UNIVERSITY OF TEXAS AT ARLINGTON
RESEARCH INSTITUTE

The University of Texas at Arlington

Dr. Frank L. Lewis, National Academy of Inventors
Fellow IEEE, Fellow IFAC
Fellow U.K. Inst. Measurement & Control
PE Texas, U.K. Chartered Engineer
Moncrief-O'Donnell Professor
University Distinguished Scholar Professor
University Distinguished Teaching Professor
UTA Research Institute
tel. 817-272-5972, fax. 817-272-5989
lewis@uta.edu
http://www.uta.edu/utari/acs/

Friday, May 16, 2014

UTA IGVC Team Faculty Advisor Statement:

I certify that the engineering design of the vehicle described in this report, the Yoshimi platform, has been significant and contributed to by all the members of the UTA IGVC team. The work is equivalent to each team member earning academic credit towards a senior design course in their respective departments.

Please contact me if you need further information.

Sincerely yours,

Frank L. Lewis, NAI, Fellow IEEE, Fellow IFAC, P.E. Texas
Moncrief-O'Donnell Professor

DESIGN OF YOSHIMI AN AUTONOMOUS HOLONOMIC GROUND VEHICLE

University of Texas at Arlington

Rommel Alonzo	Team President
Bardia Mojra	VP, Electrical Lead
Ashley Guy[1]	Mechanical Lead
Jeff Williams	Software Lead
Jesus Alcala	Sofware Integration Engineer
Haydn Allard	Product Engineer
Harris Enotiades	Product Engineer
Eric Ireri	Product Engineer
Jeff Mays	Electronics Engineer
Dr. Frank Lewis lewis@uta.edu	Faculty Advisor
Matt Middleton	Team Mentor

ABSTRACT

This paper presents the design of a new holonomic intelligent ground vehicle platform, named Yoshimi. This platform was designed and manufactured by a multi-disciplinary group of graduate and undergraduate engineering students at The University of Texas at Arlington over the course of one academic year. Yoshimi is capable of autonomously navigating an outdoor environment while avoiding obstacles and staying within defined boundaries. The chassis supports all mechanical and electronic hardware necessary for performing these tasks as no external control is used during operation. An omni wheel system is used to provide holonomic motion. GPS, IMU, camera, and motor encoder data is used to generate Hector maps of the environment and localize the platform within that environment. A D* algorithm is used to generate locomotion trajectories.

---

[1] A Ph.D. student in the Mechanical and Aerospace Engineering Department, University of Texas at Arlington, 500 W. First St., Arlington, Texas 76019, USA; ashley.guy@mavs.uta.edu

INTRODUCTION

The University of Texas at Arlington (UTA) Intelligent Ground Vehicle (IGV) Team is proud to present our 2014 platform, Yoshimi; this is a newly constructed platform iterating on the design of our 2013 entry, Marauder. Yoshimi was developed by volunteer Mechanical and Electrical Engineering students and a Computer Science Senior Design team. The most visible feature of Yoshimi is a novel omni wheel system designed for holonomic motion and vibration reduction. Some other innovations and improvements for the current platform include independent swingarm suspensions, modular chassis, custom printed circuit board (PCB) for the vehicle control unit (VCU), and improved path planning algorithms.

Team Organization

The UTA IGV Team members boast a wide range of skills and expertise, but have various other academic and professional responsibilities; as such, a decentralized organizational model was adopted to favor subcontracting of discrete labor tasks. A central planning and design committee was formed by the senior project members to establish the overall design strategy; senior members also serve as team leads for the Mechanical, Electrical, and Software subcommittees. All required tasks were assigned to one of the subcommittees for design, fabrication, and testing of that particular component. This model also facilitates inclusion of new members and interdisciplinary learning. Figure 1 shows a graphical overview of the team structure.

