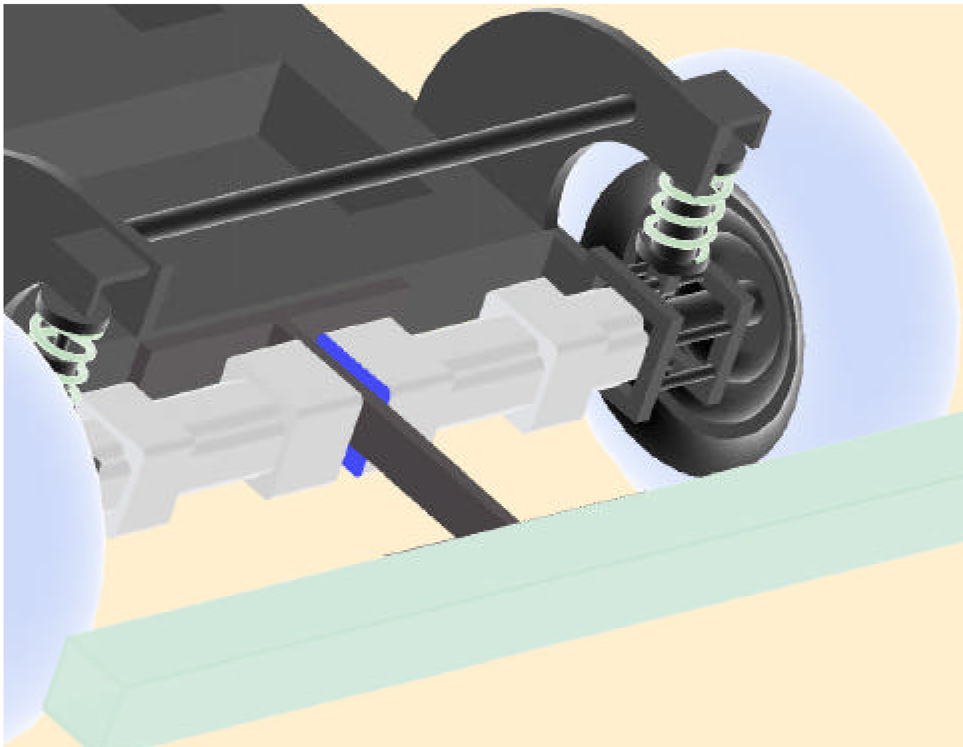
TENNESSEE STATE UNIVERSITY
COLLEGE OF ENGINEERING AND TECHNOLOGY
PRESENTS



TSU-TIGER

An Autonomous Robotic Ground Vehicle
Technical Report

Submitted to: Eighth Annual International Ground Robotics Competition
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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 four-wheel traction system for optimum skidding and 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 innovative navigational sensors including a digital altitude and heading system, a laser measurement system, auto-focus vision cameras, encoders, and many others that are discussed in Section 4.

The conceptual design of the TIGER is result of research investigation of a team of interdisciplinary undergraduate and graduate students from Mechanical and Manufacturing Engineering department at the Tennessee State University. The team composition was made of three undergraduate and five graduate students with varying backgrounds. The original design concept was conceived by pre-evaluation of previous designed vehicles by the other schools and compiling important criterions pertinent to the design and the competition. 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. Navigational strategies implemented in TIGER's development are discussed in Section 5. Software and hardware integration issues of TIGER are explained in Section 6. Team organization and project milestone activities of the project are presented in Section 7. And finally, in Section 8, we present the cost table estimation of TIGER along with man-hour time and effort spent for its development.

Our special appreciation goes to a number of researches 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

This project began in August 1999 and was divided into three areas that are mechanical structure design, electronics and circuit design, and communication and control software design. During our initial design conceptualization phase, our 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 was identified prior to formulating a set of critical criteria for consideration in design of our new robotic vehicle. Our design team consisted of three undergraduates and five graduate students. After this assessment process, we established our design criteria that we followed throughout the TIGER's design and development processes. The criteria we considered for design of TIGER included: safety, compactness, compliance to competition's rules, reliability, durability, light weight, mobility, autonomy, 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. A feasibility study was initially conducted for elimination of infeasible design concepts and regeneration of new design ideas via blending features of different designs into newer designs. 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 and off-line simulation, and open loop and close-loop control schemes.

