Michigan Technological University Unmanned Robotics

Competition Design Report
July, 2000

1. Design Process

1.1 Team Structure and Organization:

Michigan Technological University’s Unmanned Robotic Vehicle is the product of three years of interdisciplinary undergraduate research. A team of fifteen students, representing four disciplines, has devoted over two thousand hours of largely volunteer effort to the robot's development. Building on the experience of two prior vehicles, the current robot incorporates many design innovations that reflect the conscientious efforts of the team.

1.2 Design Philosophy:

Michigan Tech's team features a diverse group of individuals, each of whom has unique talents and ideas. This fact is exploited in the team structure. Small work teams are formed to design and implement a given component or system for the robot, with frequent updates given to the entire group. The small teams facilitate communication and allow an idea to be more thoroughly conceived. For example, the design of a video camera system impacts the mechanical structure of the robot, the electrical system, and the vision and navigation software. With a diverse group, all aspects of a problem can be addressed early in the design cycle, making more efficient use of time and materials.

1.3 Design Aids:

Extensive use of both 2D and 3D CAD was integral to the design of the robot. A single model of the robot, constructed in AutoCAD, is frequently referenced to design new components, and updated to ensure accuracy for future projects. MATLAB was used in the early design of image processing filters, to reduce development time in this area. Finally, CADSoft Eagle layout editor was used in the design of various custom printed circuit boards used on the robot.

2. **Mechanical**

2.1 Frame:

The frame of the robot was specifically designed to be a rugged and versatile platform on which to base our efforts. It is constructed in a cubic form factor and provides containment for all robot components with the exception of the sensors and computer. The frame is built entirely of 2-inch angle iron. All joints of the frame are welded to insure superior strength. The frame is 16-inch in height, 38-inch in depth, and 26-inch in width. These dimensions were chosen to maximize the interior space of the frame while maintaining a low center of gravity and an adequate wheelbase. Interior support members are strategically placed to allow for direct mounting of the drive train as well as to maintain rigidity of the frame. The entire frame has been coated with a protective enamel to ensure strength and integrity of the metal for years to come.

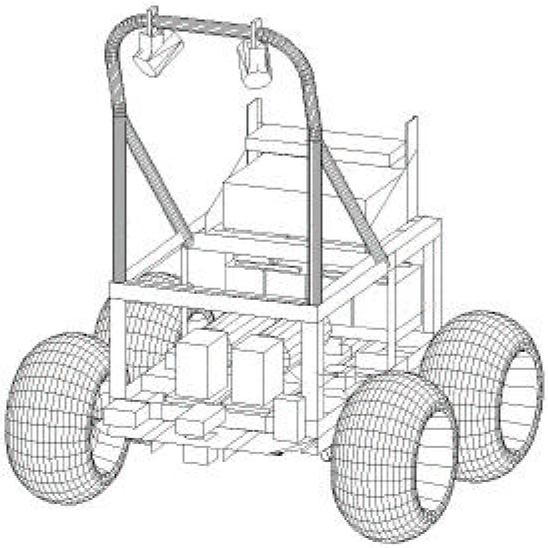

Figure 1: Wire Frame Drawing of Robot

2.2 Drivetrain:

The robot is propelled by a skid steer drive train system. This system was chosen for a number of reasons. It is a simple and durable system. Steering is handled by simply varying the speeds of either side of the robot. Such a steering scheme yields a predictable and easy to achieve response that is insulated from most external factors. Furthermore, a skid steer implementation allows for extremely accurate and tight maneuvering.

The two, independent sides of the robot are each powered by their own dedicated 1 HP permanent magnet DC motor. A gearbox with a 20:1 gear reduction is directly mated to each motor. An exposed gear on the output shaft of each gearbox and a sprocket on each axle add an additional 2:1 gear reduction. Such a gearing scheme is well suited to such a low speed task. The additional torque allows for more responsive handling as well as better performance in adverse terrain. A chain drive then directly connects the front and rear axles for perfectly matched speed. Each axle is attached to the frame with two pillow block bearings. Riser blocks are used between the bearings and the frame itself to allow for an overall ground clearance of 7-inch. Aggressively treaded ATV tires are used; and are partially inflated so as to provide a generous amount of shock and vibration dampening for the robot. This greatly aids the sensory systems as well as sensitive electronic components.

