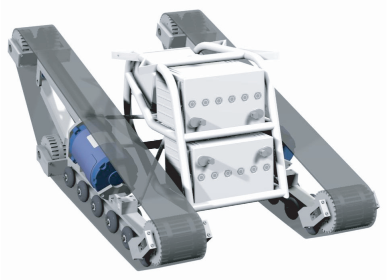
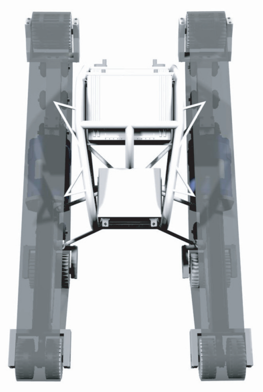
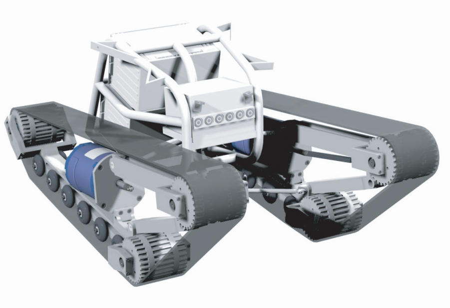
2003 Kodiak Design Report

11th annual intelligent ground vehicle competition







Presented to
William G. Agnew
Chair of Design Judging Panel

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ARVP
autonomous robotic vehicle project

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1.0 INTRODUCTION

The Autonomous Robotic Vehicle Project (ARVP) exists to develop, apply, and promote robotic technology. With a focus on design, controls, and intelligent navigation, the ARVP challenges problems such as those presented by the annual international Intelligent Ground Vehicle Competition (IGVC) to ultimately develop systems and vehicles for real-world applications. Through these efforts, the students involved with the ARVP have opportunities to gain practical skills not normally taught in a classroom thus allowing them to better prepare for their professional careers. Beyond these technical roles, ARVP members are encouraged to participate in the team's Outreach program that promotes learning about robotics and technology in the community

This report aims to outline the changes in team structure, design process, and technology resulting in the extensive improvement of the ARVP's fourth and most recent vehicle, *Kodiak*. This platform was first introduced at the IGVC in 2002 and represented an ambitious design shift from wheel to track locomotion. The successes and shortcomings of this initial concept have lead to changes throughout the project in preparation for the 11th Annual IGVC. These modifications reflect ultimate goals of safety, reliability, and versatility and result in a refined vehicle with capabilities exceeding IGVC requirements.

2.0 TEAM ORGANIZATION

Figure 1: Outreach event at the Odyssium in Edmonton, Alberta.

The ARVP's tasks and responsibilities are divided among several sub-teams of volunteer students. The Sponsorship, Logistics, Administration, and Marketing (SLAM) Team handles the various financial and event planning concerns while the Community Outreach Team assists with promotion through public activities. The technical aspects of design, construction, and testing are shared by the Mechanical Team, the Electrical Team, and the Computer and Software Development Team. The Features and Applications Team (FAT) works closely with these groups to improve the form and function of the platform through aesthetic design and the development of innovative uses for autonomous robotics. A representative from each of these sub-teams as well as an overall Project Leader comprise the ARVP executive. These individuals are elected annually from the team's membership of thirty students and meet weekly to discuss the status of the project in order to set goals and allocate funds. The executive also benefits from contact with a Faculty Advisor provided by the Department of Mechanical Engineering.

All team members are encouraged to attend weekly general meetings where upcoming plans and events are discussed and input and feedback is encouraged. The format of these meetings was changed in the past year to encourage participation and communication between sub-teams. A number of students prepared brief presentations to outline their specific task and obtain encouragement and ideas from the entire team. Further integration between sub-teams was promoted by the creation of a new website that allows for secure internal messaging, the tracking of inventory, expenditures, contacts, and documentation as well as a dynamic Gantt chart that outlines project goals and status. This enhanced collaboration allows for the interfacing, ergonomics, and accessibility needs of each sub-team to be met to achieve vehicle refinement.

The design changes and new component acquisitions proposed by the Mechanical, Electrical, and Computer sub-teams were facilitated by a continuing effort to improve the ARVP's public presence. Greater sponsorship opportunities were presented by expanding the community Outreach role to include interactive presentations at a range of venues from Girl Guide workshops to public libraries and the Odyssium, the local science center. At the same time, the FAT aims to increase public interest through the creation of a functional and attractive vehicle body as well as the development of a t-shirt launching turret for *Kodiak* to be used for promotional purposes at sporting events.

3.0 DESIGN PROCESS

The three primary goals of safety, reliability, and versatility set for the revision of *Kodiak* required a rigorous engineering design process. Problems encountered at the 2002 IGVC and in testing lead to the identification of a number of improvements outlined in Table 1. In addition to the emphasis placed on public safety and usability, performance capabilities such as response rates, sensor resolution, and all-terrain abilities were planned for enhancement.

Safety	Accessibility
	Component protection
Reliability	Redundancy
	Debugging system
	Modularity
Versatility	Performance capabilities

Table 1: 3 primary design goals and corresponding vehicle attributes identified for improvement.

The next step in the design process illustrated in Figure 2 of solution exploration was facilitated by the improved communication between the sub-teams. More significant changes could be realized through integration while better decisions were made through collaboration.