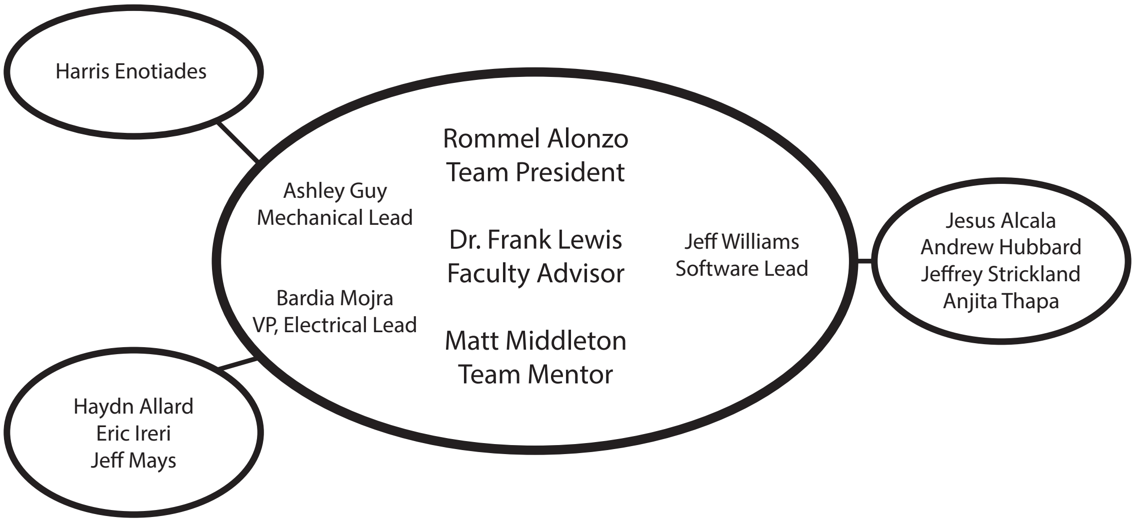

Figure 1: Organization of UTA IGV Team members.

System Integration Plan

As tasks were completed, system integration responsibilities were shared amongst team members across subcommittees. This gave our team members the opportunity to actively learn in a multidisciplinary, communal setting. Prior to integration, each system was tested in a controlled setting. Once testing was successful and integration begun, small adjustments were required in order for the unit to perform well as part of the total system.

Key Innovations and Improvements

Opportunities for innovative design were identified and explored early during the design process. These ideas came from the desire to improve last year's platform and eventually defined what the team would be focusing on for this year's competition. A summary of design innovations is listed below and details will be discussed in the later sections.

- New omni wheel design
- Independent swingarm suspensions
- Power distribution system redesigned for safe startup
- Additional protection against electrical malfunctions
- Vehicle control unit (VCU)
- New computer system more appropriate for the task
- Robust and efficient software algorithms

MECHANICAL SYSTEMS

The mechanical systems for Yoshimi iterated upon previous platform designs by first considering how *existing problems may be fixed* and then how the *design may be improved*. The primary existing problem was vibrations created by the omni wheels adversely affecting onboard electronics; it was decided that a redesign of the wheels and suspension system could greatly reduce these vibrations. Before considering chassis design improvements, the Electrical and Software teams were asked how the overall platform could better integrate with their designs; their responses are best summed up by *accessibility* and *removability* of components. The design and assembly of the wheels, suspension, and chassis are each discussed in the following sections. Unless otherwise stated, all manufacturing was done by team members on site.

Omni Wheel Design

Previous omni wheel designs used by the UTA IGV Team on the Marauder platform allowed for holonomic motion, but created substantial vibrations during operation; as can be seen in Figure 2a, the vibrations occurred because the profile of the Marauder wheel *is not a circle but a polygon*. The entire wheel was redesigned to provide the same flexible motion but reduce the unwanted vibrations. Yoshimi's wheels consist of two parts: the hub and the rollers. The hub is fitted with hardware from the motor OEM for integrating the axle. An in-progress assembly of a wheel may be seen in Figure 2b.

The hubs are custom made from 6000 series aluminum plates and barstock. Initial CAD designs of the hubs made using Creo software may be seen in Figure 3. Hub designs prioritized performance, manufacturing time, ease of assembly, and cost. Designs *did not* prioritize weight or stress; as such, stress in the hubs is significantly below failure or fatigue concerns. Milling of the hub components was done on a Bridgeport GX480 CNC.

