UNIVERSITY OF ALBERTA

Autonomous Robotic Vehicle Project
"Polar Bear"
Technical Report
June 1999

Presented to:
William G. Agnew
Chair, Design Judging Panel
7th International Ground Robotics Competition

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1.0 Executive Summary

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

With simplicity and ruggedness in mind, the Polar Bear's mechanical system has been fabricated using readily available industrial components. This strategy allows for a powerful vehicle capable of being quickly modified or repaired with ease in remote locations. Skid-steering, four wheel independent suspension and hydraulic drive motors on each wheel make the vehicle extremely maneuverable in most terrain and weather conditions. The mechanical system outperforms most student-built, outdoor mobile robot platforms because of the industry-focused design and fabrication strategy.

The electronics are designed to withstand rough field operation. Using a mixture of traditional electronics such as a camcorder and a ruggedized personal computer, the Polar Bear incorporates innovative components such as the VXOptronics StarCam™ range-finding camera system. Particular attention has been paid to the protection of circuitry from power failures and Electro-Magnetic Interference (EMI).

Using a combination of Artificial Neural Networks and Fuzzy Logic, the system's software controller is capable of being trained for various environments. By focusing on experimentally-verified learning algorithms it has been possible to mix adaptable Artificial Neural Networks with rule-based Fuzzy Logic Inference to create a robust software controller. With the addition of sensor data preprocessing the robot's reaction times have been increased.

With a sturdy steel frame, low center of gravity, expandable electronics and adaptable software, Polar Bear is breaking new ground in small all-terrain mobile robotic vehicle platforms. This approach has been so successful that Schlumberger Geco-Prakla, an international geophysical company, and Canada's Department of National Defence has expressed interest in pursing production of robotic platforms based on Polar Bear. Field trials involving Schlumberger's proprietary surveying equipment and the Polar Bear vehicle are taking place this summer and future development in a practical industrial setting are planned.

2.0 Administration/Group Dynamics

The design and fabrication process has involved a team of university students from the Mechanical, Electrical, Computer Engineering and Art and Design departments (see Page 13 for complete list of students involved). The team is divided into four subgroups: Mechanical Design and Construction; Electrical and Electronics Systems; Artificial Intelligence and Control Systems; and Shell Design and Promotion. Administrative responsibilities are divided among members throughout the different team subdivisions.

This interdisciplinary approach, combined with weekly general meetings and a delegated administrative system proved to be effective in achieving project and media promotion deadlines. The team has also focused on the pooling of project resources with other Society of Automotive Engineer vehicle groups to maximize resources available to all groups.

3.0 Mechanical System

The mechanical design emphasizes ruggedness, flexibility and low maintenance. Mechanical and electrical system power is provided by an 18 horsepower fan cooled, four-stroke Robin® V2 EH65, industrial gasoline spark ignition engine. The engine is coupled to a hydraulic pump by means of a Gates Poly Chain® GT® belt. The pump in turn pressurizes the on-board hydraulics to drive the four gear pump drive motors. This mechanical configuration allows for a powerful, simple and maintainable drivetrain.

3.1 Hydraulics

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

The hydraulic power is regulated by means of a proportional solenoid valve deck with manual overrides. Smooth and variable wheel acceleration can be achieved by using simple pulse-width modulated electronic signals. The valve deck consists of four independent valves, each controlling hydraulic flow to one of the four drive motors.

3.2 Frame

The Polar Bear's frame, constructed out of mild carbon steel, is 52 inches (1.3 meters) long, 16in. (0.4 m.) high and 28 in. (0.7 m.) wide. A-arms are connected to the frame by means of shoulder bolts and Oilite® bearings. These parallel A-arms restrict wheel motion to be perpendicular to the ground, providing vehicle stability over a large range of suspension motion.

3.3 Wheels, Motors and Suspension

Wheel configuration is symmetrical about the vehicle's center. Each wheel assembly consists of two parallel A-arms connected to an aluminum Drive Motor Plate (DMP). A hydraulic drive motor is mounted on each DMP, providing independent four-wheel power. Each drive assembly is identical allowing one jig to be used to fabricate all components. This reduces the number of spare parts required. 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).

