University of Alberta

Autonomous Robotic Vehicle Project

"Polar Bear"

Technical Report

June, 2000

Presented to:

William G. Agnew

8th Intelligent Ground Vehicle Competition

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1 Executive Summary

The goal of this project is to develop a rugged, fully- and semi-autonomous mobile robotic system for student competition and for industry. This report describes the design, construction and testing processes involved in the University of Alberta's Polar Bear mobile robot.

Polar Bear's mechanical system has been designed with simplicity and ruggedness in mind, using widely available industrial components. The result is a powerful vehicle, which can be easily modified or repaired in remote locations. The four independently suspended hydraulic drive motors allow the vehicle to be skid-steered in terrain varying from ponds two feet deep to asphalt and concrete.

The Polar Bear's electronics are designed to withstand rough field operation. Particular attention has been paid to the protection of circuitry from transient voltages and Electro-Magnetic Interference (EMI).

An Artificial Neural Network (ANN) is used as the primary means of visual navigation and control, enabling the system to adapt to multiple tasks. The resulting system provides smoother control of the hydraulic drive than is possible by most human operators.

Bear Cub, a scaled-down version of Polar Bear, has been designed and constructed as an indoor test platform. Algorithms and sensors, aided by the use of interchangeable electronics, can be tested indoors on the Bear Cub before being transferred to Polar Bear, for outdoor operation. The Bear Cub is not the primary focus of this report, but it serves as a development tool for Polar Bear.

The Polar Bear's sturdy construction, its rugged electronics and adaptable software make it an ideal platform for the development of outdoor mobile robotics. A Canadian Defence Industrial Research grant has recently been awarded to the University of Alberta to pursue the use of Polar Bear in semi-automated equipment transportation roles for oilfield and defence applications.

2 Administration / Group Dynamics

The design and fabrication process has involved a team of university students from the Electrical and Mechanical Engineering and the Computing Science departments (see Page 14 for a complete list of the students involved). The team is divided into three subgroups: Mechanical Design and Construction, Electrical and Electronics Systems, and Software. Administrative responsibilities are divided among members throughout the different team subdivisions.

An interdisciplinary approach, combined with weekly general meetings and a delegated administrative system proved to be effective in meeting project and media promotion deadlines. The team members have volunteered to promote the project through monthly grade school robotics demonstrations. The team has pooled resources with other student vehicle projects on campus, obtaining both a truck and trailer for transportation of the Polar Bear robot to field locations.

A Canadian Defence Industrial Research grant has recently been awarded to the University of Alberta, allowing students to conduct further research on the Polar Bear for equipment transportation roles in the defence and oilfield sectors.

In total, this year, approximately 800 person-hours have been spent on the mechanical section of the project, 800 person-hours have been spent on the electrical section, 1000 person-hours on software and 400 person-hours on administration.

3 Mechanical System

The most important feature of an all-terrain vehicle platform is flexibility. Keeping the moving parts on the Polar Bear simple allowed the construction of a low maintenance, rugged robot. An air-cooled gasoline engine provides mechanical and electrical system power. This 18 horsepower (13.4 kW.) engine drives a hydraulic pump that pressurizes the hydraulics to drive the four gear pump drive motors. This mechanical configuration allows for a powerful, simple and maintainable drive train. The Polar Bear has proven to be a reliable robot for outdoor testing.

3.1 Engine

The four-stroke Robin® V2 EH65, gasoline spark ignition engine provides the mechanical power for the Polar Bear. At 96.9 lbs. (44 kg.), it is relatively lightweight and compact, measuring 18.7 in. (0.48 m.) tall, by 18.8 (0.48 m.) in. wide, by 12.5 in. (0.32 m.) deep. The V-2 configuration proved to be a very stable engine with relatively low vibration. It has a flywheel magneto that provides electrical power while the vehicle is running.

3.2 Hydraulics

Hydraulic drives reduce the complexity of power transmission and provide a low maintenance solution for industrial mobile robotics applications. Customized power train components, such as transmissions and gear trains, are generally expensive. Polar Bear's hydraulic drive components are off-the-shelf and field serviceable. Parker® hydraulic components were selected due to extensive availability and use by industry. Replacing damaged hoses or wheel motors can be performed in minutes, minimizing down time.