We employed a concurrent engineering approach directed by our faculty advisor. Weekly meetings were arranged to share design ideas and bring each team member up-to-date of the design progress. The graduate students focused more on development of innovative navigational algorithms and mentoring undergraduate students. The undergraduate students participated in this project, are taking this project as their senior Capstone Design projects. They were given responsibility for arriving at new design ideas meeting and justifying their design solutions against the originally established design criteria. The first design concept of the team was done in PowerPoint and agreed upon as the most feasible design idea to pursue.

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.

3. TIGER'S MECHANICAL STRUCTURE DESIGN

TIGER's mechanical structure chassis consists of four Independent Suspension Systems (ISS), four independent geared-train drive systems, and a supporting frame. Figure 1 Illustrates four-wheel power train and chassis design of the TIGER. Figure 2 Shows design of TIGER's independent suspension system. TIGER's chassis is made of 2.5" by 2.5" 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, five power amplifiers, power distribution box, batteries, and other electronic peripherals. An aluminum housing closure protects and isolates the electronic components from upper deck electronic components as well as payload station. Four 12-Volt 33 Amp batteries are symmetrically installed at each corner of the chassis to balance their weight evenly for a better terrain traction and maneuverability.

Two aluminum supports bars between front and back anchor support 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 wheel-drive system is bolted to the side of chassis using a side-arm link and provides one rotational degree of freedom for its suspension system. Two removable iron steel bumpers are bolted to the chassis.

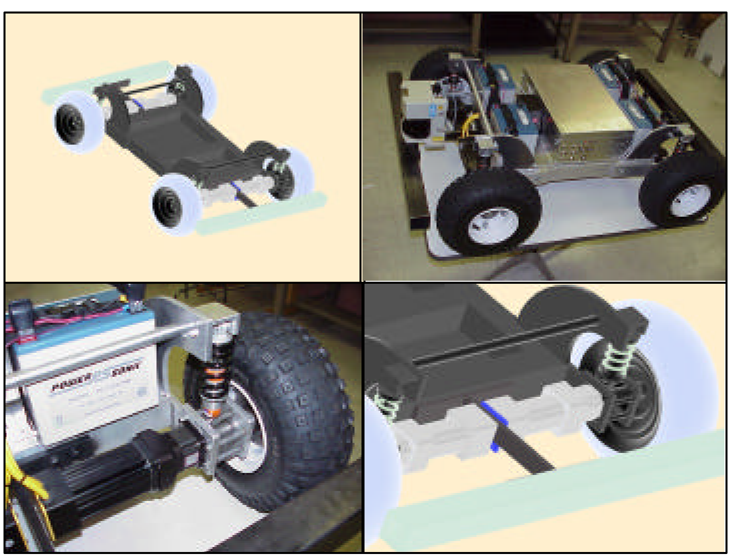

Figure 1. Illustrates Prototype Pro/E Model and Actual Physical Design of TIGER.

3.1 TIGER Upper Deck Supporting Structure and Weatherproof Body

To achieve a compact design, and yet a roomy cargo space, an adjustable height upper deck is designed. The upper deck plate is made of lightweight Phenolic material. On-board laptop computer and payload are installed on the upper deck symmetrically. The innovative design of TIGER accommodates over eight cubic feet of cargo space for the on-board payloads. An Altitude and Heading Reference System (AHRS) from Watson Industries, Inc, and a Laser Measurement System (LMS) - a laser range finder from SICK Optics Inc., are installed below the upper deck. 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 stored or resting, the unit can be pulled back inside the body shell of TIGER in order to protect the expensive LMS device from receiving any damage from the front of the vehicle. A front covering panel provides a sealed shield for the LMS device. The outer body is also another inventive design built into TIGER. Figure 2 illustrates the TIGER prototyped body and its final fabricated body.

Figure 2. TIGER Body Prototype and Its Final Delorean Style Physical Body.