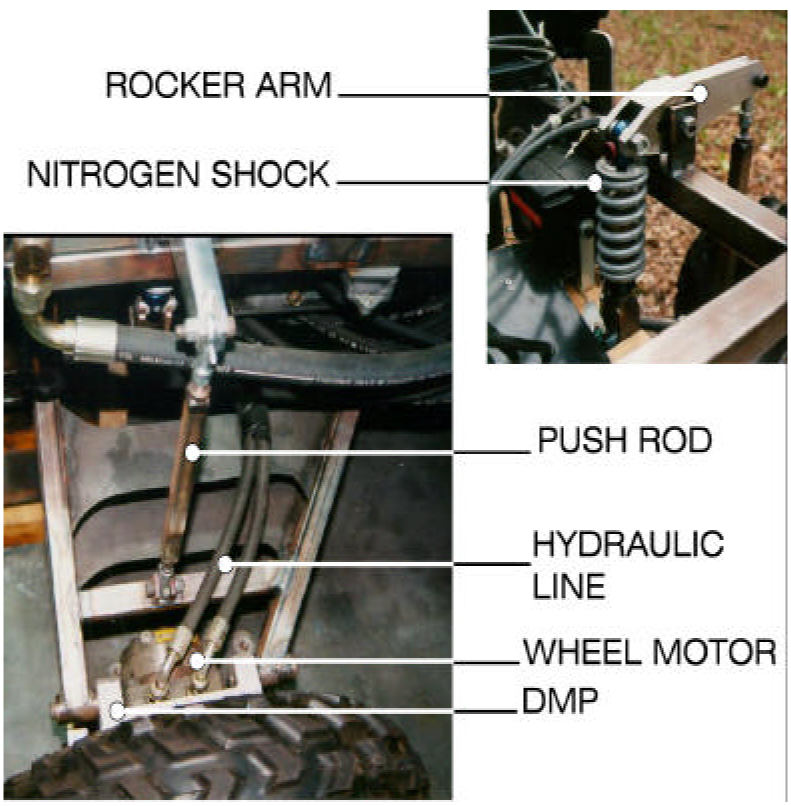

FIGURE 3.1 – Suspension Components

Due to the low-speed requirements of this vehicle it was not important to develop wheel suspension capable of complex dynamic loading. However, traversing rough terrain requires the vehicle's suspension to keep power on the ground at all times. Suspension was designed around inexpensive mountain bike spring-over Nitrogen charged shock absorbers. Push-rods connected to each A-arm assembly applies load to a rocker arm which, in turn, compresses the shock absorber. The aluminum rocker arm was designed to provide mechanical advantage in order to increase the amount of wheel travel in comparison to shock absorber deflection. Figure 3.1 depicts the suspension components.

The design process involved in the creation of the Polar Bear focused on future industrial applications. The solid steel frame and rugged hydraulic components where not chosen for their lightweight but for their durability. One third of the vehicle's 866 lbs is unsuspended weight, located at-hub (the wheel drive motors and DMP's). Having a low center of gravity and a proportionally wide wheelbase assures that Polar Bear is sure footed on almost any terrain.

