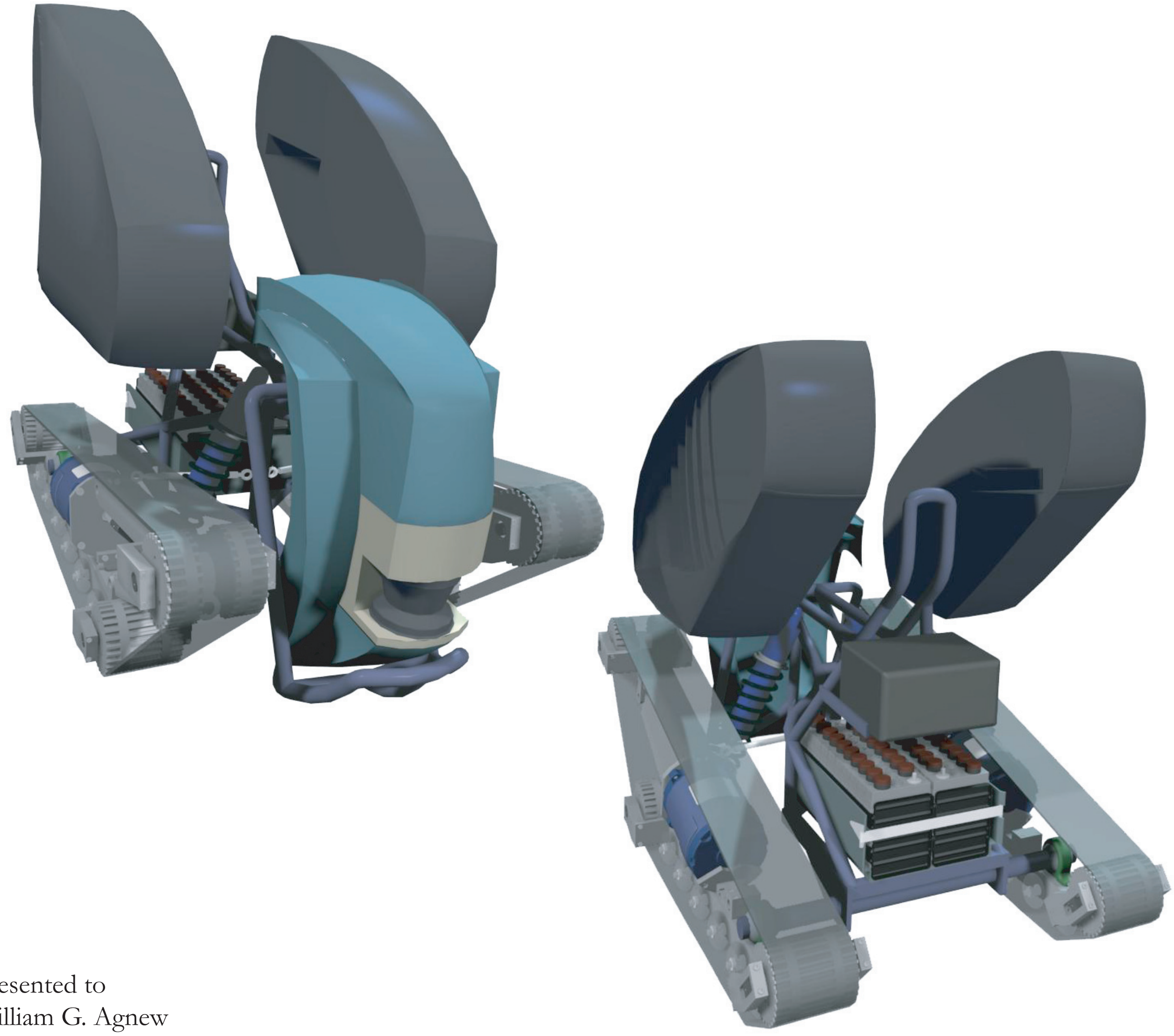
# 2004 Kodiak Design Report

## 12th annual intelligent ground vehicle competition



Presented to
William G. Agnew
Chair of Design Judging Panel

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ARVP
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## 1.0 INTRODUCTION

The University of Alberta's Autonomous Robotic Vehicle Project (ARVP) first introduced the *Kodiak* nameplate at the 2002 Intelligent Ground Vehicle Competition (IGVC). Since then, the tracked vehicle concept has progressed into a turnkey platform suited for all 2004 IGVC events and many other applications. The only elements remaining from the 2003 edition of *Kodiak* are the proven self-contained propulsion packages. Nearly all other mechanical, electrical, and software systems have been redesigned with a modular and generalized approach as to promote safety, reliability, and versatility. Improved sensors have also been added to enhance the abilities of the vehicle (see Table 1 for highlights). This report aims to outline the organization of the team, the design process and tools, and the subsequent mechanical systems, electrical systems, software strategy, and platform capabilities.

| |
|---|
| Laser scanner replaces SONAR |
| All new software system and user interface |
| Modular electrical system architecture and $I^2C$ communication replaces central microcontroller |
| Advanced power management and distribution |
| NiMH replaces lead-acid batteries |
| Digital compass and inertial measurement added |
| Simplified suspension and functional vehicle body |

**Table 1**: Major system change highlights

## 2.0 TEAM ORGANIZATION

Improvements to *Kodiak* reflect the ARVP's move to a more simplified team structure. The multidisciplinary tasks are shared by three Divisions: Platform Development (PD), Electrical Engineering (EE), and Computer Engineering (CE). Each task is assumed as a project by a student or group of students and is carried out from design to final fabrication and testing. This approach proves to be successful given the varied schedules of the forty undergraduate students that volunteer their time with this extra-curricular team. Each of these projects work with a specific Division Leader who report in turn to an overall Project Leader. As a registered student group at the University of Alberta, the team's constitution stipulates the electoral process used to choose these leaders.

