TENNESSEE STATE UNIVERSITY
COLLEGE OF ENGINEERING, TECHNOLOGY AND COMPUTER SCIENCE

PRESENTS

TSU-TIGER
An Autonomous Robotic Ground Vehicle
Technical Report

10th Intelligent Ground Vehicle Competition July 6-8, 2002

Faculty Statement:

TSU-TIGER is a considerable modified version of the vehicle that participated in the 8th Intelligent Ground Vehicle Competition. It has been completed by a group of graduate students taking a graduate-level design robotic course.

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1. INTRODUCTION

This report presents the design process of TSU TIGER, an Autonomous Unmanned Ground Robotic Vehicle designed and fabricated at the Tennessee State University. TSU TIGER, hereafter called TIGER is an innovative four-wheel servo-driven mobile vehicle supported by an innovative all Aluminum four-wheel independent suspension system chassis. The vehicle is fully autonomous and self-powered by on-board DC-power sources. The symmetrical configuration of the vehicle offers a well-balanced two-wheel traction system for mobility in all terrain. The differentially configured drive system provides a near zero turning radius feature that is desirable for maneuverability in confined spaces and avoiding obstacles. TIGER is equipped with a number of navigational sensors including an Altitude and Heading Reference System (AHRS), a Differential Global Positioning System (GPS), a Laser Measurement System (LMS), a camera, Wheel Encoders, Wireless Modem, Wireless Audio and Video Transmitter. The Modem and Transmitter are not used during the competition, but they have been added to provide the TIGER with more remote control capabilities. Section 4 of the report discusses about the navigational sensors.

The conceptual design of the TIGER is the result of research investigation of a team of undergraduate and graduate students from Mechanical and Manufacturing Engineering department at the Tennessee State University. The original design of the TIGER was accomplished by a group of undergraduate students who had attended the Eighth IGV Competition. This year the team composes of four graduate students with varying backgrounds. The design process followed in TIGER's development is presented in Section 2. The design challenges of TIGER structure as well as its mechanical supporting components are discussed in Section 3. The electronic design issues of TIGER and its supporting sensory peripheral are presented in Section 4. Various TIGER Control modes are explained in Section 5. Navigational strategies implemented in TIGER's development are discussed in Section 6. Software and hardware integration issues of TIGER are explained in Section 7. Team organization and project milestone activities of the project are presented in Section 8. And finally, in Section 9, we present the cost table estimation of modified TIGER along with man-hour time and effort spent for its development.

Our special appreciation goes to a number of research funding organizations, industry project sponsors, and the College of Engineering and Technology at Tennessee State University for support of this project. Section 9 presents an acknowledgement to our project sponsors.

2. TIGER'S DESIGN PROCESS

The original/previous design team consisted of four under graduate students. During the initial design conceptualization phase, the team reviewed many previously designed autonomous vehicles including those participated in the earlier competitions. An assessment of different designs was made and pros and cons of each design were identified prior to formulating a set of critical criteria for consideration in design of a new robotic vehicle. After the initial assessment process, the design team established the following criteria for design of TIGER including: safety, compactness, compliance to competition's rules, reliability, durability, light weight, power requirements, design aesthetic, vehicle-operator interface, ease of fabrication and operation, and control software. With full consideration of these design criterions, the team proceeded to conceptualize several primary design concepts. The vehicle design was divided originally into three main parts;

1. Design of main vehicle chassis including its independent suspension system, power train system, structural support components, on-board surveillance system, and vehicle outer shell body.
2. Design and selection of on-board COTS electronics and peripherals including electronic compartment arrangement, ventilation, circuit design, and power distribution.
3. design of system integration architecture including development of software for communication, locomotion, image processing, navigational strategies, sensory data fusion, and on-line/off-line simulation, and open loop/closed-loop control schemes.

An initial 2D model of TIGER was developed using AutoCAD release 14 and then a detailed 3D solid model of the TIGER design was accomplished using Pro-Engineering CAD software.

The highly efficient work of the design team provided the tiger with a number of unique features including the four wheel independent suspension system, all aluminum chassis, four wheel independent drive system and on-board COTS navigational sensors and electronics. Still the tiger had its own weaknesses, which were taken care in the redesign process.