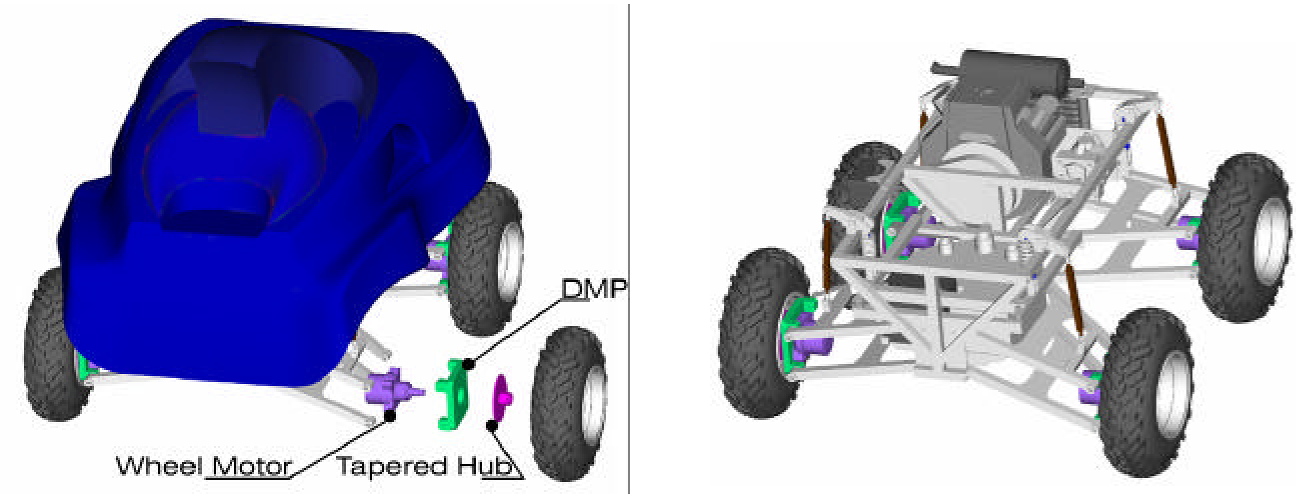

FIGURE 3.2 – Pro/Engineer Solid Model of Polar Bear

3.4 Design Tools

Parametric Technology Corporation's (PTC) Pro / Engineer 3D was used in the development of the Polar Bear. Figure 3.2 illustrates some of Pro / Engineer's rendering capabilities. Pro/Engineer allowed the team to use a process of computer aided design to assemble vehicle components virtually as they were designed. PTC's Pro/Mechanica was used for component stress analysis and optimization via Finite Element Method (FEM) techniques. As a result, costly mistakes during component fabrication were minimized and time consuming prototyping was eliminated.

4.0 Electrical and Electronic Components

The electronic system onboard the Polar Bear is designed to be rugged, reliable and inexpensive. The system components include a 120 MHz Cyrix 586 Personal Computer (PC), two Motorola 68HC11 microcontrollers, four H-bridge motor driver circuits, an array of four Polaroid SONAR (SOund Navigation And RADAR) units, one Sony™ HandyCam™ camcorder, and one VXOptronics stereoscopic StarCam™ camera.

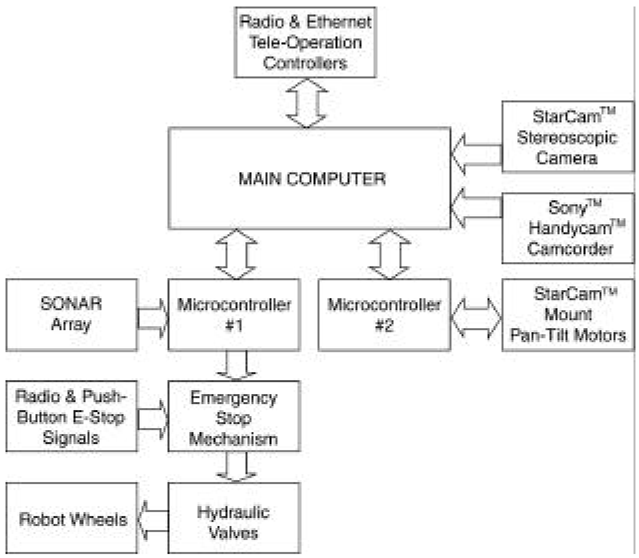

FIGURE 4.1 – Electronic System Overview

4.1 Main Computer

Polar Bear's main processing system is a ruggedized Personal Computer provided by DeltaTee Enterprises Ltd. Originally designed for use in farm equipment it features rubber shock mounts for both the motherboard and the ruggedized hard drive. These mounts are in addition to the rubber mounts already vibration-isolating the electronics section from the rest of the vehicle.

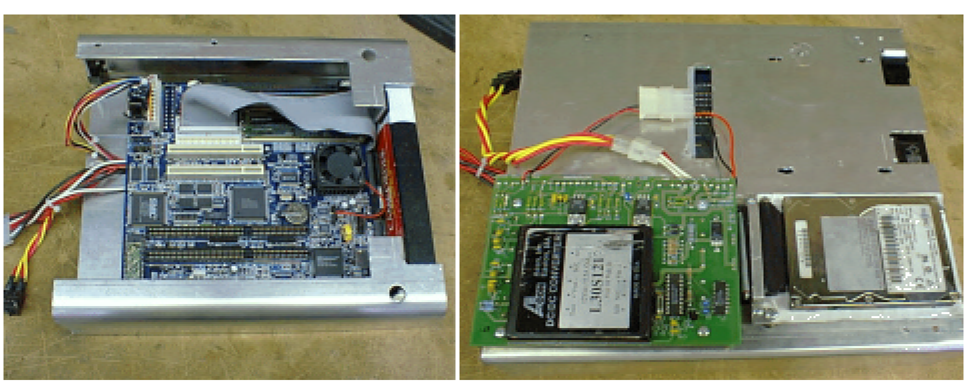

FIGURE 4.1 – Rugged PC w/ Backup Battery (left); DC to DC Converter w/ hard drive (right)