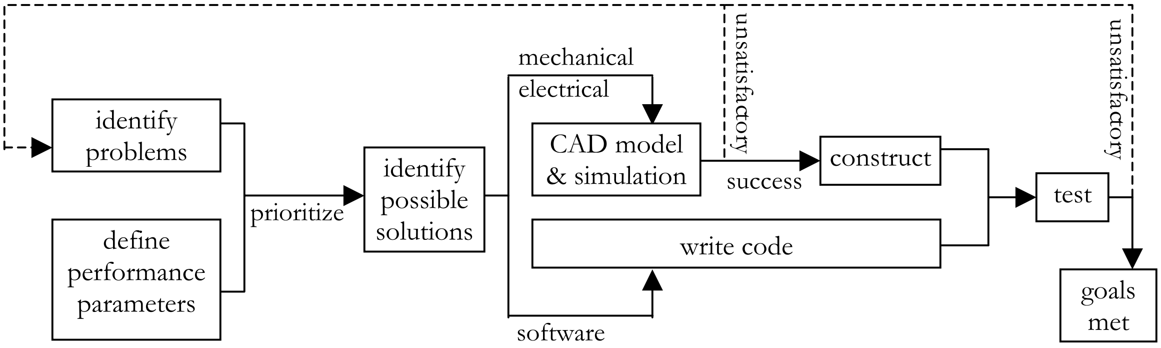


Figure 2: Vehicle refinement process diagram.

The mechanical and electrical sub-teams as well as the FAT benefited from the extensive use of Computer-Aided Design software. Parametric Technology Corporation's (PTC) Pro/Engineer was used for part design and assembly in three-dimensional virtual space while Pro/Mechanica handled component stress analysis by Finite Element Methods (FEM). 3-D modeling using Rhinoceros was also an invaluable tool for the vehicle shell design and fabrication. Protel by Album was used by the electrical sub-team for schematic and PCB design as well as simulation. All of these software packages promote optimization, serve to minimize costly fabrication errors, and nearly eliminate the need for prototyping. The parallel development by the software sub-team benefits from the maintenance of a server containing all code and documentation. This centralized approach ensures that all code is current, integrable, and available to all of this sub-team's members.

The final steps in the design process involve the actual construction, testing, and packaging of physical components and the evaluation of software to prepare the robot for demonstrations and the competition.

4.0 MECHANICAL SYSTEMS

The mechanical design of *Kodiak* maintains its focus on modularity while resolving some stability and performance issues. The two identical and interchangeable track subassemblies that house the drivetrain components have been optimized to reduce weight. Modifications have also been made to address poor performance in deep and coarse grass as experienced at the 2002 IGVC. The subframe was redesigned to accommodate a dynamic connection to each of the subassemblies as well as provide for more secure battery and electronics enclosures. A new vehicle body that attaches to the subframe has also been developed to accommodate computer components, sensors, and a payload. The modular design of *Kodiak* allowed these changes to be made independently over time and preserved the original set of components for backup. In addition, it simplifies reconstruction after transport of the robot by requiring only basic tools for assembly.

4.1 Subframe

The subframe shown in Figure 3 is constructed of mild carbon steel (AISI 1024) chosen for its workability, availability, and functional properties. The mounting brackets for the suspension are made of flat bar while all other members consist of 1" (25.4mm) diameter 1/16" (1.6mm) wall round tubing. About twenty hours of bending, TIG welding, grinding, and milling were necessary to complete the subframe. The same amount of time was spent formulating the cage-like design that protects hardware in the event of a collision or loss of control. Other design considerations include interchangeability with the previous subframe and frame configuration as well as battery accessibility and safety. Angled mounts were created that secure the batteries using their own weight while facilitating battery swapping without the risk of terminal shorting.

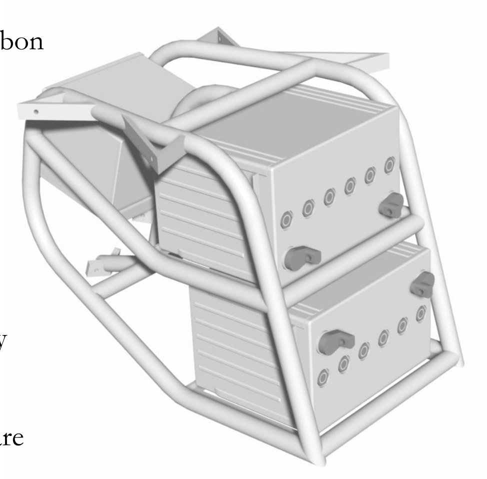


Figure 3: Model of subframe and battery placement

4.2 Suspension

To correct the instability *Kodiak* displayed on rough terrain, a three-bar suspension was created to permit the vertical translation and rotation of each track subassembly. About two hundred hours were spent creating a complete kinematic model of the suspension with Pro/Engineer. This significant amount of time was committed to eliminate any component interference, verify constraints, simulate range of motion, and determine necessary linkage dimensions. As seen in Figure 4, linkages are terminated with rod ends while suspended weight is supported by four Ryde FX AMPS X10 shocks. These shocks were chosen for their sufficient extended length and 6" (152.4mm) stroke and are preloaded to accommodate a 1:2 front to rear weight distribution. The construction of the linkages and rod end connectors required only about fifteen hours of machine shop time given their simplicity resulting from thorough design work.

