Team D.A.D. Technical Paper

DARPA Grand Challenge 2004
Version 1.3
Submitted by David S. Hall
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1. System Description

a. Mobility.

1. The Team D.A.D. entrant vehicle will be a commercially available 4-wheel drive vehicle similar to or exactly like a 2003 Toyota Tundra owned by the team leader. The specific data about this vehicle (size, weight, etc.) is readily available at http://www.toyota.com/vehicles/2004/tundra/models_access.html. We are using the SR5 V8 Access Cab model.
2. The vehicle employs standard combustion engine locomotion and standard braking.
3. The vehicle will be retrofitted with two servo motor systems, one each for the steering and brake. The servo systems are similar to, or exactly like, those used on the team leader's robot "Da Claw" as seen on Robotica and in other robots in other robotic competitions. The Tundra employs an electronic throttle and that will be controlled directly from the D.A.D. electronics.

b. Power.

1. The challenge vehicle is gasoline powered. The DSP system (see description below), GPS, and cameras consume about 10 watts. The steering servo motor will consume an estimated 30 watts. The brake servo motor will consume about 10 watts each. All electrical power will be provided by the vehicle's stock electrical system. Additionally, the DSPs will have a 12v 2400 mah NI-CAD pack backup. The audible siren and warning beacon will also be powered by the stock electrical system.
2. The Toyota Tundra generates over 240 estimated horsepower.
3. The vehicle will be retrofitted with an extra fuel cell to provide an additional 50-gallon capacity.

c. Processing.

1. Digital Auto Drive (D.A.D.) will drive the vehicle. D.A.D. employs *multiple* DSP processors and servo motors. Each servo motor is controlled by a TI TMS2406 processor, using a CAN (Car Area Network) bus communication system. These three motors are in turn controlled by one TMS2407 class DSP that has a Navcom GPS, 6 Analog Devices gyros, 4 Analog Devices dual axis accelerometers, and two Honeywell dual axis compass sensors. This processor computes waypoint distance, direction, vehicle orientation, and dead reckoning. It sends waypoint distance and direction via the synchronous serial port to the vision DSP system

(described below). It receives turn and accelerate/brake commands from the vision system via serial port.

2. The vision system represents the major effort of the project. There are two 3-CCD prism assembly sensors as used on professional broadcast equipment. It is expected that this sensor configuration will result in vision acquisition comparable to that of the average human driver. The two sensors are aligned on 12" centers. This configuration gives depth information out to about *875* feet, and has precision of a few feet at 100' range. The sensors are directly connected to a memory bus on the first of three TI TMS6414 processors running at 1 Ghz each in the system. The first processor reads the two cameras, corrects for color errors, and computes the depth via an overlap scheme of each pixel in real time. This information is sent, a line at a time, to the second 6414, which deduces and then compares colors to define the significant objects in view. Additionally, a 3-D profile is generated of the terrain in view. This information is sent to the third DSP, also a 6414, which evaluates all probable paths over the terrain in view *(see Appendix A)* that also connect with the way point (as received from the 2407). Each computed path has a G force associated with it that, in effect, determines the speed that a vehicle could go over that path. The path with the fastest possible speed is selected. The command output is steering G force, and vehicle acceleration or deceleration information.

d. *Internal Databases.*
   1. Please refer to section 1.c.2.

e. *Environment Sensing.*
   1. Please refer to *Appendix A*. No additional sensors will be used.
   2. The sensors will be mounted on the front of the vehicle.

f. *State Sensing.*
   1. Please refer to section 1.c.1.
   2. Please refer to section 1.c.1.

g. *Localization.*
   1. The vehicle will rely on a non-differential GPS system for all waypoint destination locations. The GPS unit is a Navcom 2050G unit. The accelerometers are two pairs of Analog Devices ADXL-203s. The accelerometers are used differentially feeding three Texas Instruments ADS-1251 24 bit analog to digital converters. The gyro unit consists of six Analog Devices ADXRS-150s. Each gyro pair feeds a Texas Instruments ADS-1251 A/D converter. The gyro pairs are mounted inverted from each other such that the signal cancels out any common mode error. The compass is a Honeywell HMC-1002, feeding a pair of ADS1251 A/D converters.
   2. The system uses a dead-reckoning internal navigational system with its own internal sensors (see section 1.c.1) that accounts for speed and direction, and will continue to function during GPS outages.
   3. The system will log route boundaries and employ both the GPS and Dead Reckoning system to stay within the boundaries.

h. *Communications.*
    1. No.
    2. None.

i. *Autonomous Servicing.*
    1. No.
    2. No.

j. *Non-autonomous control.*
    1. The vehicle will be manually driven to and from the competition.