4.2 Power and Solutions to Electro-Magnetic Interference

The PC's specially designed power system features a Direct Current (DC) to DC power converter and battery backup circuit. This enables the computer to use the gasoline engine's magneto charging system as an ample primary power source. Unlike electrically driven robots, Polar Bear does not require large numbers of bulky batteries onboard or recharging at a base station. The battery backup component of the DC to DC converter system also prevents the computer from shutting down in the event that the magneto charging system becomes unavailable. In the event that primary power fails, the computer's battery backup will power it for up to three hours (without monitor). The DC to DC converter also ensures that the power being delivered to the computer is free of damaging voltage spikes or drops.

Elimination and shielding of sources of Electro-Magnetic Interference (EMI) has been important in the design of the electrical system. In order to ensure the reduction of EMI in our system all electrical sub-systems share a common ground on the chassis. Where possible, these ground connections are at the same point on the chassis, reducing the possibility of voltage differences between ground points.

After extensive testing, EMI from the firing of the gasoline engine's spark plugs was found to be the primary cause of destructive electro-magnetic noise in the electronic components. By placing grounded metal shrouds around new resistive spark plugs and by enclosing the wires between the spark plugs and the engine's magneto with aircraft-grade braided shielding, the detectable EMI has been markedly reduced.

Previously EMI-sensitive electronics such as the microcontrollers have been encased in separate metal enclosures. All electronic lines connected to these components are shielded with appropriate ground connections and pass through ferrite torroidal chokes. Electronics which used to reset approximately every five minutes have been tested to run hours on end with no noticeable problems.

4.3 Communication and Video Capture

The ruggedized PC uses two of its serial ports to communicate with the low-level Motorola 68HC11 microcontrollers. A third serial port is connected to a Freewave™ 900 MHz DGR-115 spread spectrum radio transceiver. Usually found in tanks, race cars, and earth movers these radios are capable of reliable RS-232 communication over a 20 mile range at data rates of up to 115.2 KBaud. Using a second DGR-115 attached to any appropriate RS-232 terminal device (e.g. a second computer, 3COM Palm™ device or Hewlett Packard 48 calculator) the robot can be controlled remotely. This is especially important while training the Polar Bear or when transporting it from the laboratory to a field location. This radio is also capable of limited video feedback, allowing a user to remotely operate the robot even when beyond line of sight.

Testing has revealed that the DGR-115's frequency hopping techniques maintain signal integrity even if equivalent 900 MHz direct sequence radio modems are used in the same broadcasting area. The DGR-115 is robust enough to withstand interference from radios competing for the same frequencies and also interference from other sources such as unshielded engine sparkplugs, thus ensuring the connection between the robot and the operator.

Five frame per second video feedback is also available to a remote user when the onboard computer is connected via wired or wireless 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 algorithms; the user/trainer sees the world as the robot does, making the training data gathered more meaningful.

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 20-foot section without line markers. The system uses a high mounted, forward-looking Sony™ HandyCam™ with vibration dampening features to track the lines as well as obstacles. The camera can view a range of 5 to 25 ft in front of the robot and 16 ft. from side to side. Images from the HandyCam™ are transferred to the PC via an S-video cable to the Hauppage™ WinTV 404 video capture board.

4.4 Low-Level Control

Low-level control of the vehicle is achieved via two Motorola 68HC11 processor boards. These boards are used because of their reliability, ease of use, low cost and availability. The first 68HC11 controls the hydraulic valves and SONAR array onboard the Polar Bear. The ruggedized PC transmits direction and speed commands for the Polar Bear to the first 68HC11. This microcontroller controls the custom-made high-current H-bridge circuits which drive the hydraulic valves and ensures smooth acceleration of the vehicle. It also controls the timing sequences of the SONAR array and transmits relevant ranging data to the PC.

The second 68HC11 controls the pan-tilt motion required by the StarCam™ stereoscopic camera while tracking moving targets. Using a Proportional Integral Derivative (PID) control algorithm, this 68HC11 ensures that the StarCam™ points in the desired direction as determined by software on the PC. It also allows auto-panning, allowing for a 180 degree pan of the environment to be taken with the StarCam™ in approximately seven seconds.