The redesigning process began in the month of May 2002 and was divided into three areas the mechanical design structure modification, electronics and circuit redesign, and communication and control software enhancement. After considering the strengths and weaknesses of the past design, the new tiger team consisting of four graduate students, has put every effort to improve upon weaknesses and enhance the strengths of the tiger. Various navigation and image processing algorithms used earlier were also enhanced making the Tiger to function more intelligently and more user friendly/autonomously.

The vehicle redesign was carried out in the following stages:

1. Modification to main chassis including conversion of 4-wheel drive system to 2wheel differential drive system which reduces the problem of synchronization of the four motors and made the tiger less heavy. Designing of a new body for the robot out of plastic material.
2. Design and selection of new on-board COTS electronics and peripherals including electronic compartment rearrangement, new circuit design, better power distribution, reconfiguration and addition of a Differential Global Positioning System. The GPS was added to meet the requirements of the navigational challenge event of the competition.

Development and testing of system integration architecture including development of software for better communication, highly efficient algorithms for image processing and navigational strategies, sensory data fusion, and on-line/off-line simulation.

3. TIGER'S MECHANICAL STRUCTURE DESIGN

To improve the mobility of the original tiger the rear power drive systems were replaced with the passive caster wheels. Figure 1 illustrates modified TIGER from different perspective views of the TIGER. TIGER's chassis is made of 2.5" square hollow T6-6061 aluminum bars welded to form a rectangular hollow frame. The bottom side of the chassis is covered with an aluminum plate. Two internal separate cavities inside the chassis are used for housing all on-board powered train electronics including servo/stepper-motor controllers, three power amplifiers, power distribution box, batteries, data switch circuit box, and other electronic peripherals. An aluminum housing closure protects and isolates the electronic components from upper deck electronic components as well as payload station.

Two aluminum support bars between front and back anchor brackets provide additional lateral rigidity and strength to the chassis. Each wheel is connected to its gearbox and drive-motor by a steel coupling for a better and reliable rigidity, strength, and durability. Each rear caster wheel is bolted to the bottom of chassis that gives Tiger the flexibility to move in any direction. The front steel bumper is bolted to the chassis and supports the laser measurement system and also protects the tiger from accidental front collisions.