The rollers are cast from a room-temperature-curing polyurethane resin. Female molds were 3D printed and reused. To protect the resin, the cured roller was then covered in a spray-on rubberized polyurethane coating, similar to truck bed liners. A brass tube was cast into the longitudinal axis of the resin roller; the

Figure 2: Comparison between previous platform wheels (a) with Yoshimi's new wheels (b).

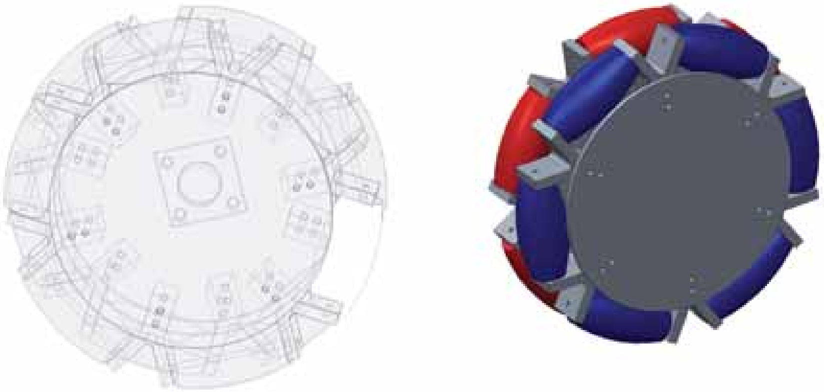

Figure 3: Initial CAD designs of Yoshimi's omni wheels in wireframe and solid view.

interior of this tube is lubricated and fitted around a 1/4 in. steel drive shaft supported by the hub.

Electric wheelchair motors were selected for wheel actuation; two of these motors provide enough power to move 600 lbs of wheelchair and passenger approximately 8.5 mph on a 12 in. wheel. The diameter of Yoshimi's wheels is 16 in. and total weight of the platform is expected to be less than 200 lbs. Given the enlarged wheels and reduced weight of Yoshimi compared to the intended wheelchair, Yoshimi is expected to be capable of reaching the 10 mph speed limit.

Suspension System

An independent swing arm suspension system was designed for each omni wheel. The swingarm is attached to the chassis near its base and has a lever arm of approximately 5 in. The swingarm supports a milled aluminum plate providing mounting for the electric motor. The suspension system may be seen in Figure 4.

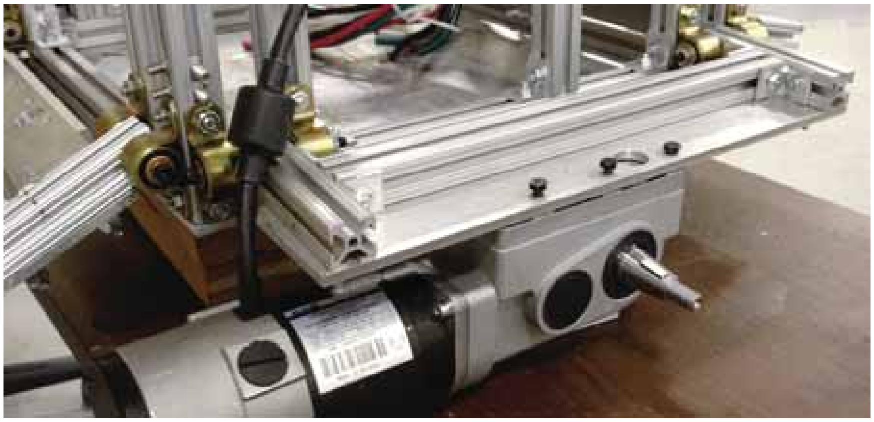

Figure 4: Independent swing arm suspension.

Modular Chassis

To meet the requests of accessibility and removability, the chassis of Yoshimi was designed to be modular. The platform can be separated into two portions, a Lower Module (LM) and Upper Module (UM). These two modules may be quickly disconnected allowing team members to work on various components simultaneously without occupying others' workspace. The platform is assembled primarily from 8020 aluminum extrusion and standard fasteners available at most hardware stores. Mounting surfaces for components include aluminum or acrylic sheets, as mechanically appropriate or specified by the Electrical team.

