aimotorvators.com

Written by: C.J. Pedersen &
Gunnar Ristroph
Dated August 28, 2005

Note: This technical paper is written in simple terms where possible, to encourage greater understanding among younger or less formally educated enthusiasts interested in learning about the technology

Abstract:

The A.I. Motorvators approach favors rugged, compact, and realistically deployable systems, which are able to be understood, calibrated and maintained by individuals with minimum technical and mechanical competence.

Rather than relying on a patchwork of off the shelf components, the A.I. Motorvators use custom designed and purpose built vehicle chassis, actuation mechanics, proprietary embedded hardware and software components which are specifically tuned for high performance autonomous vehicles. Many design choices are made as a result of automotive racing experience, including fundamental architectural choices relating to hardware and software interaction with the vehicle.

Effort has been made to keep systems as simplified as possible, and maintain a compact, neatly packaged, heavy-duty vehicle. Processing efficiency, multiple uses of sensor outputs and emphasis on minimal electrical power requirements contribute to overall design economy.

Significant work has gone into creating elegant, but simple systems. Although we enjoy having fun with the aesthetics (i.e. hood scoop and side exhaust) of the vehicle, it represents a comprehensive body of work in most aspects of its design, and control methodologies. Components and systems have been designed and developed iteratively over the last 2 years. The vehicle, hardware, software and overall architecture have been streamlined and optimized multiple times over an extended development cycle, and have been validated through extensive testing.

Team Philosophy

The A.I. Motorvators are a small but experienced team. Limited personnel resources must be applied in an efficient manner. The compressed schedule required has led us to breakthroughs in our work methods. Emphasis is placed on practical solutions and not theoretical discussion, especially during work sessions. All members share knowledge of automotive, software and hardware systems, and possess a high degree of specialized expertise in their respective areas of responsibility. All members must be willing to "get their hands dirty" and do mechanical work on the vehicle to whatever degree necessary. As there are no more than 4 persons working on the project (business and occasional help not included), design meetings are practically non-existent as a matter of policy, as are written requirements documents and formalized specifications. One-on-one meetings are preferred, combined with the occasional e-mail summary of general tasks to the team. High level decisions are made usually by the team leader and the person responsible for software, vehicle or hardware areas, with implementation methods left open for discussion and resolution. Team discussions typically take place in the truck while driving to and from testing, or in the shop at the end of a work session. The lack of formal design review is designed to save time, and eliminate tendency of group "over think," allowing team members the freedom to focus on solving problems.

Systems are kept realistic and reliable as a rule, and must be easily maintainable by a single individual. All aspects of design, programming, vehicle fabrication and maintenance are done in house, leaving few problems which the team cannot rapidly diagnose and remedy in almost any situation. Realistic systems, highly capable team members, and a results oriented approach have been essential in the success of the team.

Figure 1- A.I. Motorvators team and vehicle (from left Gunnar Ristroph, Steve Piorek, Hans Scholze, Rob Dukes, C.J. Pedersen, John Flynn, Tony Carlson, Don Tuch)

1. Vehicle Description

Vehicle is a purpose built, ruggedized, 2 wheel drive machine, featuring tube-chassis construction. Using a mixture of fabricated, OEM, and aftermarket parts and assemblies, it is designed to be lightweight, extremely durable, and moderately compact. It is powered by a 4.3 liter gasoline engine, and shifts gears through a compact 2 speed automatic transmission. A great deal of thought and development went into packaging the required components within a reasonably compact envelope. The vehicle was taken down to the frame rails and underwent a complete re-design and retrofit from its DGC 2004 configuration. The majority of components and systems are designed and developed by the team and built in house with high speed, high performance autonomous operations in mind.

The front wheels are steered by a proprietary hydraulic steer by wire system, featuring custom actuation mechanics and embedded control hardware. This is unit is simple, precise, and extremely durable. Power comes from a mechanically driven hydraulic pump. Throttle control is applied using closed loop control via proprietary actuation mechanics and embedded control hardware. Braking is accomplished with an air actuated hydraulic brake system. A sequential air shift mechanism allows the transmission to shift gears. It is important to note that the transmission “park” position is considered a manual lockout. The computer can not shift into or out of parking gear to prevent inadvertent autonomous operation of the vehicle.

The pneumatic pressure is generated by a 2 cfm onboard compressor and is stored in a 15 gallon stainless steel air reservoir at 60 PSI system pressure. Additionally a small back up reservoir, isolated by a check valve maintains brake function in the event of a pneumatic system failure.