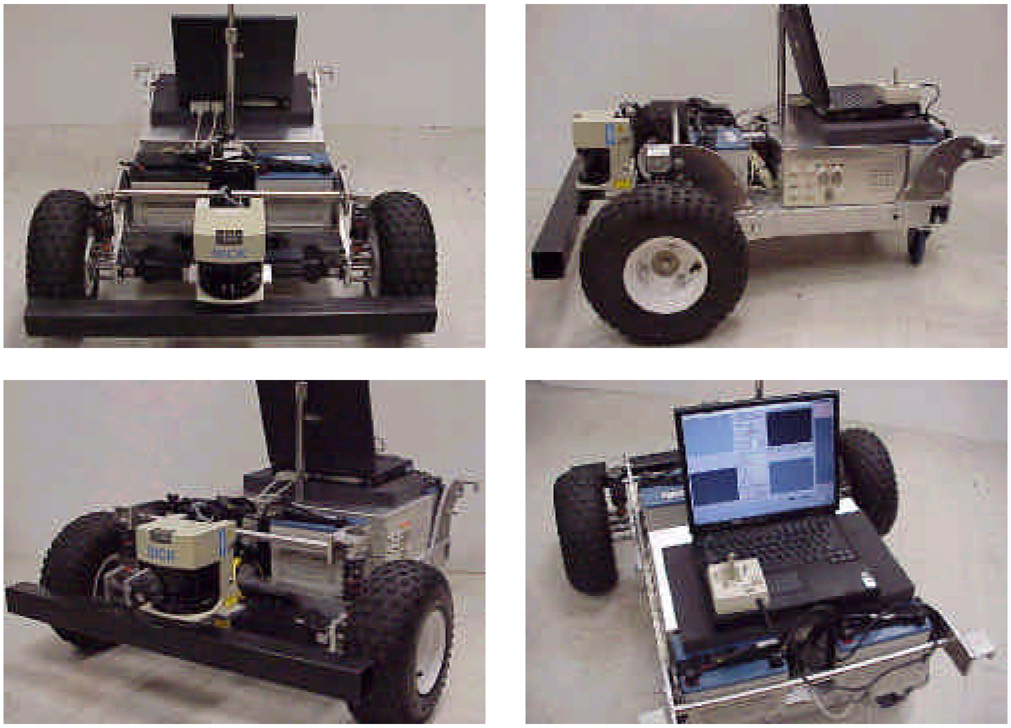

Figure 1. Different Views of modified TIGER

3.1 The TIGER's Supporting Structure

The innovative design of TIGER accommodates over eight cubic feet of cargo space for the on-board payloads. The LMS device is installed on an adjustable slide mounted on connecting I-frame of the front bumper to chassis. This innovative design idea allows the LMS to be pulled in front of bumper when TIGER is in operation. While the TIGER is resting, the unit can be pulled back inside the body of the TIGER in order to protect the expensive LMS. A swiveling telescopic shaft emerges out of the body of TIGER to provide mounting support for an observatory camera on-board TIGER. This adjustable rotating shaft is controlled by a high-torque stepper motor capable of maintaining orientation of TIGER observatory camera at any desirable angle. The outer body is still under construction at the time of preparation of this report. The outer body will be designed to be aerodynamic, aesthetically pleasing, weather resistant, open-design, ergonomic, modular, rigid, and easy to assemble and disassemble.

3.2 The TIGER's Locomotion Power Train System

TIGER is equipped with two high-performance high-torque servomotors (model no J0702 FE) from Parker Automation Company. Each servomotor is equipped with a quadrature encoder feedback returning position and velocity data to the 6k4 controller to complete close loop control. Each motor provides a peak torque of 100 Ib-in and draws 9 Amps current at its rated speed of 7500 rpm. Each servomotor takes its control command from a four-axis on-board 6K4 Controller from Parker Automation and its power from a separate servo amplifier (model no OEM670T). The selected servo amplifier is capable of providing up to 75 DC max voltage. Each servomotor has an integral 10:1 gear head (model no PX60-010) with efficiency of 92 percent to boost torque characteristic of each driver motor and slows down speed of the vehicle. TIGER's wheel tires have diameter of 14.5" and width of 5.5" designed to provide a maximum traction with the ground. With its full payload, TIGER's maximum speed reaches 8 miles per hour and this speed is limited below 5-mile per hour using software for the competition. The third controllable driver unit of TIGER consists of a 40K pulse per revolution (model no QM57-102-MO) stepper motor housed inside the lower electronic compartment of the TIGER. This stepper motor is used for swiveling the camera surveillance on-board of TIGER. All selected electronic equipment used on-board of TIGER are off-the-shelf components – highly reliable and easy to maintain and receive technical support on it. The later feature was crucial for our successful and rapid system integration design process of TIGER.

4. TIGER'S ON-BOARD ELECTRICAL AND ELECTRONIC SENSORS

4.1 Planning and Overall Electrical System Architecture

Our team's idea was to utilize all off-the-shelf components on-board TIGER, for the purpose of improving system integration, maintainability, and communication network, and entire electrical layout design. To achieve a robust and yet a simplified design, all of TIGER's sensing and control system reside in a 600 MHz Pentium III laptop.

4.2 TIGER Safety Features

For safe operation of TIGER, several safety features are considered in design of its electrical circuit including installment of an emergency switch on top of TIGER body – For ease of accessible from all directions, a remotely controlled power switch, manual power switch, and controller power switch. The activation of emergency switch automatically stops TIGER's servomotor motion and brings the TIGER to a complete full stop in less to 0.2 second. On the other hand, the power switches are used to manually cut off power from TIGER electrical circuitry and controller for ease of its maintenance. Four colored LEDs are used in conjunction with the electrical circuitry of TIGER to indicate different active power flows through the system. To minimize wiring problems, all connection cables are labeled and color-coded.