Communication in such a large team is essential. Bi-weekly general meetings are held to update all ARVP members with team progress and upcoming events. Individual projects are also presented to encourage involvement and discussion at these and other Division-specific meetings. The ARVP also maintains its own web and email server to exchange internal information and publish public results.

The scale and organization of the ARVP are also conducive to the development of non-IGVC specific interests. For example, the PD Division is currently exploring miniature and legged locomotion platforms while product development is often being considered. The community outreach aspects of the ARVP have always been one of the team's strongest points. As a means of encouraging interest in robotics, engineering, and science in general, the team continues its numerous visits to the local science center, schools, and a range of public events. New this year is an effort to bring grade school students to the University with a workshop using a small robotics kit designed by members of the EE Division. This public involvement is also essential to establish sponsors that enable the ARVP to function with the best tools and materials available.

**Figure 1**: The ARVP at the Odyssium Science Centre in Edmonton, AB in January 2004.

## 3.0 DESIGN PROCESS AND TOOLS

The changes made to *Kodiak* are a result of another iteration of the ARVP's engineering design process developed in 2003 and illustrated in Figure 2. To further enhance the primary design goals of safety, reliability, and versatility, a number of vehicle attributes were identified for improvement (Table 2). The desired product was a better performing vehicle that was easier to use, debug, and expand upon.

| | |
|---|---|
| **Safety** | Accessibility |
| | Component protection |
| **Reliability** | Redundancy |
| | User Interface (UI) |
| | Modularity |
| **Versatility** | Expandability |
| | Performance capabilities |

**Table 2**: 3 primary design goals and corresponding vehicle attributes identified for improvement

These modifications called for fundamental changes in the hardware and software architectures of the robot during the next step of the design process. Communication between Divisions resulted in the shift towards generalized system development very much akin to the Joint Architecture for Unmanned Ground Systems (JAUS). This largely platform-independent and modular approach simplifies new sensor integration while setting standards for connectivity between components and allowing for independent concurrent development.

Mechanical changes benefited from the use of PTC's Pro/Engineer and Pro/Mechanica for part design, assembly, optimization via finite element methods (FEM), and engineering drawing generation. Rhinoceros by Robert McNeel & Assocciates was used to visualize component placement, design the vehicle shell, and prepare a model for CNC machining of foam molds. Electrical aspects of the team

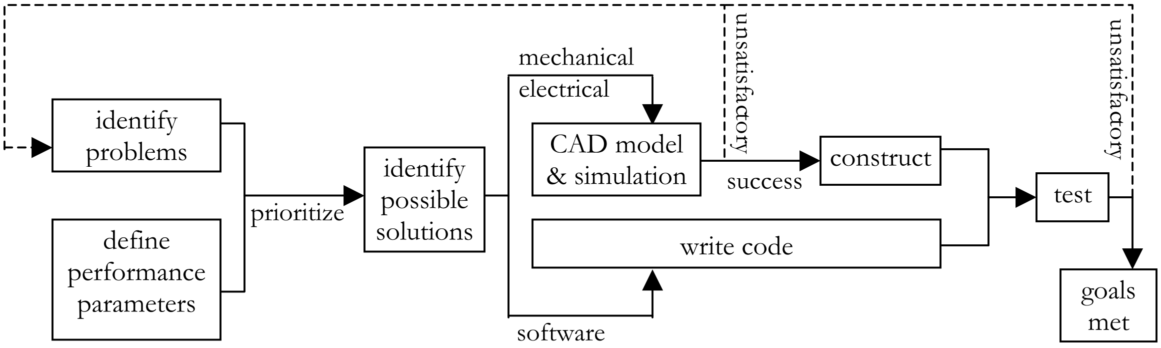

**Figure 2**: Vehicle refinement process diagram.

also benefited from CAD software with the use of Protel by Album for schematic and circuit board design. All of these software packages serve to promote optimization and reduce fabrication errors and prototyping requirements. Design tools in the software concerns of the ARVP included the better use of a Concurrent Versions System (CVS) that records a history of source files on a central server for cooperative development. The same group also benefited from the introduction of the DOxygen package that produces excellent on and offline code documentation directly from its source. This system facilitates collaboration by clearly outlining relations, dependencies, and inheritances in both graphical and text-based forms.

The ARVP has placed much more emphasis on the testing stage of the design process this year than in the past. While mechanical modifications were carried out, electrical and software development progressed with the IGVC 2001 entry, *Bear Cub*, as a testing platform. Indoor testing facilities were also established with a lane, traffic barrels, and a ramp. Once the snow stopped falling in Edmonton in late April, outdoor testing on grass was done and culminated in a Mock Competition to simulate the IGVC events.

## 4.0 MECHANICAL SYSTEMS

*Kodiak*'s mechanical systems are a reflection of the design goals outlined above. The proven track assemblies are easily adapted via simple pin connections to new vehicle configurations such as the rear-axle frame and suspension presented here. An innovative vehicle body also provides component protection while preserving accessibility. The entire assembly is designed for easy takedown, transport, and reassembly with few and simple tools. An overall view of the mechanical system is shown in Figure 3 and performance data and component specifications can be found in sections 7.0 and 10.0 respectively.