Unique vehicle features include:

Compact heavy duty chassis and ruggedized suspension
Lightweight, agile vehicle
Sealed connectors and wash down proof electronics enclosure
Shock, vibration and dust proof electronics enclosure.
Proprietary actuation mechanics
Proprietary embedded control hardware and IMU
20 hrs of “run time” or 250 mile range on available fuel (22 gals)
Explosion proof “bladder type” racing fuel cell (SCORE approved)
Minimal power generation requirements
Ease of maintenance and field repair

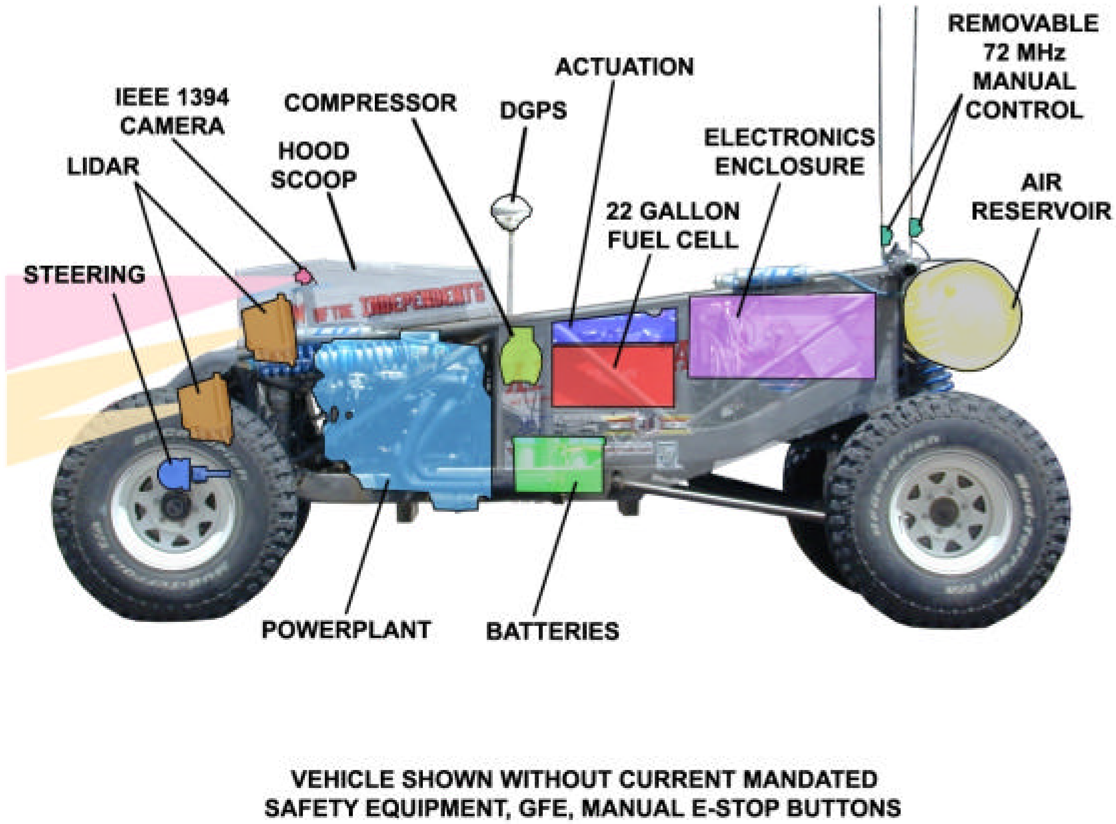

Figure 2- Vehicle components

Vehicle Specifications:

Length: 143 inches
Width: 71 inches
Height: 52 inches (less antennas)
Curb weight: 1850 lbs
Horsepower: 225
Fuel capacity: 22gallons
Electrical Power usage: 500 watts continuous (less engine starter motor)

Section 2 Autonomous Operation

Principals of operation

The software tells the hardware what to do with three key outputs: throttle position, brake force, and steering angle. Besides shifting the transmission, these commands are the only things that the software controls. Despite having only three main outputs, the software has many, many inputs. A wealth of information from terrain sensors, vehicle sensors, and GPS is constantly flowing into the computer.

Two laser scanners continuously scan the ground in front of the vehicle, giving a cross-sectional profile of the terrain. A color camera compares color pixel qualities of already driven terrain with that of the ground in front of the robot to identify similar terrain.

Sensors mounted on each of the wheels measure how fast each individual wheel is turning. Gyroscopes and accelerometers give additional information about how the vehicle is moving. Custom made hardware reads from accelerometers, gyroscopes, and wheel sensors and sends this data over Ethernet to the computer.