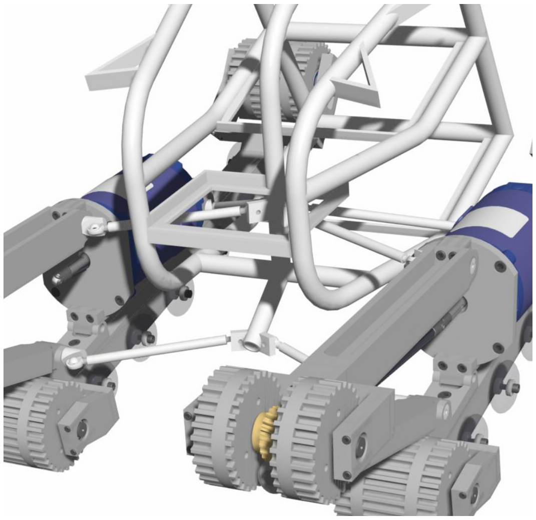


Figure 4: Suspension linkage and mounting

4.3 Track Subassembly and Drivetrain

Kodiak's track subassemblies are completely self-contained drivetrain and propulsion packages. The displacement of a single sided timing belt is accomplished by actuating the upper drive pulley with a worm gear assembly. The worm gear is connected to a Leeson Canada 24V DC motor via two universal joints and a telescoping spline shaft. The 10:1 reduction provided by the worm gear in conjunction with the 1/3 HP motor rating at 1800 RPM provides adequate torque for skid steering and overcoming steep inclines. The worm drive has the added benefit of mechanical braking when motor power is cut or lost. Lateral movement of the track is prevented by spacer discs in each pulley and a set of twelve bogeys that run in two grooves in the belt.

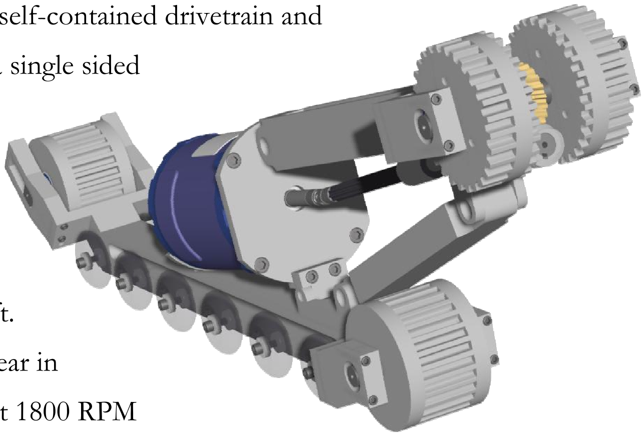


Figure 5: Subassembly drivetrain, geometry and material modifications

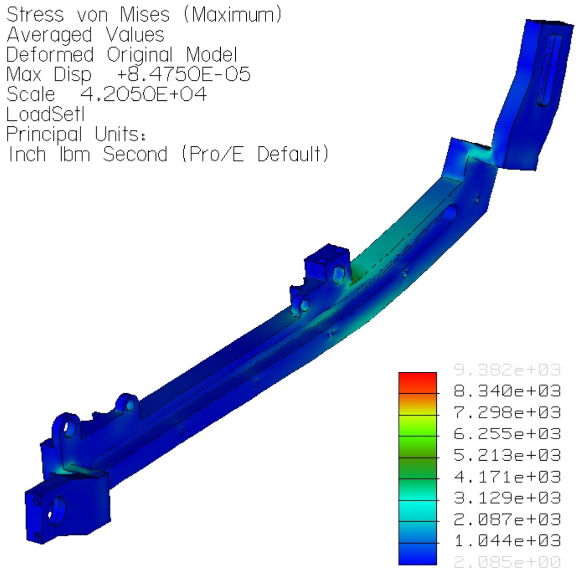


Figure 6: Stress von Mises analysis of main member

Much thought was put into changing the subassemblies in response to the 'grass catching' problem experienced at the 2002 IGVC. As a result, the rear pulley was raised to take on an idler role thus removing it from the grass and reducing its surface contact area with the belt. The ensuing geometry is seen in Figure 5. Further modifications were planned that would narrow the lower pulleys and mounts to reduce grass contact and material weight. While simplified closed form analytical stress solutions were sufficient for proof of concept, optimization was desired. Therefore, more complex and accurate loading situations were considered that necessitated finite element methods. The strain energy distortion theorem (Von Mises Stress) was applied and the maximum stress and deflection were determined to ensure that components would perform as intended. In the end, cuts could be taken from the largest members thus reducing overall weight. An visual example of the numerical analysis for the main member with material removed can be seen in Figure 6. About 105 hours were spent planning, carrying out these analyses, and machining new components.

4.4 Vehicle Body

A new body shown in Figure 7 gives *Kodiak* a finished look and feel. The pleasing animal-inspired shape is made of fiberglass and carbon fiber and provides area for displaying project decals and sponsor logos. The shell contains mounts for the SONAR array, vision system, and Global Positioning System (GPS) antenna. The laptop computer and GPS receiver are positioned ergonomically in recessed areas and protected by covers when the robot is in autonomous mode. Storage compartments are located in the nose and the upper mid-region of the shell. This upper compartment functions as a payload bay to IGVC specifications when its cover is removed. Cabling between peripherals runs in a central channel on the underside of the shell to maintain the clean appearance. Approximately fifty hours of design and an equal amount of CNC milling, material lay-up, and finishing time were required to complete the body.