The outer body of TIGER is totally modular and made of connecting three pieces, front hood, back hood, and side doors. An open architecture of TIGER styles an aerodynamic design similar to Delorean automobiles with two winged- style side doors and hinged front and back hoods provide lots of accessibility space to get inside cargo space area and lower deck compartments. The front and back hoods are also designed with tinted Plexiglas windows to give TIGER a stylish car-like appearance and a pleasant aesthetic look. The tinted Plexiglas are chosen intentionally to be transparent to block sun from blurring PC laptop on-board TIGER. The body parts are made of three-sixteenth of inch aluminum panels connected together by rivets, and piano hinges. The piano hinges create accessibility to the components within the vehicle. Overall the outer body is designed to be aerodynamic, aesthetically pleasing, weather resistant, open-design, ergonomic, modular, rigid, and easy to assemble and disassemble. A swiveling telescopic shaft emerges out of the body of TIGER to provide mounting support for an observatory camera/camcorder 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.

3.2 TIGER's Locomotion Power Train System

TIGER is equipped with four high-performance high-torque servomotors (model no J0702 FE) from Parker Automation Company. Each servo-motor is equipped with a quadrature encoder feedback returning position and velocity data to the 6k6 controller to complete close loop control. Each motor provides a peak torque of 31.1 Ib-in and draws 4.5 Amps current at its rated speed of 7500 rpm. Each servomotor takes its control command from a six-axis on-board 6K6 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 90 DC max voltage. Each servomotor has an integral 10:1 gearhead (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 fifth 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 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 latter 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 Overview

For a better clarity, we present electrical power distribution, and electronics on-board TIGER in the following four sections.

4.2 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. Our team was also charged to pay attention to future capability, expandability, and compatibility requirements on-board TIGER in selecting appropriate electronic components for on-board TIGER.

4.3 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 – easy 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 servo-motor 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.

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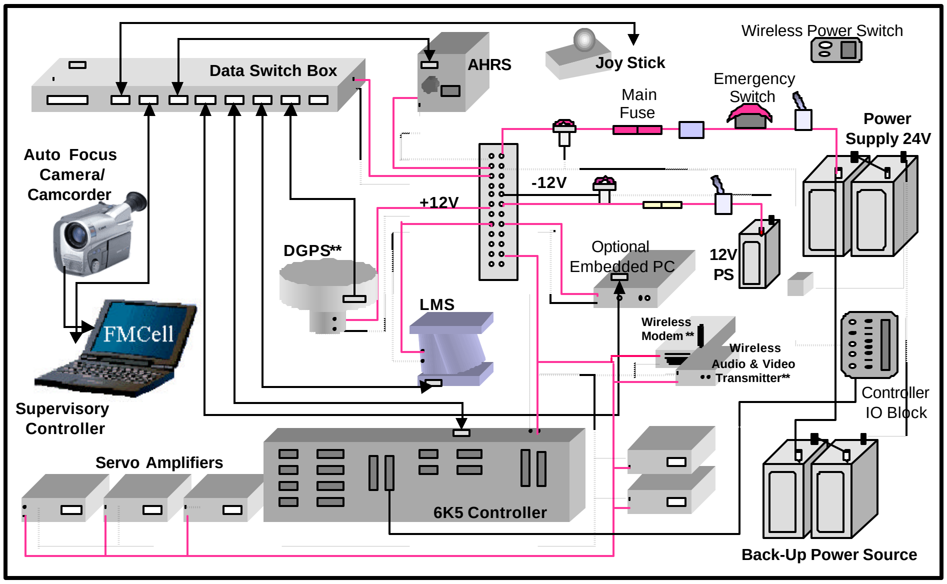

** This Auxiliary Item Not Used During Actual Competition.

Figure 3 shows various electrical and electronic components and computers on-board TIGER.

4.4 TIGER Power System

TIGER is equipped with four 12 volt 33 Amp acid sealed batteries and one 12 volt 7 Amp acid sealed battery. The latter battery is installed under lower deck inside electronic closure of TIGER to power on-board 12-volt low-amp electronic components, i.e., wireless modem, wireless audio and video transmitter, and ventilation fan. The wireless modem and audio and video transmitter are removed during competition in order to fully comply with the competition requirement than bans any wireless communication with the vehicle during its entire competition operations. Two 12 volt batteries are arranged in series to provide 24 volt power to Controller and five servo-motor power amplifiers on-board TIGER. Two other 12-volt batteries are used as backup batteries of the system. They are arranged in series to provide 24 voltage and can run parallel with the main batteries as backup. One of the backup 12-volt batteries is also placed in parallel to the internal 12-volt to extend its operational useful life. Three charging plugs are installed on-board TIGER to ease charging of its batteries. The main power lines are of the system are equipped with appropriate fuses that shuts off power line in case of power failure on-board TIGER.