2. System Performance

a. *Previous Tests.* The 2406 and 2407-based systems are proven elements. The vision system is functional and road testing will begin once the new sensors are operational.

b. *Planned Tests.* Extensive tests are planned. No driver-less vehicle operation will be attempted before the race.

3. Safety and Environment Impact

a. *What is the top speed of the vehicle?* The vision system will resolve an obstacle the size of a human at a distance of 875' and have good range information within 300'. The precision of the depth match is +/-5' at a 100' range. Thus, the top speed will be limited by the capability of the vehicle, which we estimate to be about 100 MPH.

    The latency of the system consists of several delays. First, the shutter is about 1000 µS long. Then, the first line is read out about 100 µS later. The cameras are inverted, so the area closest to the vehicle is read out first. The distance and obstacle avoidance computations are done on a line-by-line basis, and there is a one-line delay, or 60 µS delay for each stage, and the processing goes through 4 stages, for a total of 240 µS. The vehicle will abandon top speed at any non-conforming visual situation. This has a delay of about 100 µS to communicate with the master motor controller, which then talks to the individual motors, and this has a 1000 µS delay. The motors will respond immediately, but will have a mechanical delay of about 5000 µS. However, the cameras have a frame time of 60Hz, meaning that worst case, an event won't be captured for 18,000 µS later. Thus, worst case, the vehicle will travel less than about 5 feet at 100MPH before reacting to an obstacle.

b. *What is the maximum range of the vehicle?* The range of this vehicle will be sufficient to reach Las Vegas, due to added fuel capacity.

c. *Safety Equipment.*
    1. No fuel containment is planned. The vehicle will be fitted with a Fuel Safe brand model OR-150TE 50 gallon fuel cell, which will replace the existing fuel tank.
    2. No fire suppression is planned.
    3. The vehicle will contain both audio and visual warning devices as described in the rules.

d. *E-Stops.*

1. The three servo motors have a watchdog timer associated with periodic receipt of CAN bus signals. Without a CAN bus signal, the motors shut off. The CAN bus signal for those two will be routed through a relay on the E-stop receiver, causing the signal to be present as long as en emergency stop command were not present on the E-Stop receiver. The delay is about 10ms upon receipt of an E-Stop command. The brake and throttle are spring loaded to provide the required E-stop feature. The steering will continue to function, however.
2. The emergency e-stop will consist of a 10Amp fuse mounted in a 100amp battery disconnect that will be located in the center of the rear of the vehicle. The vehicle will not be capable traveling in reverse autonomously. The ignition and fuel pump for the vehicle will be redirected through this fuse. The emergency e-stop command will actuate a transistor that will blow this fuse, thereby disabling the vehicle. The disconnect will have a loop that can easily be grabbed and separate the fuse assembly from the holder. The absence of the disconnect in the socket will indicate that the vehicle has been manually disabled. The disconnect will be provided with a large, brightly colored pull ring that will be clearly marked. The normal e-stop signal will be connected to the navigation DSP, and the vehicle will be brought to a stop in a controlled manor. Disabling the emergency fuse will also be sensed by the navigation DSP, and will also cause the vehicle to come to an abrupt stop.

3. The neutral function is as on a stock vehicle with automatic transmission. The vehicle is towable.

e. Radiators.

a. The vehicle will have no EMI radiators.
b. The vehicle will have no devices that classify a hazard to eye or ear safety.
c. See section 3.e.1.

f. Environmental Impact.

a. The vehicle shouldn't represent any significant environmental hazards that aren't comparable to those of the chase vehicles.
b. The vehicle is a stock 2003 Toyota Tundra.
c. The vehicle is a stock 2003 Toyota Tundra with an added gas tank.