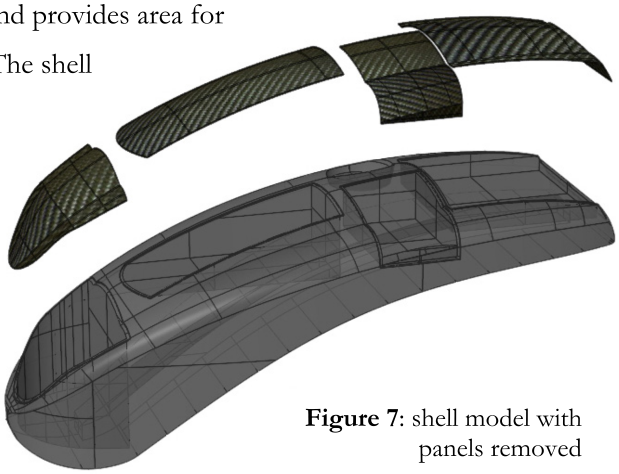


Figure 7: shell model with panels removed

4.5 Performance

Despite the simplicity of tracked locomotion, *Kodiak* is quite a maneuverable vehicle. Skid steering enables escape from dead end or trap situations while arc turning provides for smooth changes in direction when space is available. Mechanical modifications have increased the ground clearance to 6" (152.4mm) and the overall ride height to 20" (0.51m) or 42" (1.1m) with the body attached. Stability issues due to the resulting higher center of mass located about 11" (279.4mm) from the ground above the front bogey wheels are offset by the integration of suspension. The addition of the shell and new electrical components has increased *Kodiak*'s weight to 308 lb (1.37kN). However, electrical improvements have increased the vehicle's top speed and acceleration to 2.33 mph (3.75kph) and 0.15G (1.5m/s^2) respectively while enabling 30-degree grades to be overcome.

5.0 ELECTRICAL SYSTEMS

The electrical systems on *Kodiak* responsible for data acquisition, low-level control, motion control, and power have undergone major improvements in terms of responsiveness, reliability, and safety. These changes amounted in 275 hours of design, fabrication, and testing.

5.1 Data Acquisition

Kodiak detects the location of physical objects through a Sound Navigation And Ranging (SONAR) array and obtains visual data from a multiple-camera system to identify lines and potholes. The robot also acquires positional data from a GPS unit and information about its own operation through motor feedback and a debugging system.

5.1.1 SONAR

The size of the SONAR array has been increased to nine pairs of Polaroid 6500 ranging modules and instrument grade transducers that combine to produce a complete 90-degree field of view up to 32.8' (10m) ahead of the robot. A sweep of the entire array occurs every 0.54 seconds and produces ranging information accurate to within 1.18" (3cm) under all but the most extreme operating conditions. To simplify wiring and offload processing from the microcontroller, a custom MCU board was designed to perform the control, measurement, and storage of SONAR data. The interface from the SONAR unit could then be reduced to a simple RS-232 connection.

5.1.2 Vision

Vision has progressed from a single camera to a three-camera system. The Videre Design DCAM was chosen for its progressive scan image quality, on-camera color processing capabilities, and IEEE 1394 interface in a single compact package. Three DCAMs capture adjustable views from the center and corners of the front of the vehicle with a range of about 8' (2.4 m). The cameras are connected to a hub that is in turn interfaced with the onboard computer for image capture.

5.1.3 GPS

A Trimble AgGPS 132 allows for the reception of beacon or satellite differential GPS data. Position and velocity information is updated at 1 Hz with sub-meter accuracy possible given a sufficient number of visible satellites. Receiver settings are definable using a four button keypad and LCD display while interfacing with Kodiak's computer is accomplished via an RS-232 port.

5.1.4 Motor Feedback

Optical photo interrupters are used to measure the speed and acceleration of the drive shafts. An infrared light source is enclosed with a 32-tooth gear to shield external light and ultimately provide real-time feedback and closed-loop control of the drive system.

5.1.5 Debug board

A debug board was designed to monitor up to eight voltage points in the electronics system. Fully analog breakout points allow for signals to be observed by oscilloscope or multimeter. The board can also be controlled by *Kodiak*'s microcontroller or computer for self-testing and status monitoring. This new feature greatly enhances troubleshooting accessibility thus preventing problems and reducing downtime.

5.2 Low-Level Control

The low-level control of *Kodiak* is accomplished with a Motorola 68332 microcontroller and custom daughter board. The 68332 remains a good choice for redundant tasks such as motor control due to its low cost, ample processing power, and adequate I/O capacity. The daughter board serves as an interface for the microcontroller thus providing for modularity.

5.3 Motion Control

5.3.1 Motor Drivers

In response to the undesirable relay-induced delay on *Kodiak*'s original motor driver boards, custom high-powered solid state H-bridges were developed. These boards are rated at 48V, 58A continuous (100A peak) and feature thermal shutdown sensors, regenerative braking, and shoot through protection. Efficiency eliminates the need for active cooling while a simple interface was created for PWM and direction control.