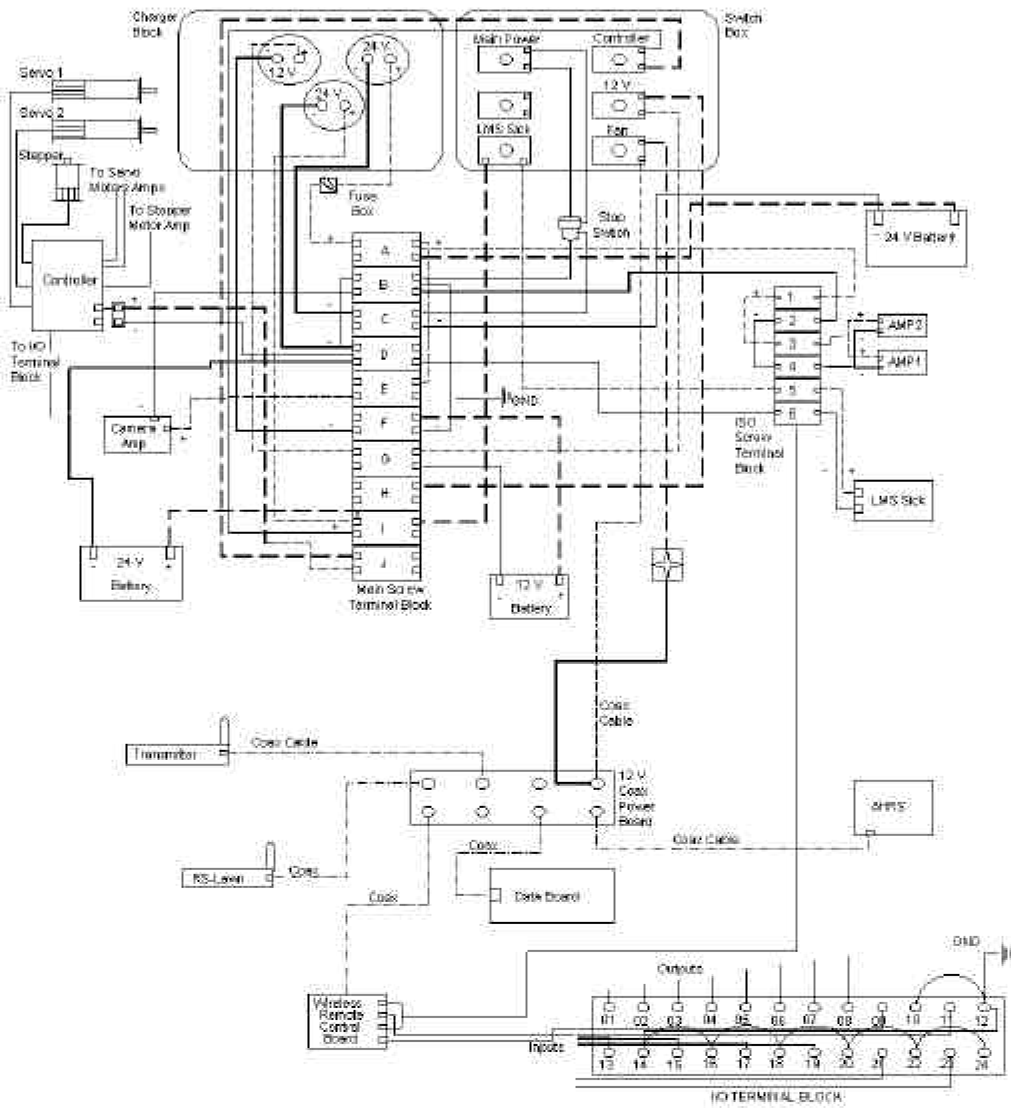

Figure 2. Electrical and Electronic Components and Computers On-Board TIGER.

4.3 TIGER Power System

The final version of TIGER will be equipped with ten 12 volts batteries of different sizes including four 33 Amp, four 18 Amp and two 7 Amp acid sealed batteries. Two of the 18 Amps batteries are used to supply

24 volts to controller and LMS. Six batteries are used to supply 72 volts to servomotors to generate the necessary torque needed to overcome the weight of the vehicle. Another two 7 amps batteries are used to provide the power to the on-board 12-volt low-amp electronic components, i.e., wireless modem, wireless audio and video transmitter, video camera, the data switch board, and ventilation fan. The wireless modem and audio and video transmitter are removed during competition in order to fully comply with the competition requirement that bans any wireless communication with the vehicle during its entire competition operations. Three charging plugs are installed on-board TIGER to ease charging of its batteries. We used two chargers, one is 24 volts charger for the batteries of the controller, and 12 volts charger for the 12 volt batteries on-board. The main power lines of the system are equipped with appropriate fuses that shut off power line in case of power failure on-board TIGER.