Appendix A

DIGITAL AUTO DRIVE (D.A.D.) VISION SYSTEM NAVIGATION, ENVIRONMENT SENSING AND OBSTACLE AVOIDANCE

Navigation, environment sensing and obstacle avoidance using D.A.D., a DSP-based stereo-vision system, is a multi-step process. First, the images captured by the two digital cameras are rendered into a comprehensive 3-D depth map, using a multiple variable-width windowing technique. This scheme allows for identification of size and distance of objects in view, including the vertical position and contour of the road surface itself. Objects are not classified into categories per se – all objects are presumed solid and, if not road surface, to be avoided.

Next, some forty imaginary rectangles are drawn and superimposed over the 3-D depth map, which represent the vehicle's possible position and angle at the forty predetermined distances in front of the vehicle. Rectangles begin about 15 feet in front of the center of vehicle and extend to about 875 feet in front of the vehicle. This denotes where the vehicle will be after it has traveled through those points. Of course, the rectangles become smaller as they are placed further away from the vehicle in the 3-D depth map. The left and right sides of the bases of the rectangles, representing the wheels of the vehicle, are positioned on the identified road surface. If one side of the rectangle is positioned higher than the other, the rectangle is "skewed" accordingly.

Once the position and skew of the rectangle has been determined, the inside of the rectangle is scanned for objects other than the road surface that have a distance equal to or less than the proposed vehicle's distance. An object inside the rectangle would represent a collision of some type. Detection of objects inside the rectangle or a rectangle that represented an unacceptable G-force delta when compared to its adjacent rectangle (calculated in all directions – up, down, and side-to-side) would result in a new rectangle being drawn, slightly left or right of the original position, and the process repeated until an acceptable rectangle is found for that distance. Finally, the proposed path is reconciled with the next GPS waypoint to be intersected, and in the case of multiple acceptable paths, the one with the most direct path to the next waypoint is chosen.

Ultimately, an acceptable set of up to forty rectangles is determined, one at each distance between 15 and 875 feet, all of which combine to indicate a clear path ahead. This is the path that the vehicle will follow, and this path is communicated to the navigational DSP/servo-motor actuator system. The offset of the rectangles from a straight, level path, either vertical or horizontal, at different distances is translated into the G-force that the vehicle will be subject to when following the proposed path at the current speed. That information will be used to determine the maximum speed that the vehicle should be traveling, and acceleration or braking commands are issued accordingly.

In the case where a partial set f rectangles showing only a partial view in front of the vehicle has been calculated (for example, going up a hill where the road drops off), the vehicle will slow to a speed that lets it react to potential unseen obstacles within its operating limits (i.e. braking distance and turning G-forces). The D.A.D. system will only issue navigational commands that steer the vehicle onto a safe drivable surface that is understood by the vision system.

Obstacle avoidance is robust when using this procedure. For example, a fence post is an easy object to get accurate distance measurement on, and clearly protrudes into the proposed vehicle path. Power line pylons are also easy to get distance information on (the steel frame members are wide enough to see from hundreds of feet away, and the concrete bases are even more robust objects than the frame). Ditches and downgrades are cases that are handled by the first part of the rectangle location scheme, in that the rectangle must be placed successfully on the road surface without excessive skew. In the case of a ditch parallel to the road, the proposed wheel contact area is either seen as excessively tilting the vehicle, or one wheel's ground position can't be seen at all. In the latter case, what is seen is either the far side of the ditch or the horizon, either of which would be rejected when finding an acceptable vehicle path. As for an unavoidable depression in the vehicle's path, the G-force measurement will show that the vehicle's path has too much vertical movement, and the vehicle's speed will be reduced so that acceptable G forces are encountered by the vehicle when traversing the depression.

The dry lake bed condition is not handled as a special case – the vision system is good enough to determine features of the lake bed that reveal it as drivable road. Since nothing will be found in terms of obstacles in the proposed path, the system will accelerate the vehicle accordingly (potentially up to 100 MPH) and navigate directly to the next waypoint.