4.5 TIGER On-board Computer and Communication Mechanisms

TIGER is equipped with an on-board Laptop 600 MHz Pentium PC with one serial, one parallel, and one PCMCIA level-II drives. Communication with various sensory devices on-board the system is achieved via an 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 VideoPort 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 to detection of obstacles, potholes, and other environmental features during operation of the TIGER.

4.6 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 Attitude & 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 attitude and heading outputs that reflect normal TIGER attitude 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.

For visually detecting positive and negative obstacles as well as for navigating through terrain and for following the leader, as required by the competition, TIGER is equipped with a high-resolution auto-focus CCD Camera/Camcoder with image stabilizer. The Camera/Camcoder is mounted on top of a manually adjustable telescopic rotating shaft controlled by the stepper motor on-board TIGER.

4.7 TIGER Control Modes

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

4.7.1 TIGER Manual Mode

A six-axis 3D Space mouse controller is used as man-machine interface between operator and TIGER during its manual operation. The six-axis mouse is attached to data-switch communication box and controlled by the PC supervisory controller. Manual mode is initiated by selecting manual mode option from FMCell supervisory control software of TIGER. Upon selection of this mode, all TIGER motions and sensory reading activities are stopped and 3D-space mouse controller is continually read to detect desirable directional movement of the operator. Upon receiving significant input from the user in a particular direction, appropriate motion command in the desirable direction is send to the Controller. In manual mode, the forward, back, left, and right force applied on the 3D space mouse controller causes TIGER to move either forward, backward, turn to left, or right respectively. Left and right twisting on the 3D space mouse controller, however, turn the TIGER's surveillance camera left and right appropriately. Manual operation stops by either pressing a button on the 3D space mouse controller or clicking an Stop Manual Operation button on FMCell operating software.

4.7.2 TIGER Autonomous Mode

In autonomous mode, TIGER uses all its on-board navigational sensors including its CCD camera/ Camcoder, 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 in stand-by mode. At first, laser range data are retrieved and next camera is rotated to three different directions to capture images from surrounding of the TIGER. Internally FMCell creates a world perception model of the environment based on which it plans its navigational strategies as it is 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.

4.7.3 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. As shown in Figure 3, both the modem and audio/video transmitter are powered by the internal 12 volt power source available on-board TIGER. 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 2 miles in open field environment.

5. TIGER NAVIGATIONAL STRATEGIES

5.1 Overview

For a better clarity of our navigational strategies, we have presented this topic in two sections that follow.

5.2 TIGER Vision System

TIGER visual perception system captures 620 x 250 gray scale images of the environment as shown in Figure 4. The feature extraction for the lane-markers is performed by using advanced image processing techniques. Pot holes are identified with the same method but with a system that detects it's Centroid of the detected pot holes. Curve fitting is performed to determine the orientation and distance of the course track relative to the robot. The positions of pixels 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/ Camcoder. Correlating pixels in the image plane with points on the ground consists of two parts: a mathematical transformation with experimental determination of the Camcoder field of view, and measurement of it 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.