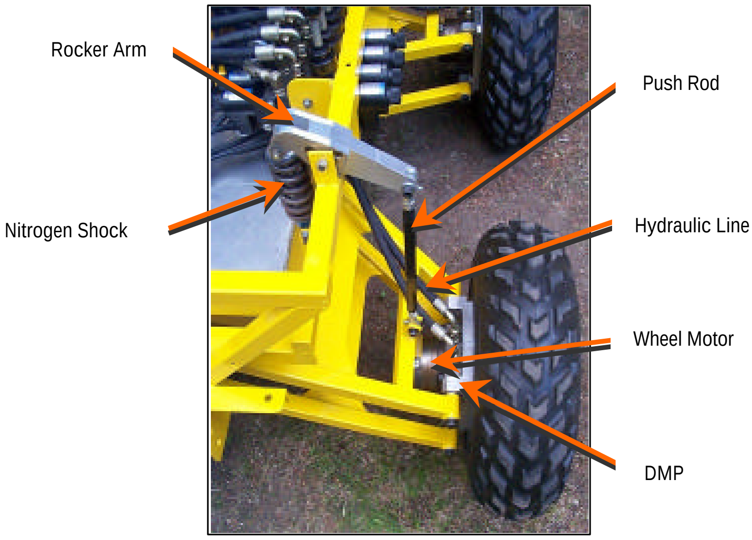

Figure 1 – Mechanical detail.

Hydraulic power is provided by a variable flow Parker® pump with a built-in pressure compensator. The Robin engine drives the hydraulic pump using a flexible belt. The hydraulic flow rate can be manually adjusted at the pump, allowing the Polar Bear's maximum speed to vary from 0 to 11 mph (18 kph).

The hydraulic power to each of the four wheel motors is regulated by means of a proportional solenoid valve deck equipped with manual override levers. The valve deck's solenoids provide the interface between the mechanical and electrical systems. Bi-directional wheel motion is achieved by using simple pulse-width-modulated electronic signals. The proportional nature of the valve deck allows the implementation of traction control and low impact turning. Due to the skid-steered nature of the vehicle, a turning radius of zero has been achieved.

3.3 Frame

The Polar Bear's frame is constructed of mild carbon steel. This material is both easy to fabricate and maintain, allowing for modifications and repairs to be made in the field. The bare frame is about 52 inches (1.3 meters) long, 16in. (0.4 m.) high and 28 in. (0.7 m.) wide. With the camera mount and wheels attached, the Polar Bear is 68 in. (1.72 m.) tall. Suspension is achieved by means of parallel A-arms that are connected to the frame by shoulder bolts and Oilite® bearings.

3.4 Wheels, Motors and Suspension

Each wheel assembly consists of two parallel A-arms connected to an aluminum Drive Motor Plate (DMP). A simple rocker arm - push rod suspension transfers the load to four compact mountain bike shocks (see Figure 1). Wheel configuration is symmetrical about the vehicle's center, reducing the variety of components required. A hydraulic drive motor is mounted on each DMP, providing independent four-wheel power. The resulting wheel base dimensions are 52 in. (1.32 m.) x 38 in. (0.97 m.) with a ground clearance of 14in. (0.36 m.).

Due to low speed requirements, complex dynamic loads are not taken into consideration; however, traversing rough terrain requires vehicle suspension to keep the wheels on the ground at all times. Inexpensive mountain bike shock absorbers with custom helical springs provide the carrying capacity for the 900 lb. (340 kg.) Polar Bear. The aluminum rocker arm provides the mechanical advantage necessary to compress the shocks, while giving each wheel eight inches of vertical travel. Turf tires, which should be installed in the near future, will help ensure that the vehicle does minimal damage to lawns.

3.5 Design Tools

Parametric Technology Corporation's (PTC) Pro/Engineer was used in the development of the Polar Bear. Pro/Engineer allowed the team to use a process of computer aided design to virtually assemble vehicle components as they were designed. PTC's Pro/Mechanica was used for component stress analysis and optimization via Finite Element Methods (FEM). As a result, costly mistakes during component fabrication were minimized and time consuming prototyping were minimized.