4.5 VXOptronics StarCam™

The VXOptronics StarCam™ acquires three dimensional visual data using two self-calibrated charge-coupled device cameras. Unique in the world, this camera provides sub-millimeter range-finding data using visual triangulation. Coupled with a Dipix FPG-44 video capture card onboard the PC it provides range-finding and three-dimensional profile data to a fuzzy controller algorithm for the Follow-the-Leader event.

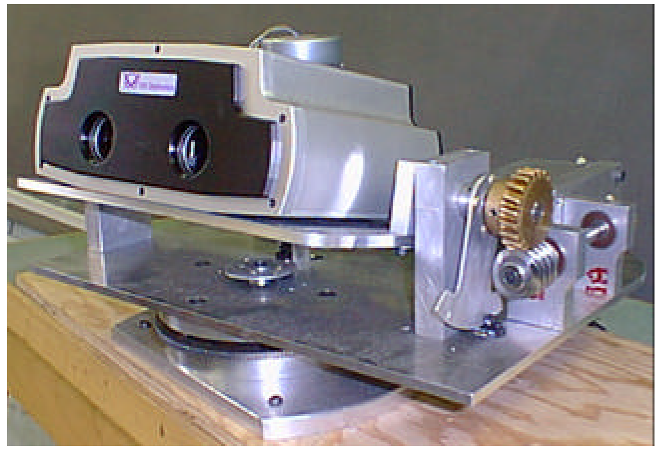

FIGURE 4.2 - VXOptronics StarCam™ and Pan-Tilt Mount

4.6 Emergency Stop (E-Stop) Mechanism

Two methods of stopping the Polar Bear exist which completely by-pass all other electronic subsystems. A push-button E-Stop located on the rear of the vehicle is placed, electrically, in between the gasoline engine's lead-acid battery and hydraulic valve drive electronics. 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 lead-acid battery and the drive electronics. In the same manner, but from up to 30 feet away, a remote user can bring the robot to a complete stop. Mechanically, when electrical power is cut off, the solenoids return to their center position and all hydraulic lines are closed off (cylinder spool valves), stopping the vehicle.

5.0 High Level Control

High level control of the Polar Bear is achieved using an Artificial Neural Network (ANN). ANNs are recognized for their ability to identify patterns in images, and for their ability to generalize training data in real world applications. In the case of the Polar Bear's control system an ANN is used to approximate an obstacle course navigation function using a train-by-example approach.

Section 5.1 deals with the ANN used in the Main and Bonus events while Section 5.2 addresses the Fuzzy Logic controller for the Follow-the-Leader event.

5.1 Artificial Neural Network – Main and Bonus Events

A feed-forward neural network with limited feedback is used to relate the sensor inputs to the direction of travel of the robot. This network is trained using an error back-propagating algorithm. Visual and SONAR data used for both the training of the network and the feed-forward operation is processed with a spatial threshold filter.

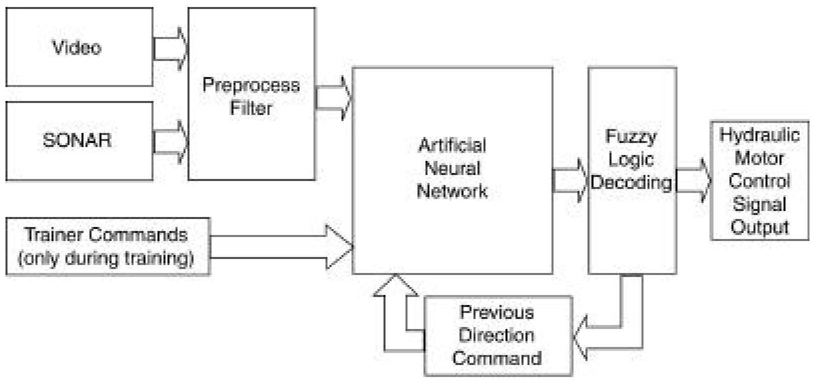

FIGURE 5.1 – Artificial Neural Network Controller

The feed-forward ANN used in the online control of the robot uses layers of interconnected computational units called neurons for processing of information. The strength of each interconnection is tailored so that the overall ANN represents the desired navigational function, as determined by the learning algorithm. Past actions also play a role as they are fed back into the input of the ANN.