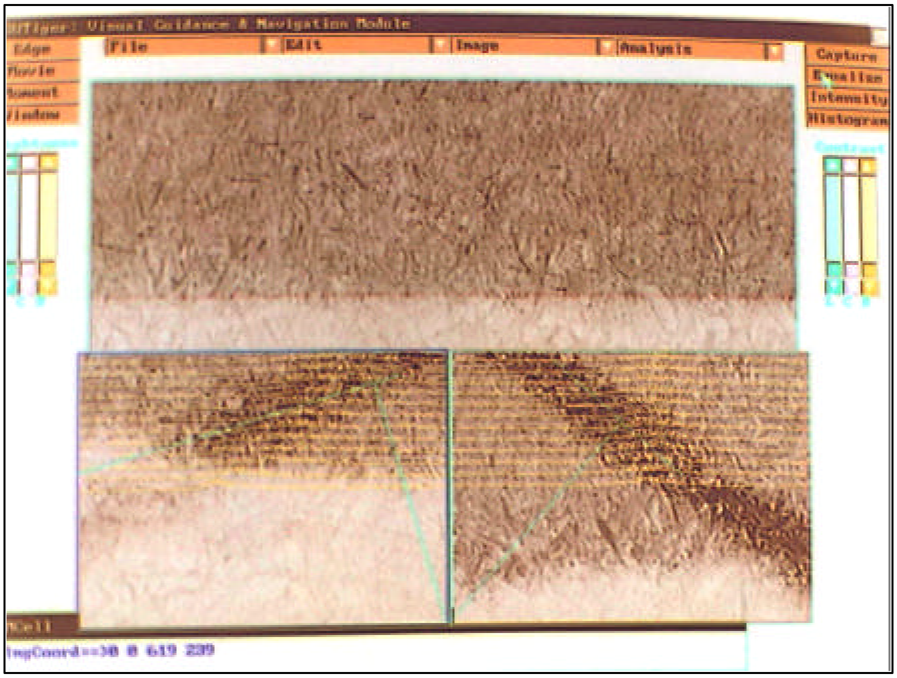

Figure 4. Illustrate Terrain Track Feature of TIGER Using FMCell Software. Lower pictures show left and right side images and upper picture show front image seen by the on-board TIGER Camera.

5.3 TIGER Navigation System

For the purpose of obstacle detection, TIGER using 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 recognition position and orientation of obstacle in front of the vehicle. The upper left-hand side image in Figure 5 shown an actual set of scanned data brought into FMCell supervisory control for analytical purposes. The upper right-hand side image illustrates restricted maneuverability area as sensed by the laser range finder. Using a custom-design navigational algorithms, FMCell navigational controller generates several collision-free opportunities for maneuverability amongst environment obstacles. Depending on desirable heading dictated by the AHRS system, FMCell issues motion command to TIGER and guide it safely through obstacles.

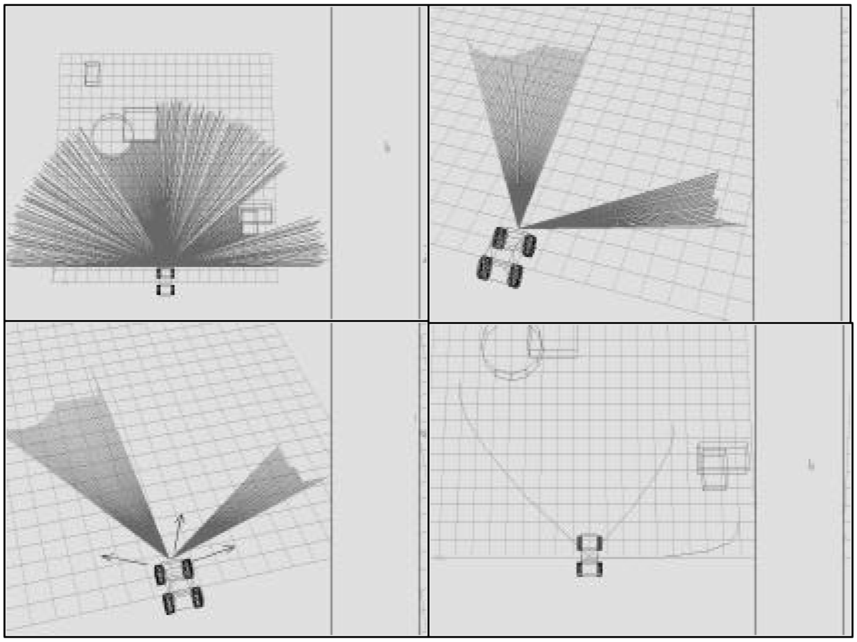

Figure 5. Illustration of Intelligent Strategies Built Into TIGER Navigational System.

6. 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 objected-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, and printers, and plotters support.