3.6 Application

The design of the Polar Bear is focused on future industrial applications. The hefty steel frame, heavy hydraulic components and 18Hp gas engine were selected for compact industrial strength. The gasoline engine allows long range operation with minimal down time. Polar Bear can tow a 6000 lb. van and can carry a 300 lb. payload. One third of the Polar Bear's 900 lbs. (340 kg.), is unsuspended weight located at-hub, giving it a low center of gravity. In addition, a wide wheel base assures that Polar Bear is sure-footed on almost any terrain. The Polar Bear is capable of traversing side slopes of ~25 deg., downhill slopes of ~40 deg., and uphill slopes of ~35 deg. This allows the Polar Bear to match or outperform many standard personal All-Terrain Vehicles.

4 Bear Cub

The Polar Bear's size, weight, and gasoline engine make indoor testing impractical. To address this concern, the Bear Cub has been designed and built as an easily transportable indoor test platform. The 33in. wide (0.83 m.), by 34in. long (0.86 m.), by 36 in. high(0.91 m.) Bear Cub is essentially a scaled-down and simplified version of Polar Bear. It has been fabricated using modular steel components, and can be transported in pieces as regular airline luggage when travelling to remote locations. Nearly all of the electronic components, except for its motor drive circuitry, can be interchanged with the Polar Bear.

The Bear Cub's four Direct Current (DC) motors and electronics are powered by two 12 Volt motorcycle batteries. Running at 24 Volts DC the motors can drive the Bear Cub up to 3 mph (5 kph). Each motor provides up to 100 in-lbs. (11 N-m) of torque, enabling the Bear Cub to be easily skid-steered. Custom drive spindles were designed and built so that the motor output shaft would not have to support the vehicle weight. The free floating design of these spindles is such that the output shafts are only subjected to pure torsion, while other loads are applied to the frame. Vertical loads of up to 150 lbs. (55 kg.) have been tested on the Bear Cub.

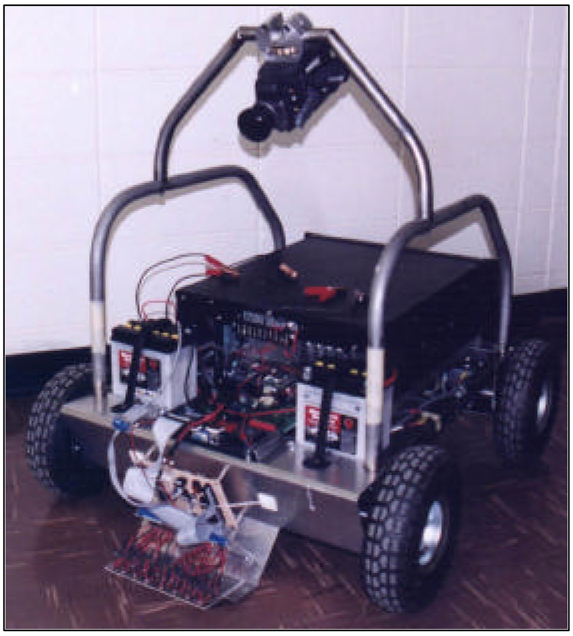

Figure 2 – Bear Cub, the indoor test platform.

5 Electrical and Electronic Components

The electronic system onboard the Polar Bear is designed to be rugged, reliable and inexpensive. The components of the system include an off-the-shelf Personal Computer (PC), a Motorola MPC555 microcontroller, four solenoid drivers for the Polar Bear's hydraulic subsystem, four electric motor drivers for the Bear Cub, six Polaroid Sound Navigation And Ranging (SONAR) units, and one Sony HandyCam camcorder.

5.1 Main Computer

The main computer on board both the Polar Bear and Bear Cub is a BX2000 motherboard with an Intel Celeron 366 MHz processor and 64 MB RAM, and uses the Debian Linux operating system.