2.3 Shell:

The robot is contained within a durable, yet flexible, fiberglass shell. The shell completely encloses all hardware with the exception of an access port to the payload bay in the front and an open rear that allows for easy access to the batteries and computer. The shell can easily be removed from the frame by detaching four thumbscrews. This enhances the ability to perform maintenance tasks on the robot. Dual fans are located in the nose of the shell to allow for cooling of internal components.

2.4 Payload Bay:

A payload bay is located in the front of the robot, directly above the motors. The bay is constructed of a steel mesh and is rigidly mounted to the frame. It offers approximately 4.3 square feet of surface area and can hold in excess of 150 pounds. The steel mesh is removable for access to the components of the drive system below.

3. Power System

3.1 Batteries:

The robot's primary source of power is a pair of 24-volt battery packs. Two 12-volt gel-cell batteries connected in series compose each pack. Gel-cell batteries are used because of their non-spillable electrolyte, high energy-to-weight ratio, and compact size. Battery packs are housed in a retractable tray located in the rear of the robot, and are easily removed. Packs are connected in parallel inside the robot, so a depleted pack may be exchanged without disrupting power to the robot.

The robot uses modular DC-DC converters to provide power to the computer and other sensitive electronics. Using DC-DC converters provides an efficient means of supplying all required DC voltages, and eliminates the weight and size penalties of conventional DC to AC inverters. Additionally, a standard AC computer power supply is included, providing long-term power when the robot is not in a mobile state. DC power flow is seamlessly switched between the DC-DC converters and the AC supply when the AC supply is energized.

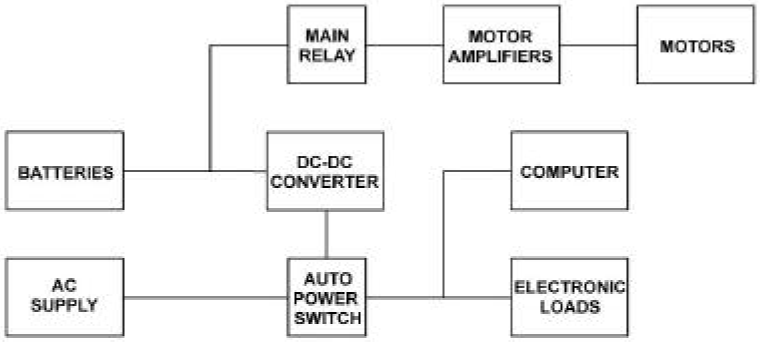

Figure 2: Power Flow Chart

3.2 Computer:

A standard personal computer platform was selected as the development base for our robot due to its flexibility in terms of hardware and software, its low cost and extremely broad hardware selection. Our system is based on industry standard components, and is easily upgradeable for future needs.

The image acquisition is done through two commercially purchased Hauppauge Win/TV Go frame grabber cards. These low cost frame grabber cards work with a low CPU overhead and provide high-resolution images to work with. Their functionality is well supported under GNU/Linux making development easy.

Motion control functions are accomplished through the use of a dedicated DSP-based motion-control card, a donation from Precision Microcontrol Corporation (PMC). The card resides on the bus of the PC, and executes motion control commands sent to it by the navigation software. The driver software needed to use this card under GNU/Linux was custom ported by our team from the source code provided by PMC Corp.

3.3 Electronic Sensory:

To aid the robot's visual system in obstacle detection, the robot uses a custom-built laser range finder system. The system utilizes a laser diode, along with a corresponding receiver to measure the distance between the robot and nearby obstacles. A time-of-flight chronometer module, embedded within the system, allows for precise measurement of the time between an infrared pulse generated by the diode and the subsequent return of the light after it reflects off an object. This measurement is then transmitted to an on-board M68HC11 microprocessor that processes and communicates this data to the robot's main computer. The range finder is mounted atop a stepping motor, which allows for measurements to be taken at 1.8-degree increments over the system's 120-degree field of view. Use of a condensing lens mounted in front of the receiver provides reliable measurements from a range of up to 16 feet. Aluminum casing for each of the system's components greatly reduces EM interference encountered by the system's electronics. The entire system is mounted at the front of the robot, close to ground level to provide an unobstructed view of the robot's path. All components are powered by the robot's main power system.

As this sensory system is based upon a laser, eye safety was naturally a concern. While the particular laser diode used in this system is capable of light intensities that can be damaging to the human eye, the configuration of the laser range finder is such that these levels are never reached. Thorough testing of the system has guaranteed the maximum output of the laser diode to be no greater than 0.4 µW, well below the 3.4 mW safety limit required by law.