4.4 TIGER On-board Computer and Communication Mechanisms

TIGER is equipped with an on-board Laptop 600 MHz Pentium III PC with one serial, one parallel, and one PCMCIA level-II drives. Communication with various sensory devices on-board the system is achieved via custom-designed eight-channel data switch box. The supervisory controller of the system has been entirely developed using FMCell robotic software an in-house comprehensive robotic simulation and control software developed by the faculty advisor. The supervisory controller on-board TIGER is capable of establishing serial and parallel communication with different device with different communication baud rates to achieve an optimum performance. The parallel port of the supervisory controller PC is connected to an eight-relay switch box for control of external devices and automatic power switching through relays. The supervisory controller PC is also equipped with a PCMCIA PC image grabber card from MRT Video Port Professional™. FMCell software provides image-processing capabilities that are used in conjunction with the image grabber board to capture real-time images for navigational analysis purposes for the detection of obstacles, potholes, and other environmental features during operation of the TIGER.

4.5 TIGER On-board Navigational Sensory Devices

TIGER is equipped with a donated "eye-safe" Laser Measurement System (LMS) from SICK Optics for the purpose of laser range measurement and obstacle detection. The LMS is a high precision laser range measurement device capable of scanning 180 degree with 0.5-degree increments and with two cycles per second with in-built noise reduction capability. The LMS unit is mounted in front of vehicle to provide 180-degree front area scanning coverage for TIGER's collision-free navigational purposes. The LMS requires 24-volt power source and configured to operate at 38400-baud rate for fast transmission of its range data to on-board FMCell supervisory controller.

TIGER is also equipped with a donated high precision Altitude & Heading Reference System (AHRS) from Watson Industries Incorporation. The AHRS contains three solid-state angular rate sensors that are coordinate transformed and then integrated to produce altitude and heading outputs that reflect normal TIGER altitude and orientation coordinates. Additional the unit provides rates of change of velocity and acceleration about three independent axis that gives TIGER full capability to measure its pitch, roll, and yaw orientation angles as well as rate of change of these angular motions. AHRS requires 12 volts power source and operates at 9600 baud rate. The AHRS is used in conjunction with a closed-loop control software to provide TIGER absolute orientation dead-reckoning capability for its robust navigational purposes.

We have installed Global Positioning System (GPS) donated by GARMIN to keep track of the global positioning of the TIGER.

For visually detecting positive and negative obstacles as well as for navigating through terrain and for following the leader, TIGER is equipped with a high-resolution Color Spy-Camera. The Camera is mounted on top of a manually adjustable telescopic rotating shaft controlled by the stepper motor on-board TIGER.

5. TIGER CONTROLS

TIGER can be operated either manually or autonomously or semi-autonomously. These operational control modes are discussed in following sections.

5.1 TIGER Manual Mode

A manual Joystick control is used to manually control the locomotion of TIGER manually. This Joystick is attached to the I/Os board, which is attached to the controller. Upon receiving significant input from the user in a particular direction, appropriate motion command in the desirable direction is sent to the Controller through the I/Os board. Manual operation stops by pushing joystick lever to the top left corner with pressing the button on the left of the joystick.

5.2 TIGER Autonomous Mode

In autonomous mode, TIGER uses all its on-board navigational sensors including its camera, laser range finder, and altitude and heading reference system. Upon initialization of this mode, FMCell supervisory control software on-board performs system checks to ensure all connected devices responding properly. Upon detection of on-board sensory devices, as appropriate FMCell initializes the device and puts the device into a stand-by mode. At first, laser range data are retrieved and next images are captured in front of the vehicle. Internally FMCell creates a world perception model of the environment based on which it plans its navigational strategies for the TIGER as they are discussed in the following sections. Certain attributes are given to TIGER that put it in different autonomous navigational modes. For example, for terrain tracking and leader-follower target tracking TIGER uses different navigational strategies. Our autonomous navigational strategies are discussed in the following sections.

5.3 TIGER Semi-Autonomous Mode

For Semi-autonomous man-in-the-control loop operations, TIGER is equipped with an internal wireless 1.2 GHz modem and one wireless 2.4GHz Audio-Video Transmitter. Since semi-autonomous mode is not permitted during the robotic competition, none of these devices are actually utilized during the main competition. Only the autonomous mode is permitted during the competition that TIGER takes advantage of it. In semi-autonomous mode, a remotely located operator can operate TIGER by sending and receiving motion commands, toggling different TIGER's operational capabilities as well as receiving audio and video signals up to a maximum distance of 1 mile in open field environment.