A Global Positioning System (GPS) receiver determines the vehicle's latitude and longitude coordinates using GPS satellites. Differential corrections from ground stations further improve accuracy. Odometry, gyroscopes, and a compass are used to estimate GPS coordinates when the signal is not available.

An emergency stop signal is available so that an operator can pause or terminate the vehicle operation.

The computer is faced with the challenge of turning this large amount of data into a few simple outputs that cause the vehicle to drive safely along its mission while avoiding obstacles and staying on the proper route. How the software achieves this is not simple. It recognizes aspects of the terrain such as roads and obstacles. Then it must choose a safe path that leads it towards its goal. Finally it generates throttle, brake, and steering commands so that the vehicle will follow the chosen path. Additionally, the software is responsible for reacting to contingencies such as if the vehicle gets stuck or if it is requested to emergency stop. All of this happens quickly and continuously as the vehicle navigates towards its destination.

By analyzing the terrain profile as given by the laser scanners, the computer can detect key features such as roads and obstacles. The laser scanner and computer are not, however, capable of detailed recognition. All obstacles are treated the same. Similarly, no distinction is made between paved and unpaved roads. The software remembers these features and also knows how it has moved relative to them based on information from its odometry, gyroscopes, and accelerometers. All terrain information is determined on the fly; no preprogrammed map data is used.

Knowledge of the surrounding terrain is only useful if the vehicle knows where it wants to go. The vehicle is pre-loaded with the RDDF, a list of coordinates that it should follow to reach its final destination. This route description forms the mission plan for the vehicle. The software uses the vehicle current latitude and longitude and refers to its mission plan to determine where it should go at any one time.

Sensor outputs are processed to locate features. The software chooses a path that avoids obstacles, stays on roads, and reaches its desired goal. This is a subjective process and many factors are weighed. Safety and speed are balanced to generate an appropriate vehicle velocity.

The computer uses a simple model of how the vehicle handles to generate steering, brake, and throttle commands. These commands are sent over Ethernet to custom made hardware that actuates the vehicle.

This sense, plan, and act cycle is repeats until the mission is completed or a contingency arises whereupon a pre-defined behavior is commanded to appropriately deal with the situation.

Processing

The main vehicle processor is a single Pentium 4 server running Linux. The server handles all of the processing for the entire vehicle including terrain sensing and image processing. The single processor arrangement was chosen for simplicity, reliability, and power considerations.

The server talks to the custom embedded hardware over normal Ethernet cables. By using standard networking equipment, all the devices can talk to each other and wiring is kept simple. The embedded hardware provides the platform for inertial sensing, planning, and control tasks. Laser scanners and the color camera talk directly to the server.