Team D.A.D. (Digital Auto Drive)
Addendum to Technical Paper

Submitted by David S. Hall
Monday, October 13, 2003

Introduction

This Addendum is intended to further describe the technology Team D.A.D. intends to employ for environmental sensing and obstacle avoidance for the DARPA Grand Challenge race. The entire contents of this paper are considered proprietary and confidential to DARPA.

Environment sensing system requirements

The Team D.A.D. vehicle will rely exclusively on a stereo-based vision system for its environment sensing and obstacle avoidance needs. This approach was selected for the race for the following reasons:

1. The contest is a 10-hour maximum race over an expected 250+ miles.
2. The vehicle will be expected to go "flat out' over the lake bed area of the course – up to 100 MPH.
3. The contest will begin at 6:30 AM and occur during daylight hours.

Criteria 1 and 2 dictate that an approach compatible with high speeds (i.e. up to 100 MPH) be employed. To achieve such speed, the sensor system has to be able to comprehend the road surface and potential obstacles hundreds of feet away in order to be effective. Very little computational time lag can be tolerated.

A high quality stereo-vision system can meet these needs. We are unaware of any other high quality vision systems in existence - the computer power to achieve these results has only been around for several years. The Team D.A.D. approach is highly integrated – all PC boards are proprietary and designed exclusively for this purpose, state-of-the-art TI 6400 DSP computers are used, and processing code is all written in low-level assembler to maximize processing speed. The result is a system that can assess the road surface and potential obstacles out to over 750 feet, and do so over 60 times per second.

Criteria 3 indicates that a vision system is an acceptable method of navigation since the race will take place in daylight. A passive vision system (as opposed to an active system that emits a signal such as radar, sonar, or other system) is preferred because it requires low power, can discern colors, and ultimately can comprehend potential obstacles at greater distances and with more accuracy than active systems.

Please see supporting photographs of the D.A.D. system on the following pages.

NOTE: Team D.A.D. would be happy to demonstrate any aspect of the D.A.D. system upon request.

Supporting photographs.
The D.A.D. system is operational and currently can sense potential obstacles in the vehicle's path. The following photos demonstrate the progress on the system to date.