## 4.1 Propulsion

*Kodiak*'s tracked assemblies are self-contained propulsion packages that are the product of three years of development. They have been optimized for weight and performance and were only slightly modified this year to accommodate a new frame. In each assembly, a 24VDC 1/3 HP motor at 1800 RPM actuates a 10:1 worm gear in the upper pulley to displace a single sided timing belt. The tracks have been recently cleated to reduce belt wear and improve climbing abilities. The torque provided is adequate for both skid and arc turning in a variety of environments thus allowing for a range of vehicle motions.

## 4.2 Frame and Suspension

*Kodiak*'s frame and suspension were redesigned to achieve a less costly, more space efficient, and suitable arrangement compared to the previous 3-bar linkage model. The new frame also accommodates a second battery form factor and an adjustable section for variable height sensor mounting. The frame is fabricated with welded round and square mild steel tubing and houses a locking battery tray and high power electronics box. Independent suspension is achieved with each side of the vehicle having a shock to provide damping and regulate track assembly rotation about a rear axle. Two front linkages per side constrain lateral motion and allow for adjustable track toe-in.

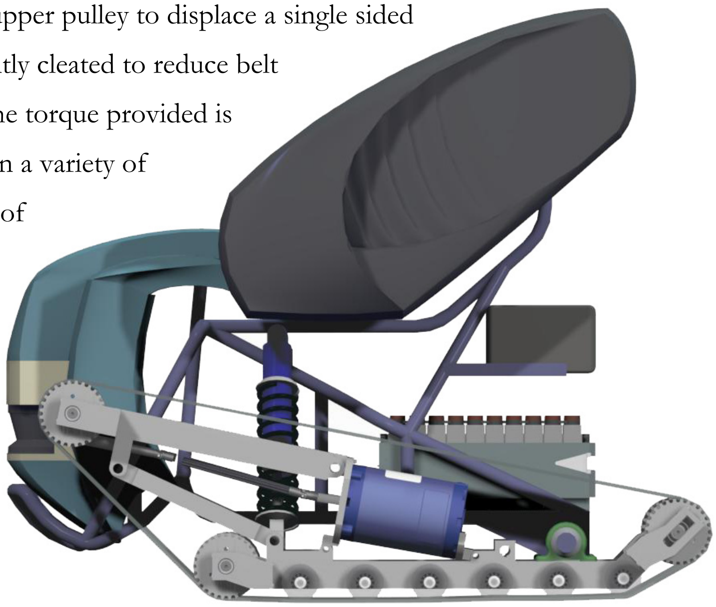

**Figure 3**: Side view of *Kodiak* showing placement of mechanical components, batteries, laser range scanner, and power box.

## 4.3 Vehicle Body

An exploded view of *Kodiak*'s new fiberglass body is shown in Figure 4. This innovative design features two symmetric pods at the top rear of the vehicle and a head located at the front. Linear bearings allow the pods to slide apart to reveal a payload bay and facilitate computer and battery access. Removing the top cover of the pods by way of quarter-turn fasteners provides access to the sensors and control electronics housed inside. New components are easily added to the shelving and sheet metal inlays inside the pods. The head unit can be

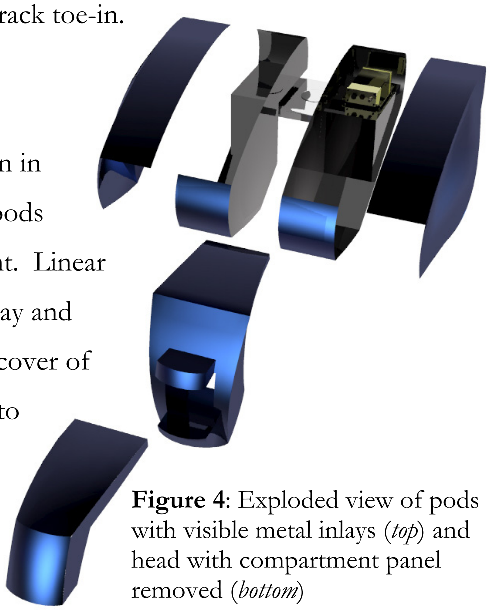

**Figure 4**: Exploded view of pods with visible metal inlays (*top*) and head with compartment panel removed (*bottom*)

moved vertically with the adjustable section of the frame to set the height of the laser range scanner. The head also features a storage area for connectivity equipment for sensors at the front of the vehicle.

## 5.0 ELECTRICAL SYSTEMS

Design goals necessitated a reorganization of *Kodiak*'s electrical systems. Changes were carried out on all levels from the addition of sensors to the overhaul of physical and communication interfaces and power distribution. The integration of these components is represented schematically in section 5.2

### 5.1 Sensors

A host of new sensors including a laser range scanner, digital compass, and inertial measurement unit compliment established digital video cameras, shaft encoders, and a differential GPS receiver to make up *Kodiak*'s perception of itself and its surroundings.

### *5.1.1 Cameras*

*Kodiak* employs three Videre Design DCAM digital video cameras that together provide a 180° view of lines and potholes ahead of the vehicle as shown in Figure 5. These adjustable full-motion capable cameras are operated at 7.5 frames per second with a resolution of 640x480 pixels and a 24-bit color depth. The DCAMs feature internal processing functions such as auto contrast calibration, a number of software-controlled parameters, and an IEEE-1394 interface.