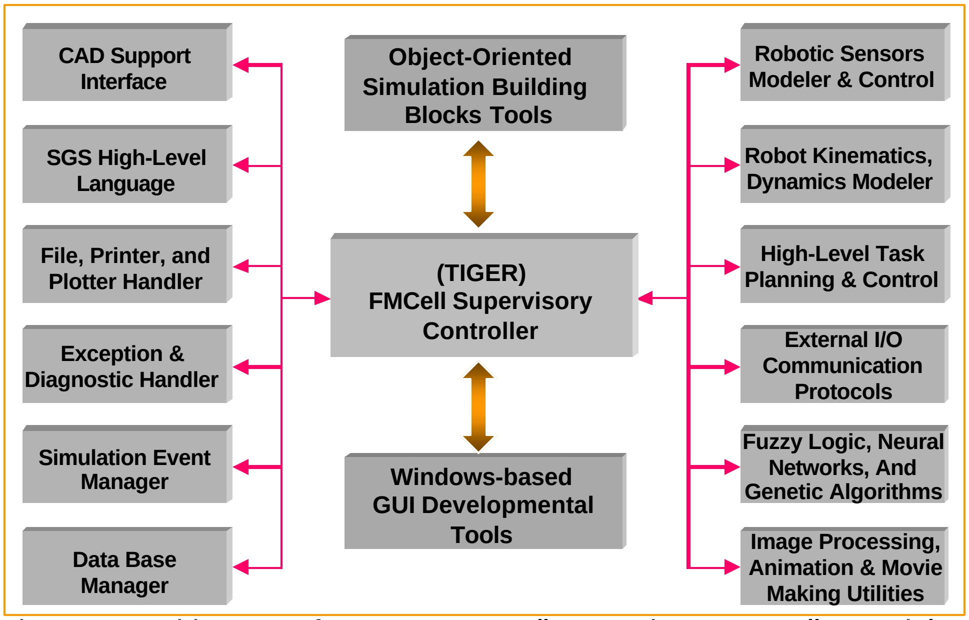

Figure 6. Architecture of TIGER's FMCell Supervisory Controller Modules

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 6K6 controller is used for monitoring and controlling of desirable maneuvers of TIGER during its navigation.

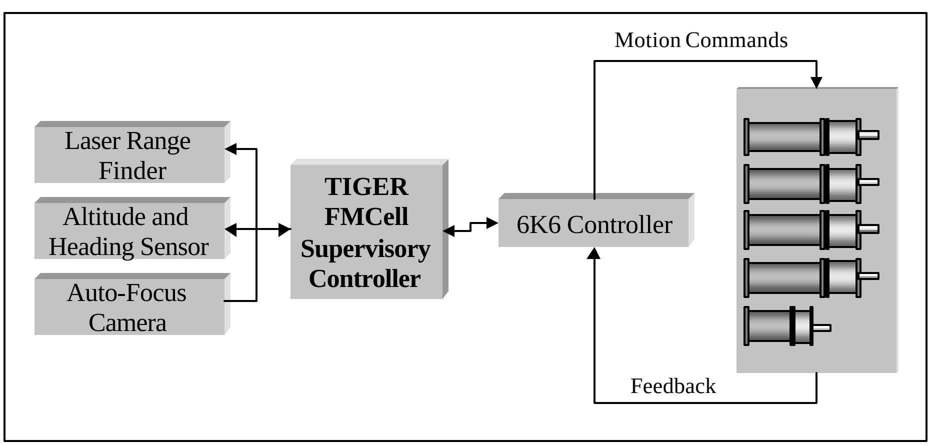

Figure 7. On-board Communication Interaction Between TIGER Supervisory Controller Components.

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
Christopher Carvalho	Chassis & Suspension System Design	ME	UG
Islam Shahin	CAD Design of TIGER Prototype	ME	UG
Deondra Carothers	CAD Design of Outer Body Design	ME	UG
Deidra Jones	Navigation Algorithms	MfgE	G
Naveen Avalareddy	Hardware/Software Communications	ME	G
Samuel Aderogba	Visual Navigation	MfgE	G
Abhijit Patkar	Navigation Algorithms	ME	G
Sirisha Rangavajhala	Follow the Leader Target Tracking	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 (6K6) 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		
Four Quadrature Encoder Cables	192		
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, SICKoptics, Carlisle Tire company, and the College of Engineering and Technology at TSU for their support of this project.