5.3.2 Emergency Stop

An emergency stop is achieved remotely by activating a UHF key ring transmitter. The 300-375 MHz signal is decoded by a powered receiver board and a pair of relays is activated accordingly. This system operates at up to 130' (about 40 m) from the robot while false triggering is avoided using flip-flops in an RC network. Protection diodes are also included on each relay to limit back-EMF when they are de-energized. An emergency stop can also be activated by pushbutton directly on the robot. This method immediately cuts power to the motors and stops the vehicle.

5.3.3 Remote (Manual) Operation

To safely and easily move the robot around people, a radio frequency remote control was implemented. To improve reliability and control, an off-the-shelf FM transmitter receiver pair with proportional analog control replaces a custom digital remote. The system has been tested successfully at a range of approximately 330' (100 m).

5.4 Power

Kodiak's motors are powered by two 12V 65 Amp-hour (Power Battery 8G24) gel cell batteries connected in series. All electronics are isolated from the motor circuitry using a third smaller 12V 24 Amp-hour (8GU1) battery. These batteries were chosen for their high current output, air transport approval, and endurance that allow the vehicle to operate for approximately three hours. Enhancements to the power system for safety purposes include a polarity failsafe and the addition of a fuse block containing fast acting fuses for motor and electronics protection.

5.5 Packaging

Another major modification to the electronics system is the method by which all components are packaged. A hexagonal box shown in Figure 8 was designed to better surface space use and accessibility. The head plate of the box contains a variety of Amphenol connectors that accept battery power, encoder and DB9 microcontroller input as well as output power to SONAR, GPS, lights, and motors. Columns acting as a conduit for wires from external components to internal circuitry connect this head plate to a base plate. Friction hinges on the base plate are attached to the six side panels. Terminal strips on the base plate connect each of the boards mounted on standoffs to the walls of the box. Venting on two of the side plates improves the airflow introduced by the 2.4" (60 mm) fan that cools the box. The end result is a 10" x 8" x 11.5" enclosure with clean wiring and easy access to all boards for testing, troubleshooting, or replacement with the complete redundant set of components on hand.

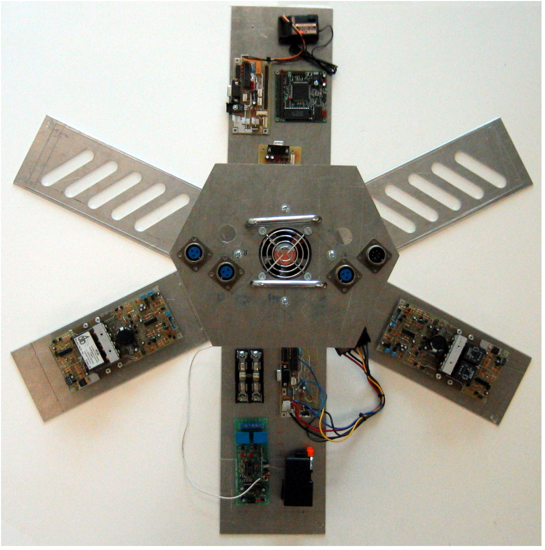


Figure 8: Overhead view of the hexagonal electronics box in the fully open position.

6.0 COMPUTER AND SOFTWARE SYSTEMS

6.1 Hardware

All of *Kodiak*'s high-level software runs on a Fujitsu Lifebook and the Debian Linux operating system. This notebook was chosen for its adequate battery life, 500 MHz Intel Celeron CPU, and 128 MB of RAM, as well as its support for a PCMCIA IEEE 1394 adapter.

6.2 Interface

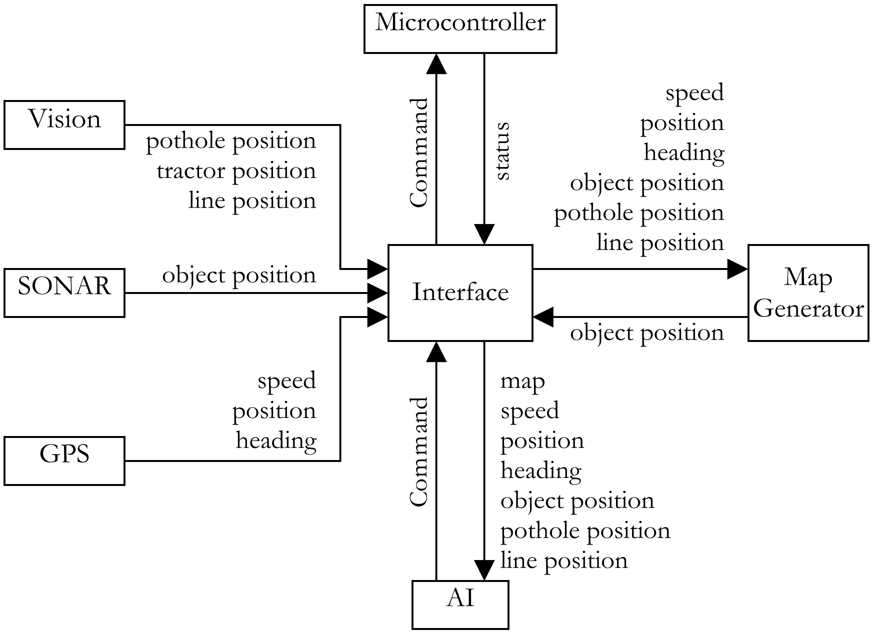
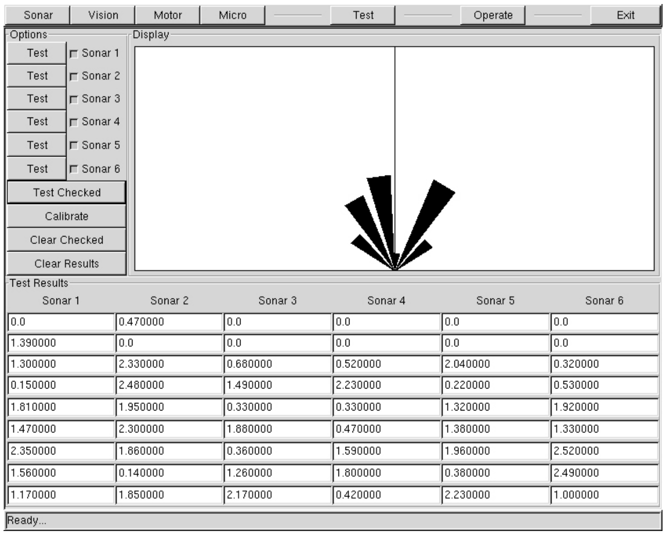