Multiple ANN outputs, each representing a different direction command can be activated simultaneously; therefore, a method for determining the ideal robot direction is required. The method of Fuzzy Set Center of Gravity decoding is used for this purpose. The result maps the ANN's real-valued navigation function to a discrete set of direction commands quickly and reliably.

Before the robot is used in any application, training is required. Using either the FreeWave™ radio system or the Ethernet connection to a base station, it is possible for a remote operator to direct Polar Bear through example obstacle courses. During the training process the operator shows Polar Bear how to navigate the course, demonstrating that it must remain within the lined boundaries while avoiding obstacles such as orange barrels and dead ends. The visual and SONAR data as well as the operator's direction and speed commands are time-stamped and stored in a file within the onboard computer.

The files demonstrating successful navigation of the course are then transferred into a back-propagating ANN learning algorithm. Back propagation is accomplished by adjusting the weights of the ANN interconnections to map the desired output (the trainer's commands) to a given input (the preprocessed sensor information). This process is repeated with the all the images and related direction commands until a tolerable margin of error is attained with all of the data within the training files.

The primary vision system, a Sony™ HandyCam™ and Hauppauge™ WinTV 404, capture captures 24 bit, 700 by 400 pixel images of the area in front of the robot. Before the ANN can process this image it must be cropped to eliminate unnecessary information such as sky, filtered to extract the most important features, and reduced in resolution to minimize inputs. The preprocessing system filters out unnecessary video information such as sunlight reflections in grass, leaving only the more relevant data associated with boundaries and obstacles. In addition, an array of SONAR sensors located on the front of the vehicle is used to detect obstacles within a 10 ft. range.

Applying spatial operation theory to the cropped image, specifically by looking at segments of the original video image and comparing these to adjustable color thresholds, it is possible to eliminate the majority of the irrelevant visual data. These thresholds can be set by the trainer to accommodate changing light conditions. Relevant data, such as the colours associated with line boundaries, barrels and other obstacles pass through the filter. The filter also correlates SONAR ranging data with the detection of the typical obstacle colors, orange and red. To further reduce ANN processing time the filtered image is then reduced to 8 by 32 pixels.

Initial trials of this control method have shown that the Polar Bear is capable of navigating simple test courses at speeds of up to five miles per hour. This approach was confirmed through experimental trials. Obstacles up to fifteen feet away can be detected and avoidance behavior should be operational by the end of May. The image processing techniques have proven effective in filtering out images of the sky while climbing ramps. Given sufficient training data during trials in late May on more complex courses involving dead ends and traps, the ANN should be able to deal with these as well.

5.2 Follow-the-Leader Event

For the Follow-the-Leader event, the VXOptronics StarCam™ is used to track the moving lawn tractor. The StarCam™ uses its profiling function and a rule-based Fuzzy Logic controller to determine relative distance and speed between the Polar Bear and the lawn tractor. Chosen because of its relative robustness, flexibility and wide acceptance in industry, the fuzzy logic controller outputs direction and speed commands to both 68HC11

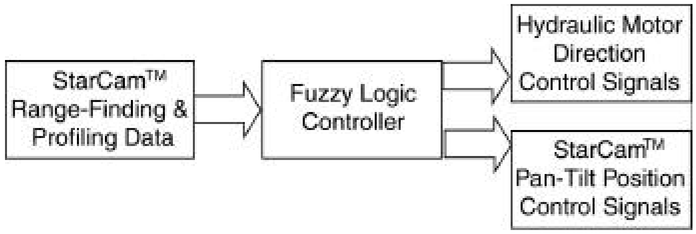

FIGURE 5.2 – StarCam™ Fuzzy Logic Controller

microcontrollers, determining the speed and direction of the Polar Bear and the pan-tilt motion of the StarCam™. Using just over 70 simple rules to control this process the fuzzy controller has been tested in the lab using the SONAR array and is capable of quickly tracking moving objects. Work is proceeding on converting the controller for use with the StarCam™ which will allow sub-centimeter ranging accuracy from 1 to 7 meters without using the cumbersome image recognition techniques required by traditional camcorder-equipped systems. Field testing will take place at the end of May and, with addition of more rules, is expected to be able to track the moving lawn tractor at about three miles per hour. This system should perform well in the first and second phases of the first heat but may have trouble tracking the lead vehicle in the tight turns due to the limited field of view of the StarCam™.