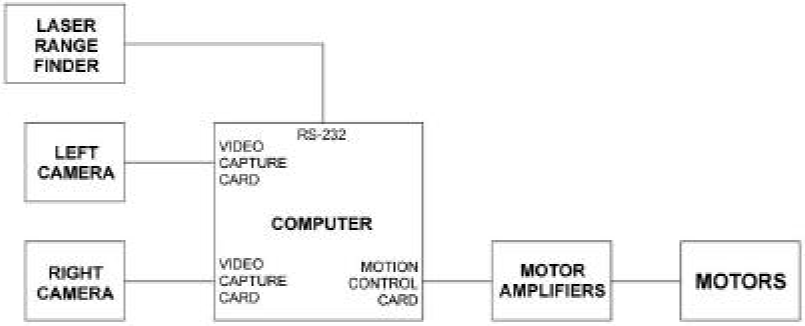

Figure 3: Sensory Flow Chart

3.4 Motor Control:

Motion control is categorized into two modes: manual control and autonomous control. A switch on the robot's control panel selects the operation mode. Two one-horsepower DC motors are used to drive the robot's two sides independently. Each motor has a dedicated amplifier, which converts 24-volt battery power into a motor drive signal. The motor amplifiers receive their drive signals from one of two sources, depending on the mode of operation.

3.5 Manual Control:

Manual control is provided as a means of maneuvering the robot during testing or transportation. Manual control is accomplished using a modified joystick with two controls, each manipulating the speed of one

DC motor. Turning is achieved by reducing or reversing the speed of one motor, allowing the robot to make precise movements with a zero turning radius. Manual mode operation does not require the computer's motion control card to be installed. In manual mode, the signals from the joystick are coupled directly to the motor amplifiers through custom interface circuitry.

3.6 Autonomous Control:

Autonomous control involves the use of the computer to control the velocities of the two motors. For an explanation of the basis for this control, please refer to Software: navigation. A motion control card, donated by Precision MicroControl, is the center of a closed-loop servo system used to generate accurate motor moves. Encoders mounted on the rear axles provide position feedback to the controller, which uses this information to precisely maintain the speed desired by the navigation software. In contrast to previous designs, control of robot position is now achieved solely through velocity changes of each motor. This scheme allows fluid motion, since the robot need not decelerate between moves.

4. Software

4.1 Operating System:

The on-board computer runs the GNU/Linux Operating System. This UNIX-like operating system was selected for its stability and efficient operation in embedded systems. Linux was also chosen over other operating systems because of its open-source license, which allows our team to install and customize the operating system free of royalty charges. All software development is performed using the C programming language, which allows efficient code development, while reducing unnecessary overhead inherent to other systems. This comes in very handy in our situation, where integrating hardware components in a near real-time environment is essential.

4.2 Image Processing

The image processing system is the primary sensor system and most computationally demanding part of the robot's computer systems. The system receives information from a pair of color cameras and all stages of processing function in color. Color processing was chosen over monochrome since our experience showed that obstacles are less distinguishable in monochrome. The system is designed to be modular and scalable so it can be integrated into a future artificial intelligence implementation.

The images are modeled as hue, saturation and intensity (HSI) information since this model provides human-like descriptions of colors. The image processing works on each component of the HSI image as if it were a single grayscale image. The results of each component are then combined into a single map for each image frame.

During the processing, histograms of image data are used to identify obstacles. An object in the image will show up as a histogram spike. By filtering noise from these histograms, the system can adaptively select ranges of component values that correspond to a particular object. For example, the grass hue will always be green but its intensity may vary with changing lighting conditions. The adaptive process used in the software will automatically determine the range of values that corresponds to the grass. Once objects are selected they are retained based on their properties or discarded if they are not considered to have obstacle properties. This will provide groundwork for later artificial intelligence implementation.

Once the scene has been removed of objects that are extraneous, the image is enhanced by removing single-pixel errors, smoothing the objects, and cataloging their locations. Once the locations of an object in the images from the left and right cameras are known, the distance from the robot is computed. A final output image is created by fitting simple geometric figures (rectangles, circles) in place of the real objects. This single image is passed to the navigation software.