Figure 9: Integration of sensors, software, and control via the new interface.

About 280 hours were spent by the Computer and Software Development Team writing new and improving existing code for the high-level control of *Kodiak*. Focus on the primary design goals was prevalent and resulted in the creation of an innovative interface through which all sensors, software modules, and control systems communicate as in Figure 9. The interface increases the versatility of the software system by allowing for the easy addition and interchange of components given proper input/output definitions. Testing was thus simplified by enabling alternative algorithms to be evaluated without having to rewrite other sections of the software. A graphical utility was also developed as a means of visualizing the data from the vehicle's sensors as shown (for SONAR) in Figure 10. At the same time, parameters can be tweaked and calibration done in the utility to improve the performance of the system for the operating conditions.



Sonar 1	Sonar 2	Sonar 3	Sonar 4	Sonar 5	Sonar 6
0.0	0.470000	0.0	0.0	0.0	0.0
1.390000	0.0	0.0	0.0	0.0	0.0
1.300000	2.330000	0.680000	0.520000	2.040000	0.320000
0.150000	2.480000	1.490000	2.230000	0.220000	0.530000
1.810000	1.950000	0.330000	0.330000	1.320000	1.920000
1.470000	2.300000	1.880000	0.470000	1.380000	1.330000
2.350000	1.860000	0.360000	1.590000	1.960000	2.520000
1.560000	0.140000	1.260000	1.800000	0.380000	2.490000
1.170000	1.850000	2.170000	0.420000	2.230000	1.000000

Figure 10: Graphical SONAR interface.

6.3 Modes of Operation and Path Decisions

Three main modes of operation were established to satisfy the IGVC event guidelines: Autonomous Challenge, GPS Navigation, and Follow-the-Leader (FTL).

6.3.1 Autonomous Challenge

The Autonomous Challenge requires the integration of vision and SONAR data to avoid painted lines and potholes as well as physical obstructions. The new three-camera setup greatly simplifies the vision system by specifically assigning each of the outside cameras to a respective line on either side of the vehicle's intended path. This straightforward relationship eliminates the need for processing high-resolution images of the robot's entire forward view as in a single camera setup. The central camera specifically looks at the lane to identify potholes. Images captured from the cameras by the computer follow an algorithm shown in Figure 12 of histogram thresholding and segmentation. The result is the extraction and interpolation of the familiar shapes of solid and dashed lines as well as ellipses. The interface then invokes the map representation module to convert the location of these shapes into real world coordinates relative to the robot. The location and size of physical obstacles is determined from the ranging data from the SONARs and placed in the map. As the vehicle approaches obstacles, their resolution improves and the map is updated. The Artificial Intelligence (AI) module makes path decisions according to Figure 13 by querying the interface for location information from the map. The AI tests all forward headings in one-degree increments to the left and right of the current heading every second. The path permitting the greatest distance of unobstructed travel is chosen and motor commands are issued at a maximum rate of 1 Hz to make directional corrections. The two modes of skid steering and arc turning are chosen according to the degree and rate of turn required.

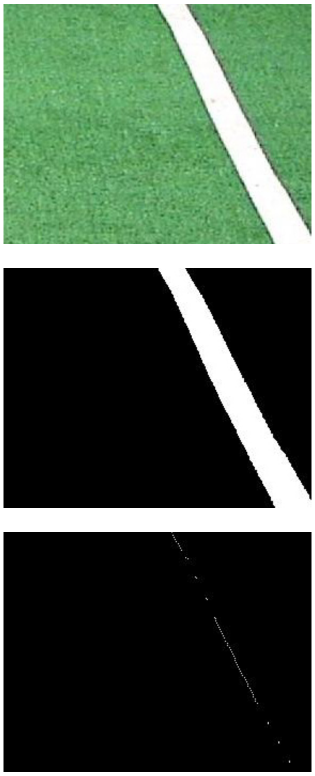


Figure 12: (*from top*) original image, histogram thresholded image, line identification