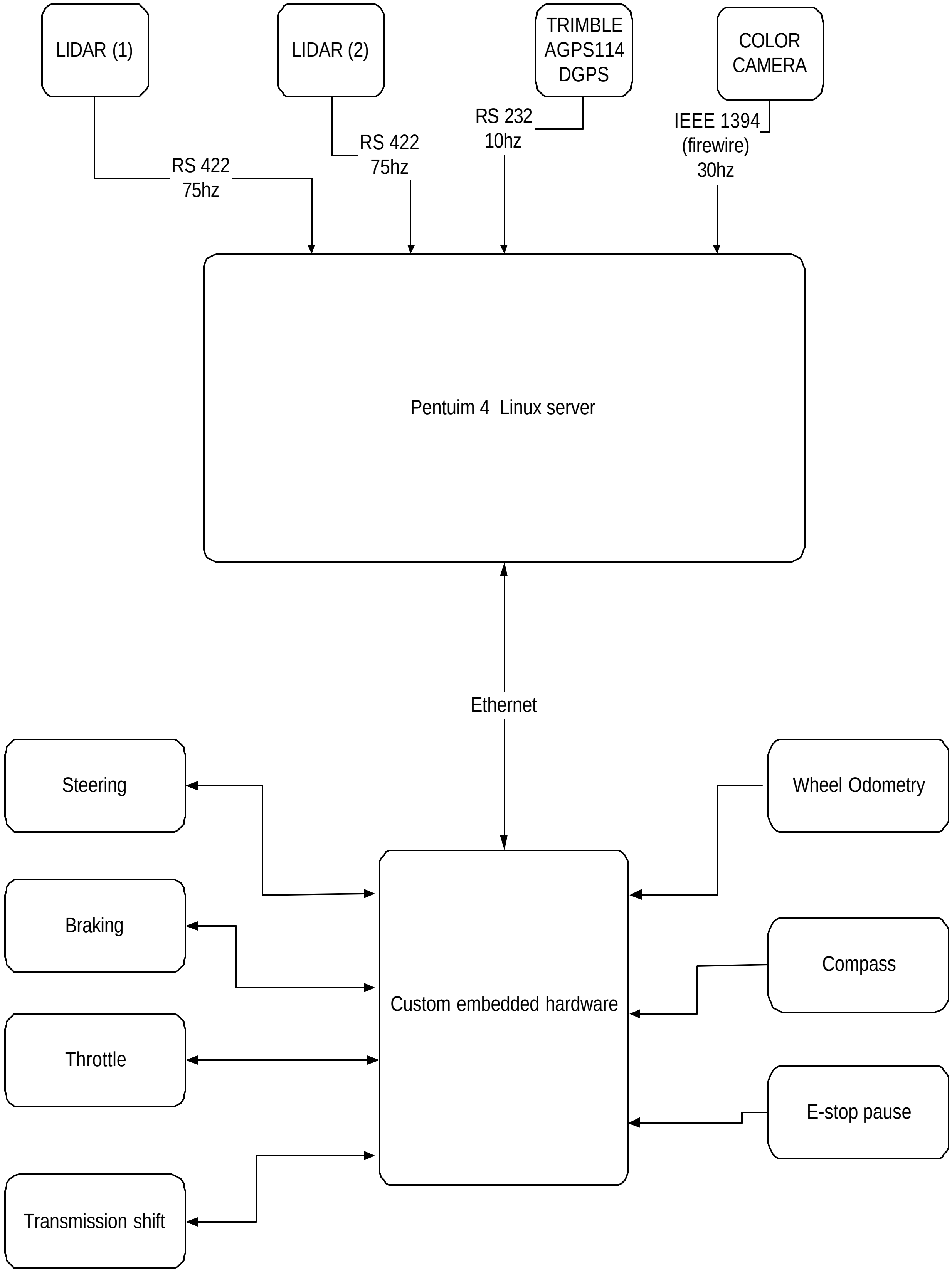

Figure 3- Network architecture

Localization

A Trimble AGPS 114 Differential Global Positioning System (GPS) receiver determines the vehicle's latitude and longitude coordinates using GPS satellites. Differential corrections from ground stations further improve accuracy. Omnistar subscription service is the source of the corrections. Odometry, gyroscopes, and a compass are used to estimate GPS coordinates when the signal is not available. DGPS Accuracy during vehicle testing was estimated as +/- 30cm.

The Embedded Control Hardware includes a proprietary Inertial Measurement Unit, which provides heading and translation of Position during DGPS outage. A Honeywell HRM 3000 compass module assists in updating heading information. This arrangement helps the vehicle with its guidance and localization updates especially during GPS outage. This has been tested with excellent accuracy (drift not significant) for over 2 minutes, and is believed to be capable of very good accuracy over longer durations.

Map Data is not used by the vehicle

Sensing

Two Sick LMS LIDAR units are used in a forward mounting arrangement along the vehicle centerline. One unit is mounted at approx 32 inches and the other at approximately 48 inches. Both sensors see a 100 degree field of view. The sensors can be adjusted to see between 20 and 150 feet in front of the vehicle. Sensors return time of flight information at 75 Hz for laser points, at 1 degree increments across the field of view.

One IEEE 1394 (Firewire) Color camera (Micropix-c640, 480 X 640 pixels) is mounted in the nose of the vehicle at approximately 48 inches in height. This camera sees approximately a 70 degree field of view and its range is approximately 250 feet. A color filtering algorithm decides similarity to already driven terrain using pixel data, and attempts to locate similar terrain in front of the vehicle. Frame rate is 30 Hz

Sensor outputs are processed to locate features. This includes drivable terrain, obstacles, negative terrain and moving objects. No local mapping of the terrain is attempted

Internal sensing includes Odometry (wheel speed and acceleration), Hardware fault reporting and Control state (steering angle, throttle position) IMU output is used to detect additional vehicle accelerations.

Vehicle Control

Common contingencies:

The vehicle must have a current mission as defined by an RDDF file, be within Lateral Boundary offsets, and have a valid path to the next waypoint to proceed autonomously. If the vehicle is stuck, an emergency stop requested, lost, or upon completion of the last waypoint, the normal planning cycle is interrupted and the appropriate pre-defined recovery behavior is commanded. This includes missed-waypoint, vehicle-outside-lateral-boundary-offset, or obstacle-detected-in-path and completion of mission.