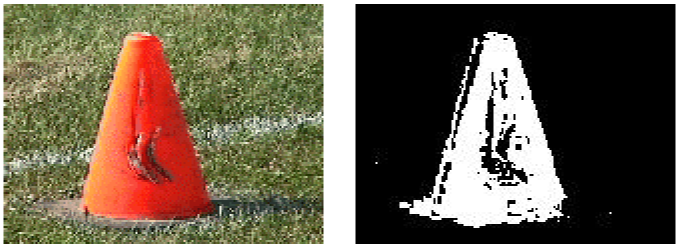

Figure 4: Before and After Images of Image Processing Software

4.3 Navigation:

Our methodology for autonomous operation is a relatively simple process. The image is acquired from the two frame grabber cards. These images are then processed using our own hybrid combination of color interpolation and edge detection algorithms. The processed images are passed to the path planning module which analyzes the given image set and the data obtained from our laser radar scanner. Our path planning will compute a best-fit curve given the borderlines to plan a general path through our field of view. In any view, both lines and obstacles are treated as objects to be avoided. The robot features a navigation system analogous to a charged particle's travel in the presence of other like charges. Objects that possess numerous sequential points are classified as lines, and are assigned a linear charge distribution. The objects that cannot be classified as lines are processed down to a single point, possessing a location in space and a "mass", that repel the robot based on their mass. Heavier-weighted objects are formed from larger-massed objects detected from either the stereoscopic camera system or the laser scanner. Objects closer to the vehicle are given greater priority. If an object is detected by both systems, the mass of the two resulting points will be added to produce a single, larger mass that will repel the robot. In this way, the camera system and the laser scanner work together to detect obstacles.

Motion control commands are issued as soon as each video capture completes, which equates to about three navigation decisions per second, sufficient to navigate at speeds up to 5 mph. Motion commands vary the velocities of each axis of the robot, in order to achieve forward and turning motion.

4.4 Avoidance of Traps and Obstacles:

Our robot's navigation system is designed to successfully detect and account for the abnormalities present on the obstacle course. If a ramp is encountered, the robot's laser scanner will detect a continuous obstacle at a constant range ahead of the vehicle, while the stereo camera array will detect only the white or yellow lines proceeding over the ramp. The navigation software will sum the charges from all objects and lines detected, as it normally does, but the continuous obstacle presented by the ramp is equally distributed to both sides of the robot, and will cancel any sideways repulsion of the robot's motion. The robot will slow down as it approaches the ramp, but once it begins climbing the obstacle will disappear and the vehicle will proceed over the ramp, staying within the white lines.

In the event of a dead-end trap, the robot will observe the obstacles using both its laser scanner and stereo vision system. Since the obstacles appear as one continuous receding wall to the laser scanner, the mass of this point is quite large, and when summed with the mass from the camera system, will cause the robot to diverge its path to the opposite side of the obstacle course. In the event that the robot mistakenly ventures into the trap, it will eventually detect a solid obstacle directly in front of it. The object will cause the robot to slow down, as it is repelled by the obstacle's force, until it eventually stops. If this situation is detected, the robot will reverse its last moves until it backs out of the trap and proceeds.

Real-time obstacles are also detected and cataloged as soon as the video cameras or laser scanner sees them. The video cameras are updated fast enough to detect dynamic obstacles before they are contacted.

The update rate for the laser scanner is slower, about one second, but once an obstacle is seen by both systems, it is weighted sufficiently so that it is avoided.

4.5 Debugging and Monitoring:

The system has been built with a robustness that allows for rapid software testing, and easy interaction during operation. An on-board wireless Ethernet system allows us to connect remotely. The GNU/Linux operating system allows for nearly every resource to be controlled remotely, just as if a user were at a keyboard connected to the robot itself. With a portable computer the team can connect to the robot and control the on-board systems. Images can be remotely viewed in near real-time, allowing the user to monitor the images as the camera sees them. In this mode the robot can be set into a fully manual mode or vary the level of autonomy. This allows for easy debugging of different parts of the computer subsystem while testing other systems.

5. Other Design Issues

5.1 Safety:

Our robot incorporates many features that ensure safe operation. Emergency stop switches are arranged to provide the ability to stop the robot in many ways. Large, easily identified pushbutton switches are located on the front and rear of the robot. In manual mode another e-stop trigger is the joystick, which must be connected for the robot to operate. When in autonomous mode a substitute “key” is used. Finally, a remote radio-frequency e-stop system is included for stopping the robot from afar. Activating any of the four e-stops will immediately interrupt power to the motors and stop the vehicle. Once stopped, mobility is regained only if all four e-stops are de-activated, and a reset button is pressed.