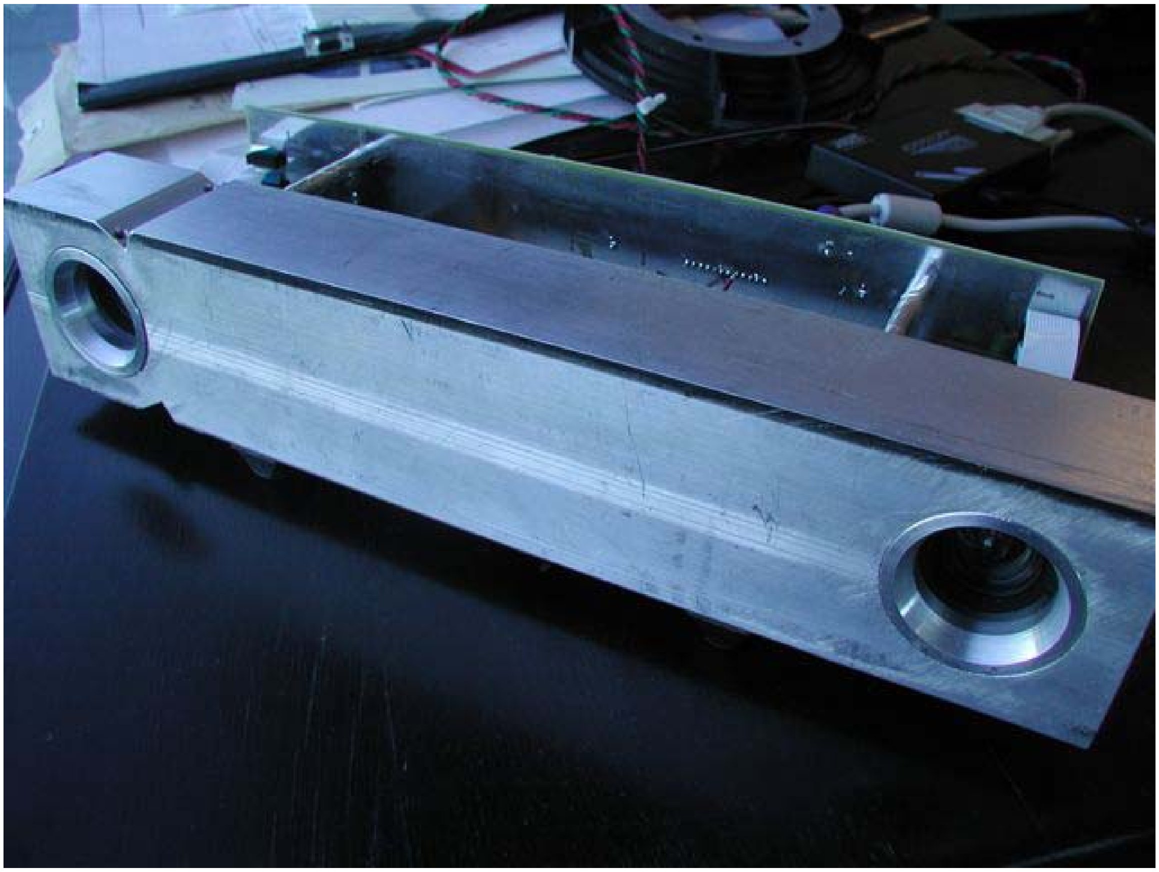

Photo 1: Camera Assembly. This photo shows the fixed stereo cameras as mounted in their custom machined housing. The exact position of the lenses is adjustable, since the cameras must be aligned to within a single pixel in order to resolve depth information. The distance between camera centers is 12", which provides for high depth resolution. This housing will be mounted on top of the race vehicle and be protected with a scrolling (i.e. self-cleaning) transparent plastic film protection mechanism.