6.0 Conclusion

With a sturdy steel frame and a low center of gravity, expandable electronics and adaptable software, Polar Bear is breaking new ground in small all-terrain mobile robotic vehicle platforms. A combination of Artificial Neural Networks and Fuzzy Logic provides a flexible software controller with the ability to operate in a changing environment. The focus of Polar Bear's electronics is *"plain and simple!"*, a blend of traditional electronics and a ruggedized PC provide reliable and flexible control while keeping costs low. Mechanical systems aboard the Polar Bear are compact and modular allowing for quick repair with fewer spare parts. The Polar Bear system is a unique and effective solution to mobile robotic platforms.

Because of the focus on design and construction for possible further development in industry there is real potential for Polar Bear to be used in real-world applications in the medium to long term. The Polar Bear team strives to make a vehicle worthy of being used in real world applications, to hold a place in the future of automated transportation development.

7.0 Team Roster

Electrical Team

Name	***Academic Major***	***Academic Year***
Paul den Boef	Electrical Engg. (EE)	2nd
Todd Carter	EE	4th
Areef Kassam	EE	2nd
Jason McKay	EE	3rd
Darren O'Reilly	EE	2nd
James Smith	EE	MSc 1
Stephen Tang	EE	4th
Sydney Tang	EE	4th

Mechanical Team

Ryan Chladny	Mechanical Engg. (ME)	3rd
Chris Kirchen	ME	3rd
Pat Kirchen	ME	3rd
Sean Michaelchuk	ME	3rd
Damien Salle	ME	4th
Aaron Saunders	ME	3rd

Industrial Design

Marc Brulotte	Industrial Design (ID)	4th
Rick Wong	ID	4th

Artificial Intelligence

Penny Ashe	EE	3rd
James Brown	Computer Engg. (CE)	1st
Jason Gunthorpe	CE	3rd
Shauna Rae	EE	MSc 1

Faculty Advisors

Dr. Roger Toogood ME
Dr. Max Meng EE

Acknowledgments

A special thanks to following who helped make Polar Bear such a success:

Ian Buttar, Bernie Faulkner and all of the other Mechanical Engineering Shop technicians, and Loren Wyard-Scott.

8.0 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	$1400	D
Hydraulic Pump	PUP 2336	Parker	1	$1200	D
Valve Deck		Parker	1	$3900	D
Pressure Relief Valve	RD 103535	Parker	1	$205	D
Hydraulic Cross-Overs	RD 103535	Parker	4	$820	D
Subaru V-2 4 Stroke 18hp Industrial Gasoline Engine	EH 65	Robin	1	$3000	D
Fox Vanilla Nitrogen Mountain Bike Shock Absorbers		Fox Racing	4	$1200	D
Custom 1000lb helical springs	n/a	Edmonton Springs	4	$195	D
Custom Aluminum Hydraulic Tank	n/a		1	$72	D
Polychain GT Pump Drive Belt	n/a	Gates	1	$25	D
Car Battery	n/a	Honda	1	$80	D
Standard 16" x 8.5" Hydraulic Heat Exchanger			1	$65	D
All Terrain 23" x 8 -11" Tires	ATT 911	Good Year	4	$200	D
11" x 8" Steel Rims	n/a		4	$400	D
3/8" Female Rod Ends	n/a		8	$128	D
Custom Shell	n/a		1	$2000	D
Assorted Hose and Fittings	n/a		n/a	$1000	D
Custom StarCam™ Pan-Tilt Mount	n/a		1	$900	P
Raw Materials	n/a			$1000	D
Custom Aluminum Gas Tank	n/a		1	$13	D
Bolts, Nuts and Fasteners	n/a		n/a	$200	D
			Sub-Total	$18003	

Electrical

Description	Model No.	Manufacturer	Quantity	Retail Value ($CAN)	Status
Microcontrollers	68HC11	Zorin & NAIT	2	$500	D
Computers	Cyrix 586	Deltatee Ent. Ltd.	2	$3,000	D
H-bridge M. Drivers	n/a	in-house	4	$500	D
Serial Radios	DGR-115	FreeWave	2	$2,000	D
Radio E-Stop	S-50	Certified Radio	1	$75	P
SONAR	6500	Polaroid	4	$300	P
HandyCam™ Camcorder	CCD-TRV715	Sony™	1	$1,200	D
StarCam™	Module X2Z	VXOptronics	1	$10,000	D
Misc.	n/a	n/a	n/a	$1,000	P
			Sub-Total	$18,575	
			Total	**$ 36,578**	