Maneuvers such as braking, starting on a hill, or making a sharp turn without leaving the route boundaries are handled by normal path planning routines. The vehicle controller software running on the computer is responsible for the proper execution these maneuvers.

New terrain information, GPS readings, and vehicle data are constantly becoming available. Therefore the whole planning cycle repeats continuously, taking advantage of the latest information.

Manual E-stop buttons disable the vehicle by shutting off the vehicle's engine and activating the vehicle's brakes. This immobilizes the vehicle independently of computer control through a dedicated E-stop relay box.

E-stop pause uses the PAUSE signal interface from the DARPA Grand Challenge Safety Radio (DGCSR) and acts through software to provide a rapid and controlled stop while the vehicle computer maintains vehicle guidance and obstacle avoidance. Software also provides for the required 5 second warning siren and initiating the warning beacon whenever the E-stop pause is released.

E-stop uses the DISABLE signal interface from the DGCSR through the E-stop relay box immobilizing the vehicle by shutting off the vehicle's engine and activating the vehicle brakes. This operates through hardware, independent of computer control.

During normal operation throttle is limited by software as well as a mechanical stop. A rev limiter in the ignition system acts as a governor to limit overall speed independently of computer control. Throttle is designed to rapidly default to idle upon power outage or air system failure.

Multiple layers of fail-safes have been designed into all systems to promote safe and reliable operations.

Non- Autonomous control: As there is no capacity for a human operator, the vehicle must be manually controlled for positioning and movement. A 72 MHz RC Radio control system is used for this purpose. Components are easily and completely removable in less than 1 minute, and will only be used for movement to and staging the vehicle in the starting chute. Upon reaching the starting chute the equipment will be completely removed from the vehicle before actual NQE runs and for the GCE event. If desired this equipment can be turned over to safety officials in case the vehicle requires extrication somewhere on the race course. We have found this system permits fast and reliable staging of autonomous runs and allows for safe and controlled movement of the vehicle at close quarters and in confined spaces.

System Tests

The vehicle went through major redesign and retrofit of systems last year. Since then we have tested hundreds of miles on actual desert terrain, and continually recreate or test scenarios which have proved difficult or might be improved. Safety procedures are in place and are adhered to each time the vehicle is run. To ensure readiness at the NQE we will continue desert testing to expand vehicle capabilities, obstacle negotiation ability, team safety procedures, Support equipment organization, towing and recovery equipment and procedures, perform a thorough cleaning inspection and replacement of worn or damaged components, followed by a final “shakedown” test.

Component reliability has been outstanding. The following test have been performed

Hundreds of miles run on actual desert terrain.

Speeds in excess of 55 mph, including high speed braking and skid recovery tests

Continuous operation in desert climate for periods in excess of 12 hours is typical during testing with out engine overheating. We let the vehicle run all day from the time it rolls off the trailer until load up. Long periods of idle do not pose a problem.

Software testing including messaging reliability, exception handling, power cycle and reboot, general stability, accuracy of path planning, speed control, acceleration control and braking, positional accuracy, repeatability, behavioral consistency, have been tested thoroughly and exhaustively.

Battery capacity allows for approx 8-9 hours of run time with a complete power generation failure. Power requirements allow for using a standard automotive alternator, easily obtainable at most auto parts stores. There have been no occurrences of alternator failure. Power usage, reserve capacity, electronics cooling, wiring connections and overall electrical system reliability have been continually improved and tested.

Fuel consumption during idle and over typical terrain has been tested. The vehicle consumes 1 gal/hr at idle and 15 miles per gallon.

Pneumatic system has been tested to twice normal system pressure. Air system consumption has been observed in various conditions to be approx 0.5 cfm. The onboard compressor is rated 2.0 cfm, continuous duty and has been extremely reliable. A backup reservoir is mounted on the vehicle to provide air pressure for brakes after a total loss of system pressure. In the event of catastrophic air loss, electrical failure, or computer failure the vehicle is designed to come to a controlled stop. No significant air system failures have occurred.

Hydraulic system and actuation have been extensively run on vehicle. Components, hoses, and connections show high reliability with no leakage of fluid.

No spillage or leakage of any of the vehicle fluids have occurred.

Heavy duty all terrain tires are used in an “aired-down” state (12psi). The vehicle has been run extensively in rugged mountain pass terrain. Due to the vehicles light weight and large tire footprint no tire punctures have occurred to date. At the same time, Our 4 x 4 chase truck (2005 Dodge Ram) has sustained multiple tire failures running over the exact same terrain.

We had concerns that computer hard drives would fail over bumpy terrain, however no computer hard drive failures have occurred thus far probably due to shock isolation of electronic components.