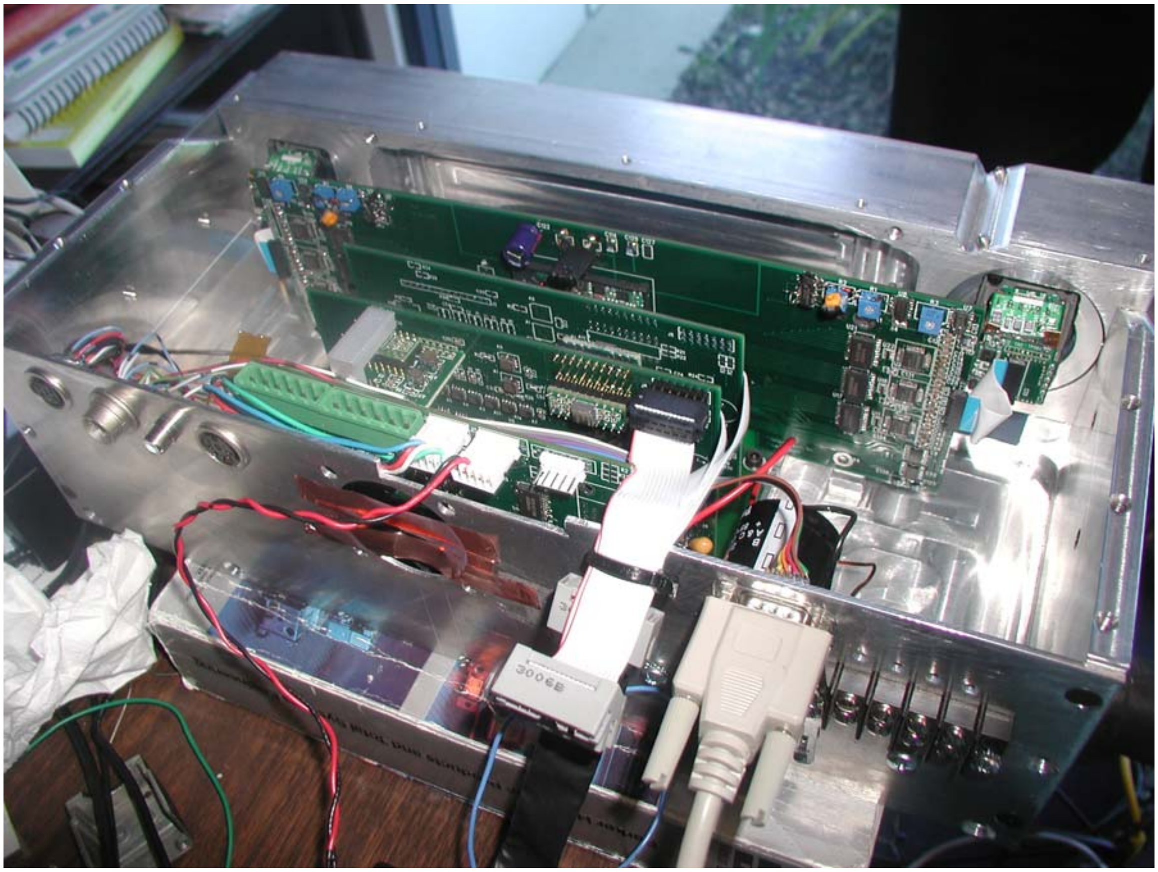

Photo 2: Supporting electronics. This shot shows the electronics associated with the camera system. The cameras themselves are broadcast quality 3-CCD color prism assemblies. Custom electronics have been fitted to the sensors (on the orange board) to capture the image data directly into the DSP's memory. Two TI 6400 DSP chips are used to process the video signal, each running at 1 GHz. Each pixel of the cameras' data (8 bits x 3 colors x 2 cameras = 48 bits) is fed into the first DSP chip in the main (green) board. There the depth calculations take place and a 3-D terrain map is created. Next the terrain data is sent to the second DSP chip, also on the main board, where the vehicle path computation takes place, and the image is formatted for the screen display (shown below). All calculations are done in real time at 60 frames per second. Approximately 30 billion pixel operations are performed each second.

This vision system data is reconciled to another board (not shown), which has a Navcom GPS, gyros, and motion sensing accelerometers on it. This board, controlled by a TI 2407 DSP, will control the vehicle's servo motors, reconcile waypoints, and correct for navigational gaps between GPS positional information input. It is on this chip's memory where the GPS waypoint data will be entered on the day of the race.

Photo 3. Generated video image #1. This is a shot looking into our parking lot. This image was captured by the two cameras, processed by the DSP chips, and the video generated by the second DSP chip. Note the light pole in the center of the screen – this is an obstacle that must be avoided.

Photo 4. Generated video image #2. This image was also generated by the DSP, however in this case the computer has been programmed to identify obstacles to be avoided in yellow. Note that the light pole is now marked with yellow, as all obstacles would be that exist at the 50’ distance range.

Another look back at photo 3 shows that certain objects behind the light pole are actually yellow – this represents an identified obstacle (in this case a hedge and several trees) about 100 feet in front of the vehicle. If this were actual navigation, this 3 foot-high hedge would need to be navigated around, as would the light pole. The D.A.D. stereo-vision system identifies all potential obstacles from 15 to over 750 feet in front of the vehicle, and does so at a rate of 60 times per second.

The system has also been tuned to identify line marking on the road surface. Notice in photo 4 the parking lot stripes that appear green. The parking lot stripes are actually white but the software has identified them as stripes by their width-to-distance ratio, and the software then turns the identified stripe green. These stripes directly yield the vehicles offset to them, as there distance is calculated via the stereo imaging. The first application of this system will be to follow the stripes on public roads. There is also identification of yellow stripes as separate from white ones.