The LM occupies approximately 32 cubic feet (4x4x2) and includes *only hardware necessary for teleoperation*, with the exception of the LIDAR mounted on the front. From above, the LM resembles a 'plus' sign with an omni wheel, motor, and swing arm suspension making each of the four points; this view of the LM may be seen in Figure 5. The wheels and suspension surround a central cavity containing the remaining hardware on the module. The cavity floor and four walls all provide rigid mounting for components. The four batteries rest on the floor in a frame built to keep them safely in place during operation; they may be removed as needed from above. The east and west walls (consistent with Figure 5) provide mounting for the motor controllers. The south wall provides mounting for the VCU. The north wall features the electrical panel. Immediately above and to the outside of the electrical panel is the switch panel allowing users to disable systems or the entire platform as necessary. When the UM is not attached, a removable panel covering the central cavity is seen. When that panel is lifted, the central cavity is exposed allowing team members to access all of the hardware within to run diagnostics, exchange batteries, etc.

The UM includes hardware necessary for *autonomous navigation*, again, with the exception of the LIDAR. This hardware includes the onboard computer, GPS and IMU sensors, wifi router, and cameras. The UM also provides a central space for attachment of the required payload. The bottom surface of the UM is guided into its mounting on the LM upper surface by linear strips of magnets attached to the both surfaces. Once the UM is in place, it is further secured by clamps along the exterior. By separating the autonomous and teleoperation systems and compartmentalizing each in their respective modules, Yoshimi can be fitted with various UM systems to accomplish different tasks.

Figure 5: Top-down view of Lower Module.

ELECTRONICS SYSTEMS

The electrical and electronics systems of Yoshimi are an iterative improvement over last year's platform. New designs focused on hardware protection in the event of a surge or malfunction, modularity of individual systems - such that one system may be disabled while the remaining systems remain online, and compatibility with with various hardware. An overview of the electronics systems may be seen in Figure 6.

Power Supply Units

Yoshimi features two power supply units, an M4-ATX and DCDC-USB-200, and a backup unit for quick repair or future electronic integration. The power supply units were selected based upon their high efficiencies of 95%. The DC-DC converters step down 24 V DC to a wide range of regulated DC voltage levels. M4-ATX provides 3.3, 5, and 12 V DC for maximum power output of 200 W. DCDC-USB-200 provides one regulated output rail with configurable voltages from 5 to 24 V and a maximum power of 100 W. The power distribution system is capable of outputting an overall maximum of 400 W. Air circulation ensures the dissipation of heat produced by step-down inefficiencies. A switch-mode power supply and linear voltage regulator were key to achieving high efficiency and steady, direct current.

Batteries

Two sets of 24 V DC batteries are connected in parallel to increase operation time to four hours at maximum power draw. Each battery set contains two 12 V DC lead-acid batteries, rated at 20 AH, connected in