5.2 Communication and Video Capture

The main computer uses two serial ports for communication purposes. One serial port allows communication with the MPC555 low-level controller. The other is connected to a remote laptop via two spread spectrum radio transceivers. The radios use frequency hopping to avoid interference, have a 20 mile (32 km.) range and are used for tele-operated training and transportation of either robot.

Six frame-per-second video feedback is available to a remote user when the Polar Bear's onboard computer is connected via Ethernet to a base station. This Ethernet connection allows tele-operation with visual and SONAR feedback to the user.

This type of feedback is important while training the Artificial Neural Network algorithm because the user sees the world as the robot does.

The course traveled by the robot is outlined by lines on either side of the vehicle, detectable by an onboard camcorder. Special attention is given to the section of the course without line markers. The system uses a high-mounted, forward looking video camera to track the lines and obstacles. The camera can view a range of five to 25 feet (1.5 to 8 m.) in front of the robot and 16 feet (5 m.) from side to side. Images from the camera are transferred to the PC via a cable and video capture board.

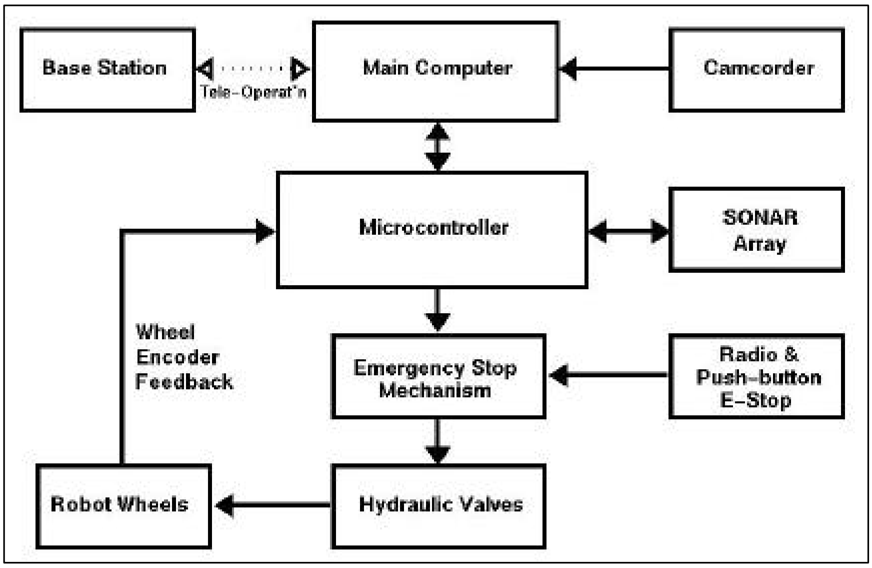

Figure 3 – System block diagram.

5.3 Power and Electro-Magnetic Interference

Two lead-acid batteries and the gasoline engine's magneto power the electronics on the Polar Bear. The engine eliminates the need for a large number of bulky batteries or a recharging station. The robot's main computer can operate for up to 45 minutes on the main battery, without requiring that the magneto be engaged. To prevent voltage dips, a recreational vehicle battery splitter ensures that when the engine is started the necessary electrical power is taken from the smaller secondary battery.

If need be, the robot's batteries can be quickly recharged using an automobile and booster cables. In order to ensure the reduction of Electro-Magnetic Interference (EMI) in our system all electrical sub-systems share a common ground point on the chassis. To further reduce EMI, shrouded resistive spark plugs and shielded power cables are used in the EH65 ignition.

5.4 Low-Level Control

The heart of the low-level control system is the MPC555 embedded PowerPC microcontroller, Motorola's most advanced automotive powertrain controller. The MPC555 does not require extensive shielding and is able to withstand both wide temperature ranges (-40C / -40F to +125C / +260F) and the Electro-Magnetic Interference (EMI) found near the Polar Bear’s engine.

On both the Polar Bear and Bear Cub, the MPC555 is responsible for executing motion control commands from the main computer, as well as control of the SONAR sensor array. These tasks are delegated to the MPC555's two Time Processing Units (TPU). Rudimentary closed-loop feedback control of the wheel motors using the TPU has been implemented on the Bear Cub’s motors. Testing during operating conditions will need to be performed before the algorithms are transferred to the Polar Bear. Once testing is complete the Polar Bear will be able to achieve better traction control in most terrain types.