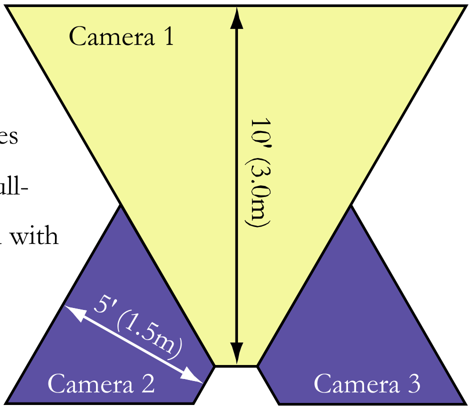

**Figure 5**: A three-camera arrangement provides a 180° view in front of the vehicle.

### *5.1.2 Laser Scanner*

The replacement of a nine element SONAR array with a Sick LMS-291 laser range scanner (LMS) has increased the angular resolution of the physical obstacle avoidance system by over forty times to 0.5 ° increments across a 180° field of view. This reliable industry standard solution maps obstacles up to 98.4' (30m) away with 0.39" (10mm) accuracy and a 26ms scan time. The LMS streams high-speed serial data over a RS-422 to USB converter allowing for up to 500kbps transfer rates.

### *5.1.3 Differential GPS*

The ARVP continues to use the Trimble AgGPS 132 for the reception of differential GPS (DGPS) position and heading information. The unit is user-programmable and features a selectable 1,2,5, or 10 Hz update rate with data transferred via serial RS-232.

#### *5.1.4 Digital Compass*

For heading information while stationary, a Honeywell HMR3100 digital compass was introduced. This unit provides an angular resolution of ±5° (RMS) relative to the Earth's magnetic field and is calibrated automatically by a custom host board. Communication is by serial RS-232.

#### *5.1.5 Shaft Encoders*

The E3 optical encoders by US Digital measure the revolution rate of each motor shaft. These sensors close the control loop by providing feedback necessary for predictable and efficient motor response.

#### *5.1.6 Inertial Measurement Unit (IMU)*

A Rotomotion six degree of freedom (6DOF) IMU supplies three-dimensional rotation and acceleration information. This data can be used to determine vehicle velocity and displacement much more accurately than the shaft encoders that cannot account for track slippage inherent in *Kodiak*'s skid steering system. The IMU is also used to sense tilt when traversing over obstacles and ramps.

### 5.2 System Integration

To facilitate the integration of the new sensors and simplify the interfacing of components, a new system architecture was developed to overcome the limitations of the previous central microcontroller arrangement. In addition, the main computer has been substantially upgraded and packaging has been redesigned to improve accessibility. The command structure and device diagram of the new system is shown in Figure 6.

#### *5.2.1 Main Interface*

The focus of the revised electronics system is the Main Interface (MI). This device is a Master that routes signals between the main computer and specific Slaves over an Inter-IC Control ($I^2C$) bus. This design offloads actual functionality to each Slave thus simplifying the integration and expansion of new features. A good example of a slaved device is the User Interface (UI) built around the Earth LCD PicL and RC Systems V8600A voice synthesizer. The programmable integrated circuit (PIC) based PicL has been used to create a button-based menu for controlling devices and viewing system properties such as battery level on a 240x64 pixel display. Prompts from the voice board are useful during testing and debugging stages.

The MI also communicates with a radio controller, emergency stop, and the motor drivers and encoder feedback to provide proportional, integral, and derivative (PID) motor control.

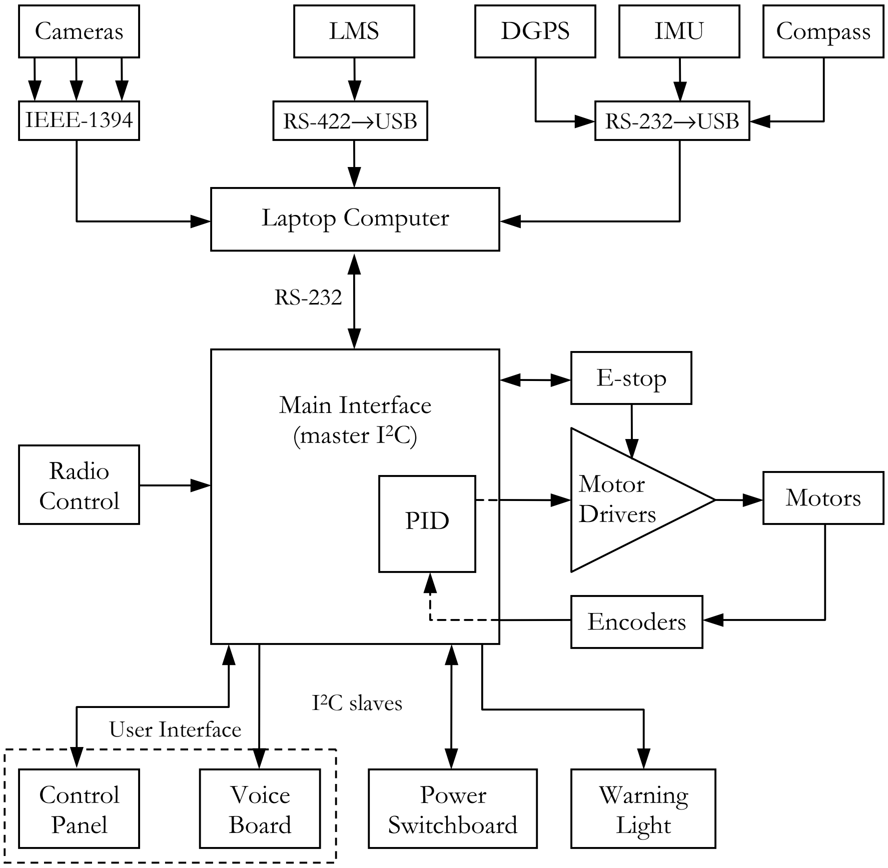

**Figure 6**: Electrical system command structure and device diagram.

### *5.2.2 Main Computer*

The main computer connected to the MI via serial RS-232 is a Dell Inspiron 5150. This unit features a 2.66 GHz Pentium 4 CPU and 512MB of RAM. A laptop computer remains the form factor of choice for the ARVP as it functions equally well both on and off the robot. Also, it can also be accessed remotely by 802.11b/g wireless Ethernet for development and monitoring. Interfacing is achieved using the built in IEEE-1394 bus for the cameras and USB to serial adapters for all other connections.