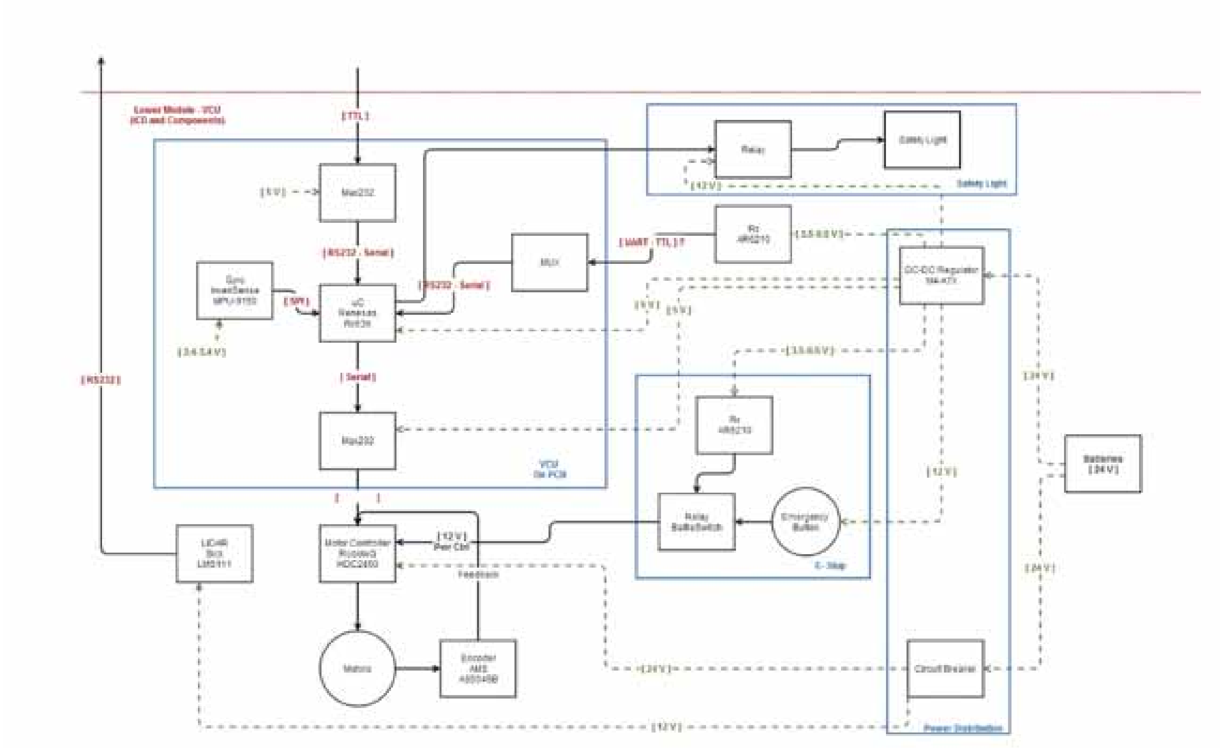

Figure 6: Electronics system architecture.

series. The batteries are connected to a Hot Swap circuit allowing batteries to be exchanged without a full system shutdown. Each battery also has its own slow-blow fuse to avoid long-term damage.

Vehicle Control Unit (VCU)

The vehicle control unit (VCU) is mounted within the main cavity of the LM and facilitates the teleoperation capability of the LM. The VCU is capable of receiving signals sent remotely by operators - via a AR6210-X Spektrum Satellite receiver - or from the main computer on the UM. Figure 7 shows the Satellite receiver communicating with the Renesas micro controller via UART protocol. Input signals may be received via Ethernet or Serial ports; these signals are converted into PWM power signals. An InvenSense MPU-9150 nine-axis gyroscope, accelerometer, and compass MEMS motion tracker is installed in the unit for rotation detection. The VCU also features a JTAG interface for on-board testing and debugging. The VCU's power electronics uses SMPS and a linear regulator; this design was inspired by the M4-ATX motor controller power supply unit which is both reliable and highly efficient. The VCU outputs signals to the motor controllers via an RS232 serial port.

Single Board Computer (SBC)

During the 2013 competition, vibrations created from the previous omni wheel system dislodged RAM from the main computer's motherboard. In addition to redesigning the wheels to reduce vibration, the previous computer - which contained parts standard to a desktop PC - has been replaced with an EM-6335 single board computer (SBC). The SBC features an AMD embedded GX-210HA SOC (D/C 1.0 GHz), HDMI, VGA, LVDS, GLAN, COM, USB, SATA, and Mini-PCIe ports. This SBC also dissipates much less power than the previous system.

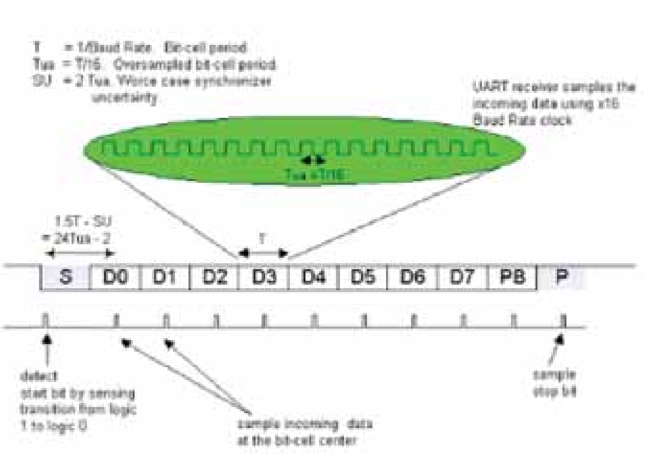

Figure 7: UART signal bit structure.