The solenoids controlling the Polar Bear’s hydraulic valve deck have lower current and Electro-Magnetic Force (EMF) feedback protection requirements than the electric motors on the Bear Cub. Each of the Polar Bear's valve solenoid pairs draws up to 2.8 Amperes at 12 Volts DC, permitting the use of low amperage drivers. These drivers are different from those on the Bear Cub, which consist of discrete transistor and relay switches. The Bear Cub's DC motor drivers are rated for up to 15 Amperes at 28 Volts, continuous, and generally do not draw more than 6 Amperes at 24 Volts. Filtering capacitors and transient voltage suppressors on the main power bus, and buffers between the microcontroller and the drivers ensure that voltage spikes from the Polar Bear's engine or valve deck, or the Bear Cub’s DC motors cannot damage the MPC555.

An array of six SONAR units, each with a range of almost 30 feet (10 m.), is available to both robots. These units are arranged to provide basic obstacle detection in a 60 degree arc in front of the robot. By combining knowledge of the robot's velocity and the velocities and ranges of objects in front of the robot, it is capable of following moving targets. Polar Bear’s reaction time for following a moving person, including reversing if the person approaches the vehicle, was found in be under a second in trials conducted in September, 1999.

5.5 Emergency Stop Mechanism

Two methods of stopping either robot exists which completely by-pass all other electronic subsystems. On the Polar Bear, a series of push-button Emergency Stops (E-stop) are located on perimeter of the vehicle, including one at the rear of the vehicle. These E-stops are electrically in line with the main lead-acid battery and the hydraulic valve drive electronics. On the Bear Cub the single E-stop button is placed on the rear of the camera mount. By depressing the E-Stop button an open-circuit is created and no power can reach the drive electronics, thus bringing the robot to a stop.

Similarly, a radio E-Stop circuit is also placed between the main battery and the drive electronics. A remote user can bring either robot to a complete stop from up to 50 feet (15 m.) away using the radio E-stop. When the electrical power is cut off, the Polar Bear's valves return to their center position and all hydraulic lines are closed off, immediately stopping the vehicle.

6 High Level Control

Polar Bear's high level controller design centers around an Artificial Neural Network (ANN). ANNs are widely used in pattern recognition applications and are useful for their ability to generalize training data to real world applications. The Polar Bear's ANN control system approximates an obstacle course navigation function using a train-by-example approach.

Figure 4 – Training the Polar Bear.

A feed-forward ANN is used to relate a low resolution image of the terrain in front of the robot to its direction of travel. Before the robot is used in an application, its ANN must be trained. A remote operator at a base station computer can train the robot on obstacle courses using either an Ethernet cable or the robot's radio link. During the training sessions, the operator demonstrates to the robot that it must remain between the boundaries.

Experimental trials of the ANN controller at the University of Alberta farm have shown that the Polar Bear is capable of navigating simple test courses at speeds of up to five miles per hour. Surprisingly, during trial runs the ANN has shown that it can navigate curves more smoothly than a human operator can.

Obstacles can be detected up to fifteen feet away. Avoidance of obstacle behavior will be operational by the end of June. Given sufficient training data during more complex trials in late June, the ANN should be able to direct the robot around obstacles and potholes. Further training with dead ends and traps should allow the ANN to avoid these pitfalls as well.

7 Image Capture and Processing

7.1 Hardware

A Sony Handycam camcorder and a PC-based image capture card are the main hardware components of the Polar Bear's vision system. Alternative video cameras, including a Hitachi security camera and a Canon infrared sensitive camera, have been tested but did not provide the image stabilization or picture quality of the Handycam.

Several light filters fastened in front of the Handycam's lens provide a simple and efficient way of preprocessing the video images. A polarization filter reduces glare and lens flares associated with reflected sunlight. Two other filters provide a method of reducing the direct light from the sky and enhancing contrast. These filters help to linearize the luminance and intensity of sunlight in the field of view of the camera, reducing the complexity of software processing on the images.