### *5.2.3 Packaging*

To isolate high power and control electronics and reduce the amount of heavy cabling, all high power components such as the motor driver boards are located in a box on the vehicle frame while sensors and control electronics are housed in the fiberglass body. This arrangement provides for easy access to components and reduces noise issues compared to the densely packed hexagonal electronics box presented in 2003. Signals and regulated power are transmitted to the shell via a single 37-conductor cable for rapid connectivity.

## 5.3 Motion Control

### *5.3.1 Motor Drivers*

Two NCC70 motor drivers by Q4D continue to be a good choice for *Kodiak*. These robust boards more than satisfy the motor power requirements by allowing for the delivery of 100 Amps at 24 V continuously.

### *5.3.2 Emergency Stop*

There are three methods of stopping Kodiak in an emergency: a physical switch on the robot, a wireless keychain transmitter, and a software halting mechanism. The physical switch is located at the rear of the vehicle to IGVC specifications while the wireless E-stop functions at up to 131' (40m) on the UHF band. The software E-stop prompts the computer to cease sending commands to power the motors when inevitable danger is sensed.

### *5.3.3 Remote (Manual) Operation*

Manual remote operation of the robot is necessary for busy public places and facilitates loading the vehicle for transport to special events. As a result, an FM transmitter receiver pair with proportional analog control is used and has been shown to function up to a range of about 60 – 90' (20 – 30m).

## 5.4 Power System

The new frame location is only one of many changes to *Kodiak*'s power system that have improved efficiency and reduced vehicle weight (see Figure 7).

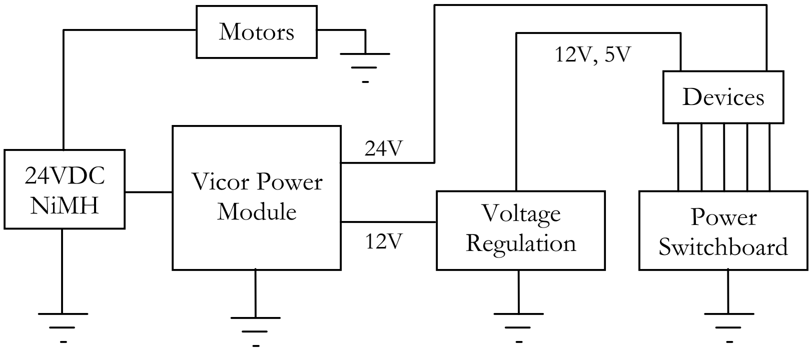

**Figure 7**: Power system diagram.

### *5.4.1 Power Source*

Two 12V 95 Ah NiMH Panasonic EV-95 batteries in series replace sealed lead acid batteries (SLA). The new batteries power the motors directly and all other electronics indirectly through a custom power module from Vicor. This arrangement contrasts a previous one where a third battery was used for electronics power as to physically isolate these devices from the motors. The greater power density of the NiMH cells compared to the SLAs in conjunction with the outright elimination of a battery resulted in a 40% reduction in battery weight (nearly 50 lb) without affecting overall system battery capacity. The result is a vehicle capable of 80 minutes of continuous use.

### 5.4.2 *Power Distribution*

All of *Kodiak*'s electronics share a common ground. Through voltage regulation, 5V, 12V, and 24V devices can be powered. The activation of each device is controlled by a custom power switchboard that closes a path to ground. This solid state switchboard can be accessed through the MI by the computer or the UI as to only power devices that are being used and preserve battery life.

## 6.0 SOFTWARE STRATEGY

The ARVP has placed a great deal of emphasis on a new software system for *Kodiak* in 2004. All development continues to be done in the C/C++ language on the mature, stable, and freely available Debian Linux operating system. The open source nature of this environment provides for a large library of software to build upon.

### 6.1 The Hazard Oriented Obstacle Detector (HOOD)

The HOOD is a completely new system architecture that maintains only a few vision and machine intelligence ideas from previous years. It is completely modular by design with functionality assumed by system modules that act as filters that take data in, process it, and output relevant information. Examples of this arrangement will be explored below.

### 6.2 Integrated User Interface (UI)

The HOOD also features an integrated user interface (UI) that greatly simplifies software development, testing and debugging, and final vehicle operation. Each module in the HOOD has an associated Viewer that abstracts live module data and decisions. The UI also facilitates on the fly parameter changes that are especially useful in vision and calibration concerns.

### 6.3 Software Modules

The primary HOOD software modules are discussed below.

### 6.3.1 *Cameras and Vision*

The Camera module receives raw data from the DCAMs over the IEEE-1394 bus and outputs images to the Vision module. This vision system takes a general approach to image processing by creating obstacles from shapes identified by chosen colors rather than restricting itself to a lane-following environment. As shown in Figure 8, the vision system consists of a number of filters that operate on an image to crop and clean, threshold, and partition to ultimately classify relevant features and build a map of the vehicle's surroundings.