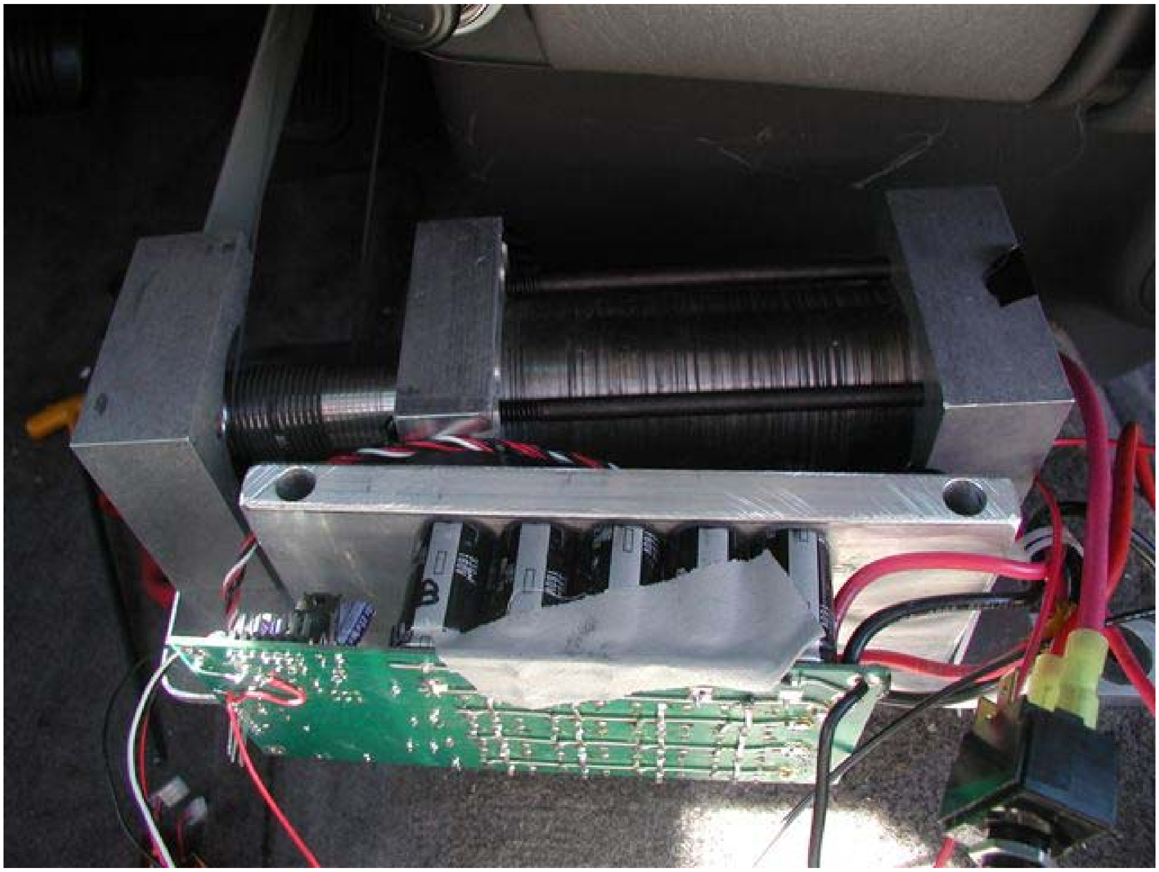

Photo 5. Servo steering motor and controller assembly. This image shows one of the custom motors to be used for vehicle navigation. Each motor is a rare earth magnet brushless motor generating up to 20 HP. Note the pulley and cable assembly on the left. The attached circuit board is the motor controller, and is based on a Car-Area-Network (CAN) bus technology. This motor/controller assembly is proven technology as it has been used successfully in various fighting robots in the past.

Photo 6: Servo Steering motor and controller assembly mounted in the race vehicle. This image shows the steering motor as mounted in the race vehicle. The pulley assembly connects to another pulley assembly above and to the right of the gas pedal, and the cables terminates at another custom pulley mounted onto the steering column. Like assemblies will be installed for gas pedal and brake manipulation.

Conclusion.
Team D.A.D. is hard at work on our entry for the DARPA Grand Challenge and we've made tremendous progress. Our technology is viable and our timeline is achievable. We expect that our stereo-vision system will allow the Team D.A.D. race vehicle to achieve speeds of up to 100 MPH, allow for obstacle avoidance and provide overall navigation that combine to give us a realistic chance to win the race.

Again, any aspect of the D.A.D. technology can be demonstrated upon request.