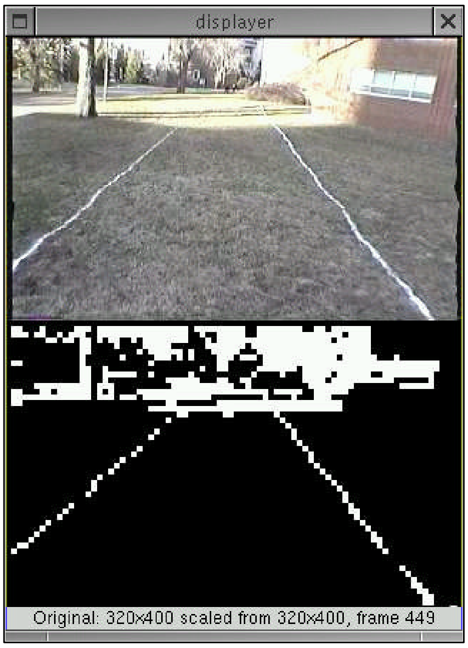

Figure 5a – Original captured image (top) and processed image with reduced resolution (bottom).

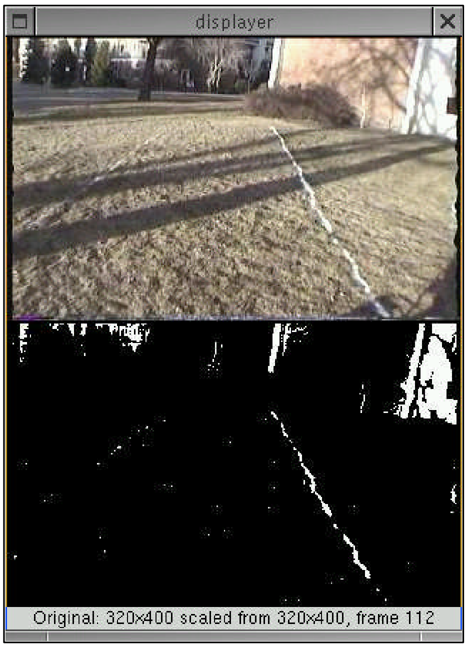

Figure 5b – Original captured image with shadows (top) and processed image (bottom).

7.2 Software

The image capture system uses open-source Linux software and provides up to six 24-bit colour images every second to the image processing algorithms used in target tracking and line following.

7.3 Algorithms for Line Following

Keeping the Polar Bear between two white lines is an easy task if one can isolate the lines from the green grass. This is a relatively simple task under controlled light conditions – the naive approach is to highlight the white pixels in the captured image in order to extract the lines. However, the inherently unpredictable lighting conditions of the course pose many challenges to the competitors. The image processing system uses a combination of techniques to isolate the white lines and obstacles in the course from background information. These techniques can also isolate black potholes and remove shadows from the image.

First, because lighting conditions vary from minute-to-minute outdoors, the contrast and brightness levels of the images are dynamically adjusted. This is achieved by analyzing the red, green and blue component histograms of the image. A simple threshold summation is performed on the resulting colour, black, and white components of the image, thereby accentuating them. An operation to solidify spotty colour, based on Y-luminance Intermodulation Quadrature (YIQ) system introduced by the National Television System Committee (NTSC), is then applied. The YIQ operation helps reduce computational time on the image in later stages.

Because the information contained at the bottom of the image, and thus being closer to the robot, is more important than that at the top, a top-down gradient filter is then applied. Finally, the image is passed through a binary threshold, and is rescaled and cropped, which converts it to a format acceptable by the Artificial Neural Network.

This algorithm should prove to be sufficient for isolating relevant image information from the main and bonus event courses. It can properly identify white lines and black objects resembling potholes on brown-green grass. Work is proceeding on the identification of coloured objects such as traffic barrels. The algorithm will also be effective at ignoring the shadows caused by the trees on the competition course.