**Figure 8**: Vision system flow from camera images to a real-world coordinate map of features around the vehicle

To highlight the colored features of interest, Hue/Saturation/Luminance (HSL) thresholding is done to create a binary (black and white) image. This HSL thresholder (see Figure 9) selects blobs of color (namely white and yellow for the Autonomous Challenge) in a more natural way than the red/green/blue (RGB) scheme used previously. Next, a Partitioner extracts groups of points from the blobs that are sent to a Classifier. The Classifier interprets each group as an obstacle and tests how "line-like" each one is. Those identified as lines are approximated by linear regression for simplification while others take on eight-sided polygon pothole shapes. Finally, the coordinates of the obstacles are translated from the 2D image space to 3D real world space using a camera calibration model based on a pinhole camera scheme by Roger Tsai. At any point in this vision process flow, additional filters may be implemented to eliminate extraneous data. An example is seen in Figure 11 where noise in the image is eliminated by a Dust Filter.

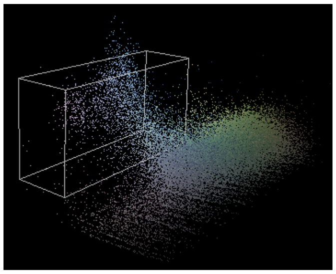

**Figure 9**: HSL histogram of colors present near a line a camera image. Only the pixels contained in the white box are kept after thresholding.

### 6.3.2 SICK

The ARVP developed the SICK software module to control and receive data from the LMS. As seen in Figure 10, the ranging information from the LMS is sent to an Objectifier that finds obstacles of interest based on sharp changes in range values at a distance of up to 15' (4.6 meters). Interpolation of nearby values reduces the number of points that define an obstacle. Arc-shaped objects are also extrapolated to closed circular obstacles to gain insight into occluded features. The final output of this module is defined in the same way as the vision system for real-world mapping. An example of the LMS data visualization is shown in Figure 12.

**Figure 10**: SICK software module process flow

### 6.3.3 GPS

The GPS software module receives OmniStar differentially corrected GPS data from the Trimble receiver. The position and heading information provided is used in aviation formulae to calculate the distance and optimal heading to the next target waypoint. At slow speeds, heading information from the digital compass is also used.

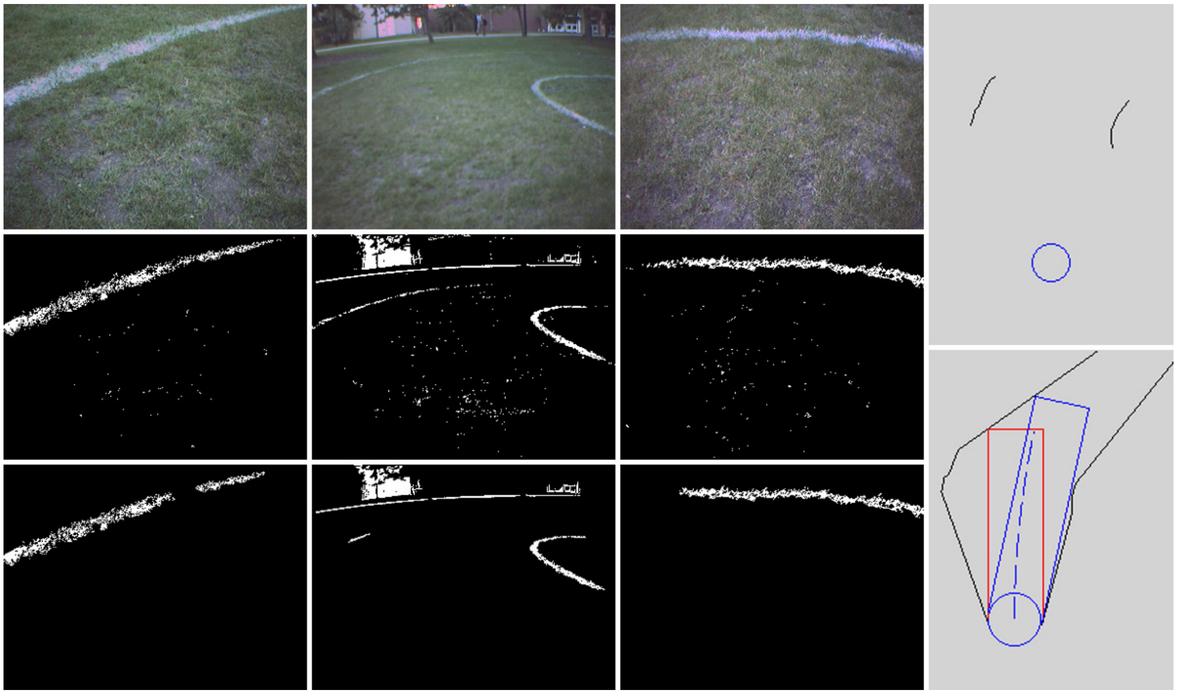

**Figure 11**: Vision system and pathfinding for *Kodiak*'s 3 camera setup. (*top row*) Original camera images; (*second row*) HSL thresholded for white; (*bottom row*) Dust Filtered output; (*top right*) identification of lines in real-world coordinates relative to robot (blue circle); (*bottom right*) raycasting AI output and maximum possible travel distance at current heading (red box) and optimal heading (blue box). The calculated path is shown as a dotted blue line. (see section 6.3.5).