Motor Controllers

Yoshimi has been equipped with two RoboteQ HDC2450 motor controllers, each driving two motors. The controllers amplify PWM signals received from the VCU via RS232 connector. The controllers also feature an internal PID controller and analog power control for emergency shutdown which is utilized by the emergency stop system.

Emergency Stop

The emergency stop subsystem is designed to disable the motor controllers rather than shutdown the entire platform; this eliminates the requirement of a full system reboot following a stop. This system uses a modified Spektrum AT6210 6-channel DSMX receiver and Battle Switch relay connected to the motor controllers' power control line.

Sensors

A Sick LMS100 LIDAR is installed for object detection and mapping. The LIDAR uses time-of-flight technology to provide real-time environment measurement. Scanning frequency is adjustable from 25 Hz to 50 Hz with a power consumption of 8.4 W to 12 W. The LIDAR can scan up to 20 m with a 270° arc at 0.5° resolution. Yoshimi is also fitted with PlayStation Eye cameras for lane detection and an Xsense GPS/IMU device.

Electrical Protection

The power distribution system is equipped with individual switches and fuses for each subsystem with the exception of the emergency stop; the hardware was chosen based upon tolerances to minimize damage in the event of malfunction. Individual fuses for each subsystem accelerates any necessary troubleshooting. A master circuit breaker has been installed for when Yoshimi is not in use.

Motor Encoders

An encoder is installed at end of the motor shaft to provide velocity feedback. A custom PCB was designed using eagle software; this PCB is combined with an AMS AS5045B rotary sensor and AS5000 magnet for detecting rotation of the shaft. The motor encoder PCB may be seen in Figure 8.

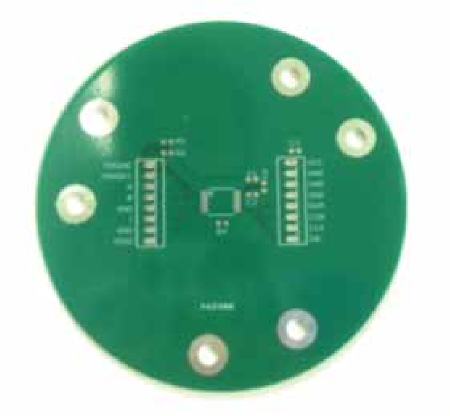

Figure 8: Motor controller PCB.

Hazard Light

The hazard light was designed to produce alarming brightness with minimal power consumption. A 2.4W LED bulb at 24 V DC is used to generate 120 lumens. A custom LED driver was designed and assembled using a power MOSFET.

SOFTWARE SYSTEMS

For a platform to navigate an environment and avoid obstacles, it must first detect its surroundings. Yoshimi is fitted with a combination of sensors to help detect obstacles and navigate through a series of GPS waypoints; these sensors include Each of these sensors allow the Yoshimi to detect particular aspects of the environment and the platform's orientation with respect to that environment. Using a pre-existing Message Passing Interface (MPI) framework, an efficient software architecture is implemented that can accurately detect the environment and use this information to generate appropriate platform movements. These movements follow an obstacle-free path through the course.

Software Architecture

Our software system uses the Robot Operating System (ROS) framework as a foundation. ROS allows us to develop code in a modular manner while efficiently facilitating communication between programs. Individual programs are implemented as ROS nodes which compile and run independently. When nodes run under the ROS frameworks, they are able to publish or subscribe data steams containing valuable system information. Figure 9 displays an overall view of the entire software architecture implemented in Yoshimi; a main priority in this architecture is data flow. Our goal was to design a system that allowed sensor information to be easily translated into motor actuation.