7.4 Algorithm for Target Tracking

An object recognition and tracking system as the basis for the Follow-the-Leader event algorithm has been implemented using the robot's main computer and video camera. By programming the relevant camera parameters (focal length, CCD pixel density, etc.) and the dimensions of the target to be tracked, this system can determine the three-dimensional coordinates and orientation of the target when it is within the field-of-view of the camera. The system relies on the Perspective-Three-Point machine vision algorithm and identifies up to five feature points on the target.

Tests of the system in April, using a simpler target than the Follow-the-Leader event’s lawn tractor, have revealed that it is capable of tracking in real time at a rate of up to 4.25 frames-per-second. The target can be up to 23 feet (7 m.) away and up rotated up to 60 degrees from the camera. Accuracy of the tracking system is currently ±2 in. (5 cm.) and ±5 degrees. Modifications to the algorithm to specifically track the lawn tractor, taking into account outdoor lighting conditions, need to be made before it can be fielded at the competition. If the modifications are successful, the robot should be able track the lawn tractor at the correct distance and speed while also being able to avoid stationary obstacles.

8 Reinforcement Learning Robot Simulator

A simulation of the robot learning to drive on a sample course has been implemented. This simulator enables the team members to test machine learning algorithms before attempting to implement them on either the Polar Bear or the Bear Cub. The simulator allows the robot to explore a virtual environment using a technique called “Reinforcement Learning.” This process uses a point system to reward the robot when it behaves correctly and to punish it when it does not.

8.1 Simulator Implementation

The simulator, shown in Figure 4, approximates the camera and SONAR sensor inputs which the robot would receive on an actual obstacle course. It also approximates the output of the robot's Artificial Neural Network controller. Just as the robots entered in the competition do not know the layout of the course, the simulated robot has no preliminary knowledge of the course. As the simulation is executed, the robot, in an attempt to gather as many positive rewards as possible, gradually learns to navigate between the lines denoting the boundary of the course.

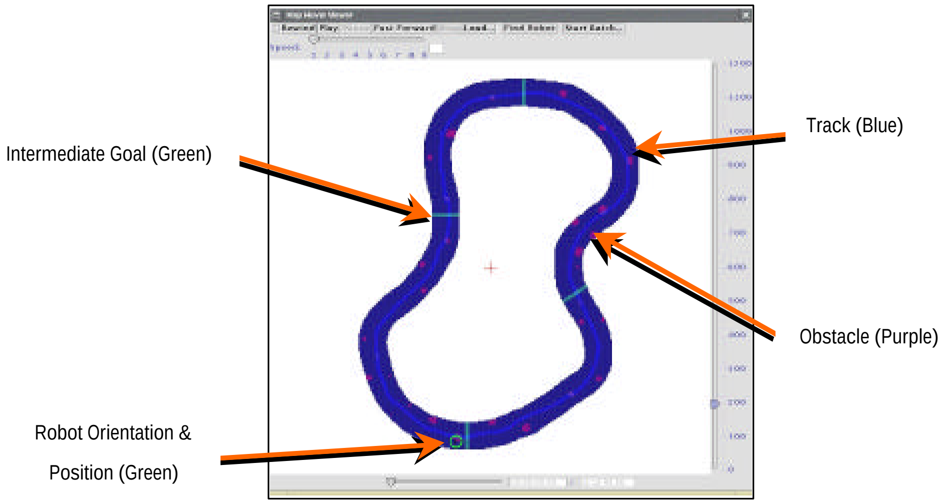

Figure 6 – Simulator detail.

Although a convenient and informative method for testing navigational algorithms the simulator requires further modification in order to become more effective. It currently provides only noise-free sensor data and does not take into account the mechanical dynamics of the real robot.

9 Conclusion

The Polar Bear is a unique university student built robot. Its rugged mechanical system, expandable electronics and adaptable software make it an ideal platform for outdoor mobile robotics. The Artificial Neural Network approach taken for the high level control of the robot allows the system to be trained in an intuitive manner. The electronics and mechanical components have been designed to be reliable and easily serviceable.

Development of the electronics and sensors as well as software for low- and high-level control has been made easier this year with the introduction of Bear Cub. Bear Cub enables the team members to prototype and test electronics and software indoors before implementing them outdoors on the Polar Bear. Software development has also been made easier this year with the introduction of a simulator.