6. TIGER NAVIGATIONAL STRATEGIES

6.1 Visual Navigation

TIGER visual perception system captures 320 x 240 color images of the environment. In order to successfully complete the Lane Following challenge of the competition image processing is being used. Using the color camera installed at a predefined height, images are captured. These images are then processed at a faster rate to detect the lines or objects that are present in the image. There are several steps involved in our image processing viz. Change of Image Polarity; Normalizing; Applying a Look-Up to

Alter Image Contrast Properly; Applying a Band Pass Filter; Taking Image Variance; Applying an Image Averaging Filter; Applying a Noise Reduction Filter; Taking Binary Image Moments; Sorting Blob Size; Applying Blobs Feature Detection Technique to Identify Obstacle, i.e., Pot Holes, Trees, etc.

Figure 3. Image Processing Operations for Lane Detection

Figure 3 shows various image processing operations being performed for detecting the lane. The robot aligns itself parallel to the moment of the detected lane if any and then moves parallel to the lane orientation. Using an internal model of the left and right lanes, we provide motion instruction to the robot in case no lane is detected at a given time. This model is continually updated as soon as next lane is detected. Any high inclinations or ramps in the track are detected by the LMS and are not treated as obstacles. Whenever the robot reaches any ramp the change in inclination is detected using AHRS and the motors are supplied with the additional power required to overcome these ramps. Whenever the robot gets into a trap the robot starts scanning the surrounding environment using the laser measurement system and if any openings are present the robot will find a free path among them.

The positions of pixels in the image are transformed to a ground coordinate system using an algorithm that considers the geometry of the captured images depending on the orientation of the camera. Correlating pixels in the image plane with points on the ground consists of two parts: a mathematical transformation with experimental determination of the camera field of view, and measurement of its position, and orientation. The transformation results were experimentally varied to formulate a mapping between the physical environment and its corresponding image pixels distributions. This effort enables us to predetermine the best configuration for the camera.

6.2 Range Sensor-Based Navigation

To meet the requirements of the **Navigational Challenge** part of the competition the robot carries a Differential Global Positioning System. The position of the robot is obtained from the GPS and is represented in a simulated environment. All the moves of the robot are effectively represented in this window along with the relative position of the targets. A highly user-friendly interface has been developed for this aspect of the competition. The minimum time required for the robot to reach the targets is calculated taking into consideration the obstacles in the path of robot and its immediate target. The robot follows the optimized path that leads to the accomplishment of the maximum number of targets in the shortest possible time.

For the purpose of obstacle detection, TIGER uses scanned range data from the "eye-safe" Laser Measurement System on-board. The scanned data are filtered as they are read into FMCell supervisory controller and world perception of the environment in front of the TIGER is created to recognize position and orientation of obstacles in front of the vehicle. Using a custom-design navigational algorithm, FMCell navigational controller generates several collision-free opportunities for maneuverability amongst environment obstacles. Depending on desirable heading dictated by the GPS system, FMCell issues motion command to TIGER and guide it safely through obstacles.

Follow-The-Leader algorithm uses the range data from the LMS. The objects ahead are detected and the readouts from the LMS are used to determine the change in position and orientation of the leader ahead of the robot.