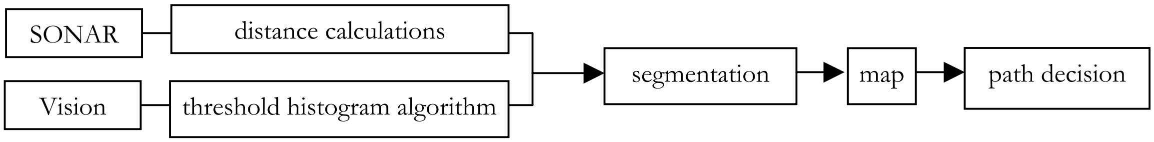


Figure 13: Autonomous Challenge sensor to path decision process

6.3.2 Follow-the-Leader

Kodiak's Follow-the-Leader mode employs the same components and a similar process as the Autonomous Challenge. The cameras are used to find the largest shape of a calibrated color and return its four bounding coordinates via thresholding and edge determination as shown in Figure 14. The bounding corners give an idea of the target's distance and relative off-center displacement. As seen in Figure 15, these coordinates are compared with SONAR data to positively and accurately identify the location of the target vehicle in the map. As the robot follows the lead vehicle, the SONAR data is continuously mapped to avoid obstacles en route. However, the reference data from the camera ensures that the FTL AI module is able to always identify the object it is meant to track. A distance of roughly 10' (3 m) between the robot and the lead is maintained by varying *Kodiak*'s speed. For safety purposes, the robot is issued a stop command if the camera ever loses sight of the target.

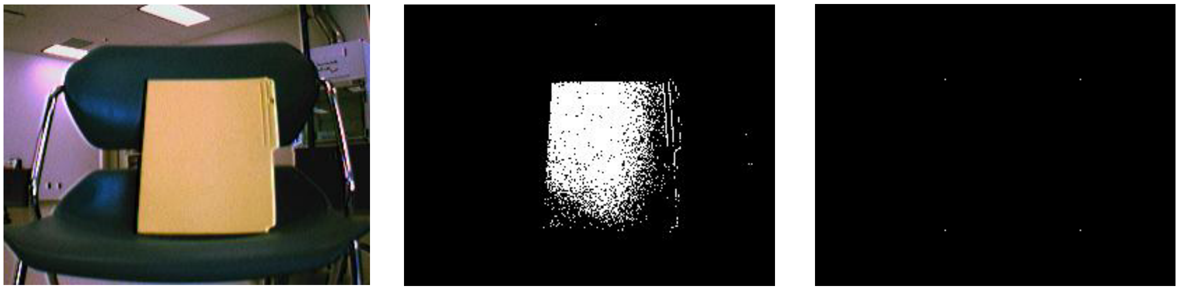


Figure 14: (*left to right*) simulating FTL target vehicle, thresholding identifies target, 4 boundary points found

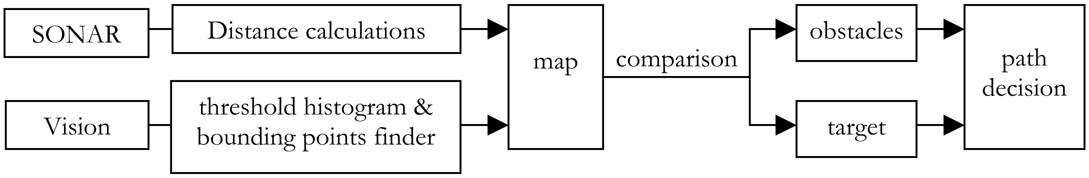


Figure 15: Follow-the Leader sensor to path decision process

6.3.3 GPS Navigation

GPS Navigation is accomplished using differential corrected data from the GPS receiver and SONAR information. Prescribed waypoints are visited in the order determined by a pre-computed shortest path algorithm. Along the way obstacles are to be avoided. However, beyond a distance of about 10' (3.0 m), the diverging nature of the SONAR cone introduces significant lateral obstacle location uncertainty. As a result, the following cases numerated in Figure 16 are considered when an obstacle is detected in *Kodiak*'s path to a waypoint:

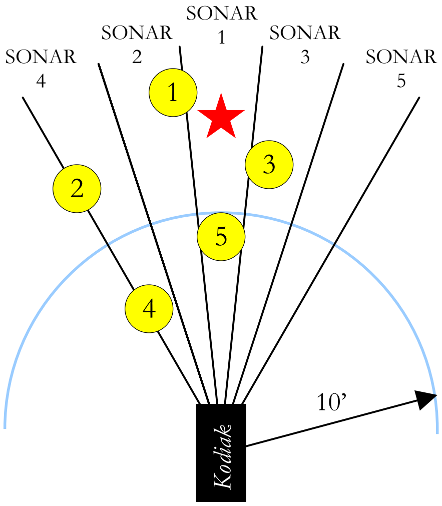


Figure 16: Cases of obstacle (yellow circle) placement relative to next waypoint (red star) considered for GPS Navigation.

1. Obstacle beyond waypoint is ignored.
2. Obstacle far away (>10') and outside path of central SONAR cones is ignored.
3. Obstacle potentially in path of robot is monitored until within 10' range.
4. Obstacle close enough to determine an accurate position outside path to waypoint is ignored.