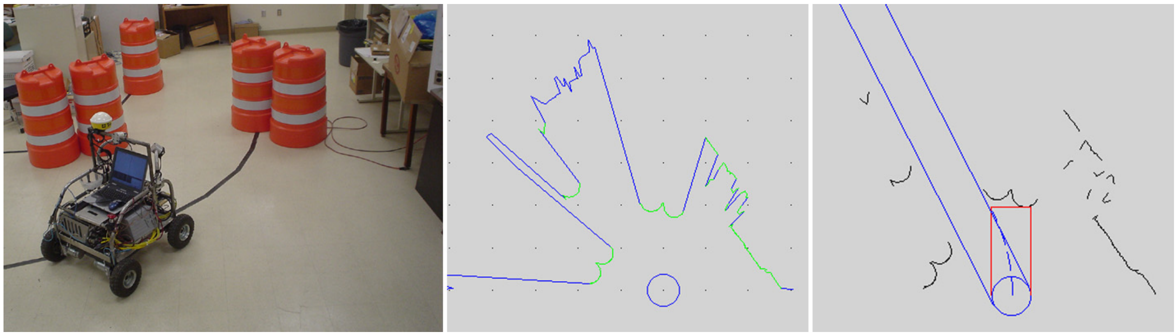

**Figure 12**: Laser range scanner data visualization and AI. (*left*) overview of scene; (*middle*) obstacle front surfaces shown in green and raycasts in blue; (*right*) maximum possible travel distance at current heading (red box) and optimal heading (blue box). The calculated path is shown as a dotted blue line.

### *6.3.4 Hardware Abstraction Layer (HAL)*

The HAL interprets generic hardware-independent commands and converts them to the proper format for the underlying hardware. The HAL communicates directly with the Main Interface to control all devices on the robot.

## 6.3 Path Decisions

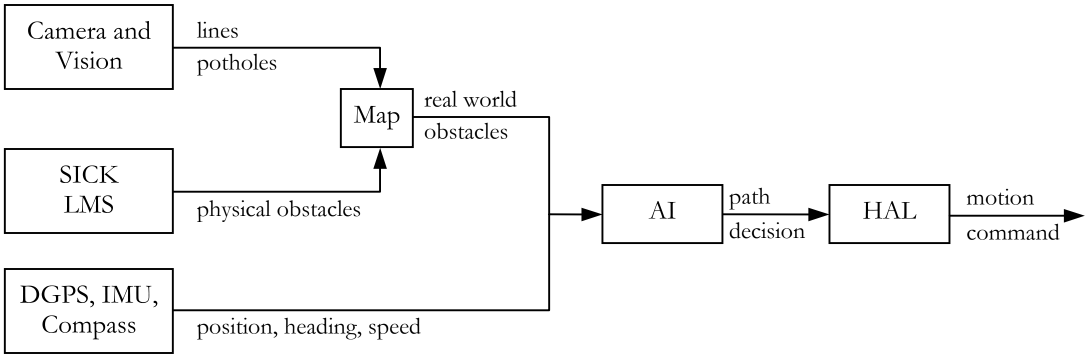

**Figure 13**: Sensor and software fusion for path decisions in the Autonomous Navigation Challenges

### *6.3.5 Autonomous Challenge*

Before passing the map generated by the Vision and SICK modules to the Artificial Intelligence (AI) module for path planning, additional filtering is done. The most important step is a map modifier that joins line segments that result from imaging actual broken lines as well as those that arise when combining parts of the same line that are viewed with different cameras. Additional filtering is done to eliminate features that are unlikely to represent physical obstacles. The modified map is then passed to the main decision-making AI. As shown in Figures 11 and 12, this AI casts parallel virtual rays the same width as the vehicle for all directions ahead of the robot. The maximum possible travel in any of these directions is evaluated and the appropriate arc turn commands are issued to follow a clear smooth path. Skid steer commands can also be issued when a dead end or trap is encountered. The robot's velocity is scaled proportionately to the distance that is can travel without obstruction so it moves more quickly in straight-aways than tight corners. The entire sensor data capture, interpretation, and decision-making processes are completed in 200-300ms.

### *6.3.6 GPS Navigation Challenge*

The optimal closed path between a given set of GPS waypoints is calculated using a traveling salesman algorithm. Using the position and heading information from the GPS software module, an AI attempts to maintain an optimal heading toward the next waypoint while avoiding obstacles. The modular design of the software system allows the same obstacle avoidance of the Autonomous Challenge to be used in this event as well. The precise nature of DGPS allows for waypoint arrival within inches.

## 7.0 CONCLUSION

Kodiak is intended to be a turnkey vehicle. This mentality is pervasive throughout the design from the proven and optimized track assemblies to the electrical and software interfaces. Beyond the three options of emergency stop, safety concerns are reflected by the isolation of power and control electronics as well as the inclusion of fusing and diode protection throughout. Versatility is ensured by the robust platform and electrical and software architectures that facilitate technological insertion.

| Kodiak Properties and Performance | |
|---|---|
| Outside dimensions<br>(l x w x h) | 56” x 28.5” x 41”<br>(1.4m x 0.7m x 1.0 m)<br>56” x 37” x 41”<br>(1.4m x 0.9m x 1.0 m) |
| Weight | 295 lb (134 kg) |
| Payload capacity | 120 lb (54.4 kg) |
| Maximum speed | 2.6 mph (4.4 kph) |
| Maximum grade | 30 ° |
| Turn rate | 90 °/s |
| Battery life (continuous) | 80 minutes |
| Remote E-stop range | 131’ (40m) |
| GPS accuracy | 6” (15 cm) |
| Camera field of view | 180°; 10’ (3m) |
| LMS field of view | 180°; 15’ (4.6m) |
| Overall reaction time | 300 ms |