Safety during normal operation is also an important design feature; orange chain guards protect operator's and technician's hands from injury by sprockets and chain. The area around the output shaft of the gearbox and the two open gears has been completely enclosed in Plexiglas. With these guards installed, the only access to the chain drive and gearing is from underneath the robot. Electrical safety is also practiced throughout the vehicle. DIN-rail terminal blocks provide organized wiring with identified terminals, making servicing easier and safer. Extensive fusing is used to minimize the danger from accidental shorts. All wiring is protected by plastic spiral wrap, shielding it from abrasions and environmental conditions.

5.2 Ruggedness:

A rugged design was of high importance to our team. Our vehicle's drivetrain is designed to function in many environments, including mud and snow. Our robot has proven very capable and mobile in sand, deep snow, and ice. A minimum of seven inches ground clearance is provided, with sensitive components mounted within the frame for added protection. All-terrain tires provide a cushioned, high-traction connection to the ground. Critical electronic components are shielded mechanically and electromagnetically to ensure proper function in all environments.

5.3 Serviceability:

In designing any product, serviceability is an important attribute. Our robot is no exception. Modularity is a key feature of this approach, and is evident in all the robot's systems. A 19" equipment rack is installed in the rear of the vehicle, and houses the main computer, and interface circuitry. The rack chassis provides an easy means of exchanging or adding components. Modular connectors are used to ensure that systems cannot be coupled incorrectly.

5.4 Original Content:

A custom laser-range finder has been designed and constructed by our team. This approach was selected over a commercial unit, and provides comparable performance with a cost savings of nearly five thousand dollars.

Our robot uses a DC-DC converter system as an alternative to inefficient power inverters. Our team assembled the converter system from smaller modules into a single system that provides stable DC power to our entire robot.

Finally, our software contains a high degree of original content. Our software team has developed device drivers for the Linux operating system, as well as developing the navigation code from scratch. Our novel stereoscopic image processing code is also largely an original effort, in both its obstacle detection and sensor fusion algorithms. Overall, the robot represents a significant degree of original design that is the product of our team's devotion and hard work.

6. Budget

Our project is funded primarily by in-kind donations from industrial sponsors. Over ninety percent of our robot's cost has been covered by donations. We are appreciative of this fact, for without our sponsors' support, our project could not have been a success. Funding for purchased items is provided by the Michigan Tech IEEE Student Branch and the MTU Department of Electrical and Computer Engineering. We are also grateful to the MTU Office of Student Activities, for funding our transportation needs for the 2000 competition. Shown in Table 1 is a summary of the budget for this year's robot.

Table 1 1999-2000 Budget

System	**Component**	**Vendor**	**Donation**	**Cost**
Mechanical	Frame	Bretl	50	
Mechanical	Motor Mounts (2)	MTU	25	
Mechanical	Axles, Hubs (4)	MTU	20	
Mechanical	Wheels, Tires (4)	Evergreen	250	
Mechanical	Bearings (8)	SKF	200	
Mechanical	Camera Mount	MTU	20	
Mechanical	Misc Assemblies	Varies	50	
Mechanical	Shell	FibreGlast		250
Mechanical	Gearboxes (2)	Boston	1121.02	
Mechanical	Sprockets (6)	Boston	160.96	
Mechanical	Chain	Boston	86.8	
Mechanical	**TOTAL**		**1983.78**	**250**
Power	Motors (2)	Leeson	988	
Power	DC DC Converters (2)	Vicor	368	
Power	Battery Connectors (4)	Anderson	43.2	
Power	Main Contactor	Allied		28
Power	E-Stop Switch	Allen-Bradley	75	
Power	Batteries (4)	Johnson Controls	250	
Power	Misc Wiring	Surplus	75	
Power	Misc Connectors	Varies		50
Power	DIN-Rail Terminal Blocks	Altech	250	
Power	**TOTAL**		**2049.2**	**78**
Elecrtronic	Wireless Ethernet	RadioLAN	1500	
Elecrtronic	Cameras (2)	MCM		520
Elecrtronic	Computer System	Varies	50	150
Elecrtronic	Motion Control Card	PMC	895	
Elecrtronic	Image Capture Cards(2)	WinTV		108
Elecrtronic	Encoders	Allen-Bradley	1386	
Elecrtronic	Misc Electronic Components	Varies		75
Elecrtronic	Motor Controllers	4QD		400
Elecrtronic	Laser Range Finder	Varies	350	350
Elecrtronic	**TOTAL**		**4181**	**1603**
	TOTAL:		**8213.98**	**1931**
	TOTAL VALUE :		**10144.98**	