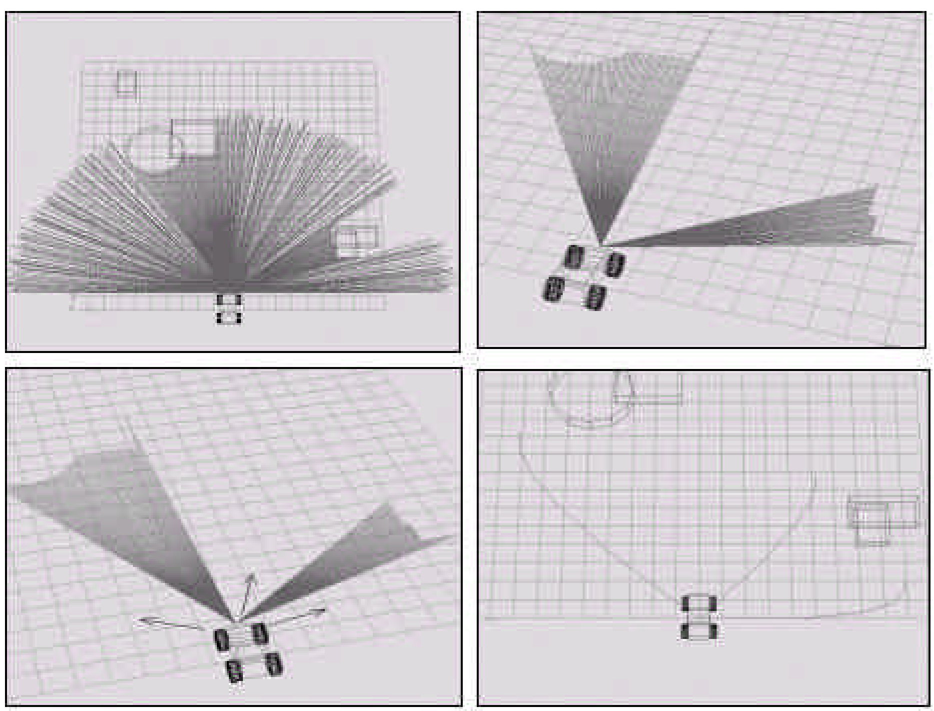

Figure 4. Illustration of Intelligent Strategies Built Into TIGER Navigational System.

7. SOFTWARE AND HARDWARE INTEGRATION

We used FMCell because of its comprehensive capability to accommodate both software and hardware integration aspect of the TIGER. Figure 6 illustrates various modules built-in into FMCell software. The software provides variety of tools for modeling, simulating, and analysis complex robotic systems. It provides object-oriented building blocks for development of complex simulation models of physical robotic systems as well as window-based graphical user interfaces for development of essential man-machine interfaces. FMCell provides a number of functions for robotic navigational sensor modeling and control such as range and sonar sensors, vision cameras, touch sensors, proximity sensors, and etc. Built-in kinematics and dynamics functions in the FMCell, allows one to develop an accurate model of the physical robotic systems with high degree of fidelity. FMCell offers a number of high-level functions for achieving task planning control aspects of both stationary and mobile robotic systems. It has built-in protocols for communication with external devices such as robots, machine, and other serially connected computers, sensors, and modems. FMCell also provides control capabilities using techniques such as Fuzzy Logic, Neural Networks, Genetic Algorithms or a hybrid combination of above techniques. Image processing tools in FMCell allow for real-time image capturing and processing. The SGS interpreter language in FMCell provides hundreds of highly optimized callable functions for consistent modeling of complex robotic systems. Other auxiliary features of the FMCell include: dynamic graphical animation, movie making, printers, and plotters support.

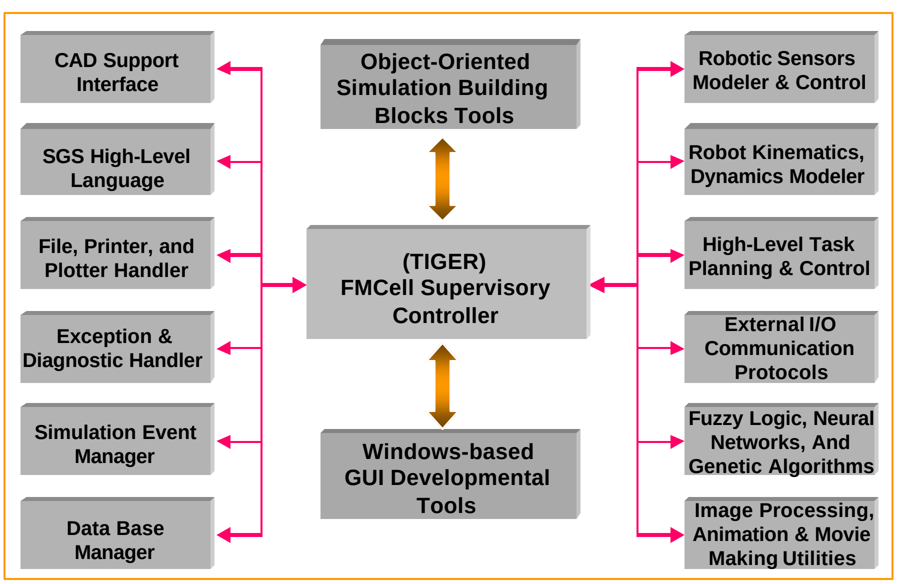

Figure 5. Architecture of TIGER's FMCell Supervisory Controller Modules

FMCell communicates with the on-board navigational sensory devices and issues motion commands to servo and stepper motor as appropriate. Figure 7 shows the communication block diagram between TIGER FMCell supervisory controller and navigational sensors and power train system on-board TIGER. Feedback from the 6K4 controller is used for monitoring and controlling of desirable maneuvers of TIGER during its navigation.