Because of a focus on design and construction for further development in industry Polar Bear is beginning to find a niche in the oil and defence sectors. A Canadian Defence Industrial Research grant has recently been awarded to the University of Alberta, further enabling students to conduct research on the Polar Bear.

10 Team Roster

Name	Academic Major	Academic Year
Mechanical Team		
Ryan Chladny	ME	4
Pat Kirchen	ME	4
Sean Michaelchuk	ME	4
Aaron Saunders	ME	4
Jeff Woo	ME	3
Electrical Team		
Paul Den Boef	EE	3
Darren O'Reilly	EE	3
James Smith	EE	M.Sc. 2
Software		
Kit Barton	CS	4
Aden Grue	CE	1
Jason Gunthorpe	EE	3
Doug Kondor	CS	3
Andrew Pearse	CS	4
Jim Qualie	EE	4
Faculty Advisor		
Dr. Roger Toogood	ME	

ME - Mechanical Engineering
EE - Electrical Engineering
CE - Computer Engineering
CS - Computing Science

11 Bill of Materials

Mechanical

P = Purchased
D = Donated

Description	Model No.	Manufacturer	Quantity	Retail Value ($Can)	Status
Hydraulic Drive Motors	114A-088-HS-0	Parker	4	$ 1,400	D
Hydraulic Pump	PUP 2336	Parker	1	$ 1,200	D
Valve Deck	N/A	Parker	1	$ 3,900	D
Pressure Relief Valve	RD 103535	Parker	1	$ 205	D
Hydraulic Cross-Overs	RD 103535	Parker	4	$ 820	D
Subaru V-2 4 Stroke 18 HP Industrial Gasoline Engine	EH 65	Robin	1	$ 3,000	D
Vanilla Nitrogen Mountain Bike Shock Absorbers	N/A	Fox Racing	4	$ 1,200	D
Custom 1000lb helical springs	N/A	Edmonton Spring	4	$ 195	D
Custom Aluminum Hydraulic Tank	N/A	N/A	1	$ 72	D
Polychain GT Pump Drive Belt	N/A	Gates	1	$ 25	D
Car Battery	N/A	Honda	2	$ 160	D
Standard 16"x8.5" Hydraulic Heat Exchanger	N/A	N/A	1	$ 65	D
All Terrain 23" x 8-11" Tires	ATT 911	Good Year	4	$ 200	D
11" x 8" Steel Rims	N/A	N/A	4	$ 400	D
3/8" Female Rod Ends	N/A	N/A	8	$ 128	D
Assorted Hoses and Fittings	N/A	N/A	1	$ 1,000	D
Raw Materials	N/A	N/A	N/A	$ 1,000	D
Custom Aluminum Gasoline Tank	N/A	N/A	1	$ 13	D
Bolts, Nuts and Fasteners	N/A	N/A	N/A	$ 200	D
Paint	N/A	N/A	N/A	$ 300	D
			Sub-total	**$ 15,483**	

Electrical

Description	Model No.	Manufacturer	Quantity	Retail Value ($Can)	Status
Microcontrollers	MPC555	Motorola & Axiom Man.	2	$ 2,500	D
Computer	Celeron 366	Best Computers	1	$ 500	D
Solenoid Valve Drivers (Hydraulic -- Polar Bear)	N/A	in-house	1	$ 80	P
Motor Drivers (DC Motor -- Bear Cub)	N/A	in-house	1	$ 120	P
DC Motors	GMX-8MC045A	Matsushita Electric	4	$ 240	P
Serial Radios	DGR-115	FreeWave	2	$ 2,000	D
Radio E-Stop	S-50	Certified Radio	1	$ 75	P
SONAR	6500	Polaroid	6	$ 400	P
SONAR	9500	Polaroid	3	$ 200	P
HandyCam Camcorder	CCD-TRV715	Sony	1	$ 1,200	D
Infrared Camera	CI-20R	Canon	1	$ 1,000	D
Miscellaneous	N/A	N/A	N/A	$ 1,000	P
			Sub-total	**$ 9,315**	

Total ($CAN)	**$ 24,798**
Total ($US)	**$ 16,532**