## 8.0 TEAM MEMBERS

| Name | Division | Undergraduate Discipline | Year |
|---|---|---|---|
| Arthur, Rhyan | CE | Physics | 4 |
| Ball, Michael | EE | Engineering | 1 |
| Barkwell, William | PD | Engineering | 1 |
| Bezuidenhout, Louis | PD | Engineering Physics | 3 |
| Blinzer, Michael | PD | Mechanical Engineering Co-op | 2 |
| Bothe, Juval | PD | Engineering | 1 |
| Davis, Paul | EE | Engineering | 1 |
| Dunn, Sean | EE | Engineering | 1 |
| Edwards, Keith | EE | Electrical Engineering | 2 |
| Fischer, Lee | PD | Engineering Physics | 3 |
| Friesen, Joseph | PD | Engineering | 1 |
| Gendre, Andrew | PD | Engineering | 1 |
| Glatz, Jennifer | PD | Mechanical Engineering | 4 |
| Hammerlindl, Andy | CE | Math & Computer Science | 4 |
| Henkemans, Dirk | CE | Computer Science | 4 |
| Kastelan, David | Project Leader | Engineering Physics | 4 |
| Klaus, Jason | CE | Computer Engineering Co-op | 5 |
| Klippenstein, Jonathan | CE Leader | Engineering Physics | 4 |
| Knowles, Robert | PD | Computer Engineering | 3 |
| Korz, Martin | CE | Engineering | 1 |
| Kulkarni, Ajinka | PD | Engineering | 1 |
| Lau, Dorothy | EE | Computer Engineering | 4 |
| Lees-Miller, John | CE | Engineering | 1 |
| Long, Shannon | EE | Electrical Engineering | 3 |
| Loo, Chris | PD | Electrical Engineering Co-op | 2 |
| McIvor, Jake | PD | Mechanical Engineering | 2 |
| Ng, Jason | EE | Engineering Physics | 4 |
| Noor, Nouman | EE | Electrical Engineering | 3 |
| Orr, Brennan | PD | Mechanical Engineering | 4 |
| Ozeroff, Chris | CE | Engineering Physics | 4 |
| Pegoraro, Adrian | EE | Engineering Physics | 4 |
| Quong, Michael | CE | Engineering Physics | 3 |
| Schoettler, Tyson | EE | Electrical Engineering | 4 |
| Teschke, Brandon | PD | Engineering | 1 |
| Tutschek, Monte | PD Leader | Computer Engineering | 4 |
| Wilson, Tom | EE | Electrical Engineering | 4 |
| Wong, Edmund | PD | Engineering | 1 |
| Wong, Bryant | EE Leader | Electrical Engineering | 4 |
| Toogood, Roger | Faculty Advisor | | |

## 9.0 COMPONENT COST SUMMARY

| Component | Model | Quantity | Unit Price | Donated |
|---|---|---|---|---|
| **Mechanical Components** | | | | |
| Mild Steel Tubing | 20'-1" OD 1/8" wall AISI 1024 | 1 | \$64 | ✓ |
| Steel bar stock | 24"-2" OD AISI 4041 | 1 | \$15 | ✓ |
| Aluminum stock | 2" x 2" x 60" AISI 6061 | 1 | \$98 | ✓ |
| Aluminum stock | 6' of ½" OD solid AISI 6061 | 1 | \$116 | ✓ |
| Rod Ends | Aurora VCM-5/VCB-5 | 8 | \$4 | ✓ |
| Shocks | Ryde FX 9200 | 2 | \$119 | ✓ |
| Motors | Leeson Canada C4D17NK9C | 2 | \$391 | ✓ |
| Tracks | single-sided timing belt | 2 | \$325 | |
| Bearings | NSK-6004 20 mm | 16 | \$7 | |
| Bogey wheels, bearings | 72 mm diameter, ABEC-5 | 24 | \$9 | ✓ |
| Worm gear | | 2 | \$59 | |
| Spline shafts | | 2 | \$42 | ✓ |
| U-joints | | 4 | \$24 | |
| Pillow block and bearing | NSK UC205D1LLJ | 2 | \$30 | |
| Vehicle body | milling, sheet metal inlays, fasteners, finishing materials | 1 | \$1725 | |
| | IGUS Drylin linear bearings and hardware | 2 | \$525 | ✓ |
| | | | | |
| **Electrical/Computer Components** | | | | |
| Laser range scanner | SICK LMS-291 | 1 | \$3600 | |
| GPS | Trimble AgGPS 132 | 1 | \$3700 | ✓ |
| Video Cameras | Videre Design DCAM | 3 | \$210 | |
| Inertial measurement | Rotomotion 6DOF IMU | 1 | \$300 | ✓ |
| Digital Compass | Honeywell HMR3100 | 1 | \$250 | |
| Shaft encoders | US Digital E3 | 2 | \$95 | |
| Motor Controllers | Q4D NCC7024 | 2 | \$260 | |
| Power module | Vicor Custom | 1 | \$450 | ✓ |
| Batteries | Panasonic EV-95 | 4 | \$250 | ✓ |
| Main computer | Dell Inspiron 5051 | 1 | \$1500 | |
| LCD | Earth LCD PicL | 1 | \$100 | ✓ |
| Voice Synthesizer | RC Systems V8600A | 1 | \$130 | |
| Remote Control | 72 MHz Analog FM | 1 | \$140 | |
| E-Stop | Custom | 1 | \$140 | ✓ |
| Electrical components and PCB manufacturing | Main interface, power switchboard | 1 | \$620 | |
| Interfacing hardware | USB-serial converters, USB hub, IEE-1394 hub, connectors, and cabling | 1 | \$350 | |
| | | **TOTAL \$19,076 (USD)** | | |

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*This report and the ARVP's efforts at the 2004 IGVC are dedicated to the memory of teammate Dirk Henkemans who passed away suddenly in early April 2004. Beyond his technical contributions, Dirk is remembered for his friendly smile and wonderful spirit. He is greatly missed.*