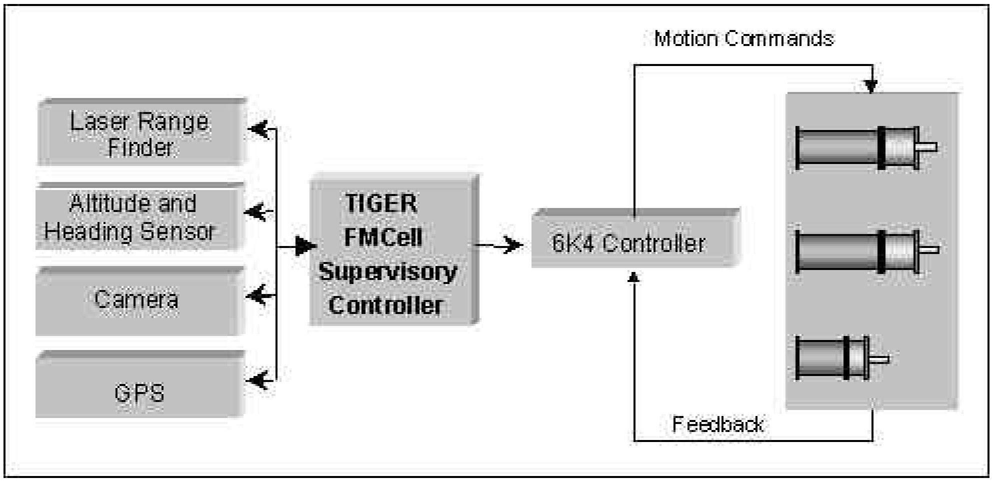

Figure 6. On-Board Communication Interaction Between TIGER Supervisory Controller Components.

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7. TEAM ORGANIZATION

Table 1 presents team members of TIGER project and their project responsibilities.

Table 1. TIGER Team members

NAME	FUNCTION	MAJOR	ACADEMIC LEVEL
Muhannad Hajjawi	Visual Navigation, Hardware Setup	MfgE	G
Tejinder Devgan	Man-Machine Interface	MfgE	G
Sudhirbabu Dabbugottu	Sensor-Based Navigation	MfgE	G
Chirag C. Patel	Visual Navigation	MfgE	G
Dr. Amir Shirkhodaie	Faculty Advisor	ME	Assoc. Prof.

8. TIGER Cost Estimation

Table 2 presents the cost estimation of TIGER and donated components as provided by our project sponsors. Total man-hour for completion of the project is estimated about 8400 hours.

Table 2. Cost Estimate of TIGER

Component Description	Price	Purchased	Donated
Parker Automation (6K4) Controller	2,878	X	
Five Servo/Stepper Amplifier (Parker Automation)	2,712	X	
Four Servo and one Stepper Motor (Parker Automation)	3,386	X	
Four Servo and one Stepper Gearbox (Bayside)	1,924	X	
Data Switch (WTI – CAS81)	445	X	
Auto focus Camcorder camera (SONY)	675		X
Motors Cables and Peripherals	357	X	
Four Quadrature Encoder Cables	192	X	
Four 12 Acid-Sealed Volt Battery (Power Sonic)	376	X	
Three 12 Voltage Battery Chargers (Power Sonic)	348	X	
AHRS Three-Axis Digital Gyro (Watson Industries)	9,800		X
Laser Measurement System (SICK)	7,500		X
Four Knobby Tires with Hubs (Amerathon)	120		X
Laptop (Pentium 600Mhz)	2,200		X
Image Grabber (MRT Video Professional-PCMCIA)	200	X	
Remote Switch	54	X	
Four Maintain Bike Shock absorbers (FOX, Vanilla)	760	X	
Embedded PC (JK MicroSystems)	380	X	
Chassis Materials and Fabrication Cost	3,000	X	
All Aluminum Weatherproof Body	1,500	X	
Accessories (Cables, DB9 Connectors, switch, LED)	750	X	
TOTAL PROJECT COSTS	$39,557	$19,362	$20,295

9. ACKNOWLEDGEMENT

We like to express our gratitude to our project sponsors: U.S. Army Tank Automotive and Armament Commands, Watson Industries, SICK Optics, Carlisle Tire company, Garmin and the College of Engineering and Technology at TSU for their support of this project.