5. Obstacle position known to be directly in the desired path and course correction is made to avoid it when approaching the waypoint. As the vehicle nears the obstacle, its position is more accurately determined and the error in the direct waypoint connection path is reduced.

7.0 CONCLUSION

Kodiak has been improved as a fully autonomous robotic vehicle through the design and manufacturing efforts of students from the University of Alberta's Autonomous Robotic Vehicle Project. The primary design goals of safety, reliability, and versatility were carried through the mechanical, electrical, and software design. The vehicle is capable of operating in a variety of indoor and outdoor environments and specializes in lane following, obstacle detection and avoidance, and GPS navigation challenges proposed by the 11th Annual Intelligent Ground Vehicle Competition. The ARVP is proud of its accomplishments with this platform and plans to continue attending the IGVC in the future.

8.0 TEAM MEMBERS

Name	Sub-Team	Discipline	Year
Barton, Christopher	Software Team Leader	PhD Computing Science	1
Bezuidenhout, Louis	Mechanical Team	BSc Engineering Physics	2
Blinzer, Michael	Mechanical Team	BSc Engineering	1
Buksa, Graham	ARVP Team Leader	BSc Electrical Engineering	4
Cooke, Terry	FAT	B.A. Industrial Design	5
Fischer, Lee	Mechanical Team	BSc Engineering	1
Huisman, Dwayne	Mechanical Team	BSc Electrical Engineering	2
Huston, Carolyn	SLAM	MSc Biology	1
Kachurowski, Allen	Electrical Team	BSc Electrical Engineering	4
Kastelan, David	SLAM Team Leader	BSc Engineering Physics	3
Khan, Kevin	Mechanical Team	BSc Mechanical Engineering	2
Klaus, Jason	Software Team Leader	BSc Computer Engineering Coop	4
Klippenstein, Jon	Software Team	BSc Engineering Physics	3
Knowles, Robert	Mechanical Team Leader	BSc Computer Engineering	3
Laint, David	Mechanical Team	BSc Computer Engineering	4
Lau, Ben	Mechanical Team	BSc Mechanical Engineering	2
Lee, Roger	Software Team	BSc Computer Engineering	3
Loo, Chris	Mechanical Team	BSc Engineering	1
Marcos, Joseph	Mechanical Team	BSc Mechanical Engineering	3
McIvor, Jake	Mechanical Team	BSc Engineering	1
McVea, Mark	Mechanical Team	BSc Engineering	1
Ng, Jason	Electrical Team	BSc Engineering Physics	3
Ng, Richard	Mechanical Team	BSc Engineering	1
Noor, Noumann	Electrical Team	BSc Engineering	1
Orr, Brennan	Mechanical Team	BSc Mechanical Engineering	4
Sieben, Vincent	Electrical Team Leader	BSc Electrical Engineering	4
Tutschek, Monte	FAT Leader	BSc Computer Engineering	3
Wong, Bryant	Electrical Team	BSc Electrical Engineering	3
Yuen, Stacey	Outreach Team Leader	BSc Mechanical Engineering	2
Toogood, Roger	Faculty Advisor		

9.0 COMPONENT COST SUMMARY

Component	Model	Quantity	Unit Price	Subtotal	Donated
Mechanical Components					
Mild Steel Tubing	20'-1" OD 1/16" wall AISI 1024	1	$64	$64	✓
steel bar stock	24"-2" OD AISI 4041	1	$15	$15	✓
Aluminum stock	2" x 2" x 60" AISI 6061	1	$98	$98	✓
Aluminum stock	6' of ½" OD solid AISI 6061	1	$116	$116	✓
Rod Ends	Aurora VCM-5/VCB-5	16	$4	$64	✓
Shocks	Ryde FX AMPS X10	4	$119	$476	✓
Motors	Leeson Canada C4D17NK9C	2	$391	$781	✓
Tracks	single-sided timing belt	2	$325	$651	
bearings	NSK-6004 20 mm	16	$7	$115	
rollerblade wheels	72 mm diameter	24	$5	$125	✓
rollerblade bearings	ABEC-5	24	$4	$94	✓
worm gear		2	$59	$118	
spline shafts		2	$42	$84	✓
u-joints		4	$24	$96	
Shell	milling, resin, finishing materials Fiberglass, carbon fiber	1 1	$650 $310	$650 $310	 ✓
Electrical/Computer Components					
Hexagonal box	Custom	1	$110	$110	
Micro	Motorola MC 68-332	1	$99	$99	
LCD		1	$12	$12	
Motor Controllers	Custom H-Bridge Drivers	2	$140	$280	
Debug Board	Custom	1	$105	$105	
Remote Control	72 MHz Analog FM	1	$140	$140	
E-Stop	Custom	1	$140	$140	✓
Batteries	Power Battery EG24	4	$120	$482	✓
Power Circuitry	Custom	1	$90	$90	
GPS	Trimble AgGPS 132	1	$3,700	$3,700	✓
SONAR array	Polaroid 6500,Transducers,MCU	1	$539	$539	
Video Camera	Videre Design DCAM	3	$210	$630	
Shaft encoders	Custom	2	$18	$36	
Notebook	Fujitsu Lifebook	1	$423	$423	
PCMCIA Firewire	Evergreen Technologies Fireline	1	$78	$78	
		TOTAL ($USD)		**$10,721**	

Total time to complete modifications: 1055 hours.