Lane Following

Three PlayStation Eye cameras are used for lane detection. A ROS node receives a 640x480 image and performs a hysteresis thresholding; this process filters any data not falling within a specified range. The

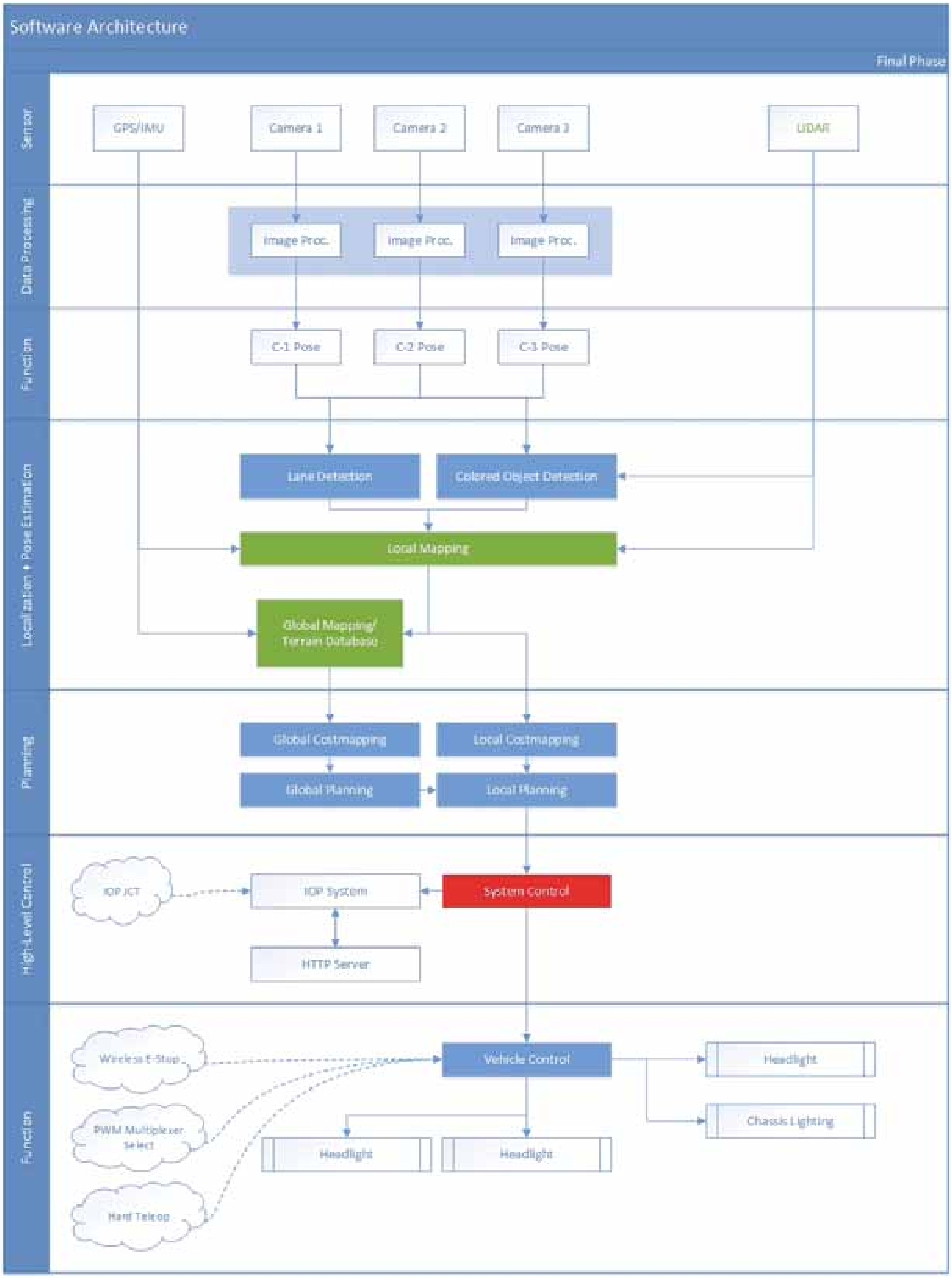

Figure 9: Overall software architecture.

filtered bitmap is passed through a probabilistic hough transform to predict the possibility of several lines present in the image [1]. Based off of a stated confidence level, the number of detected lines can be reduced; an average can be taken to further reduce the number of possible lines to one. Finally, using the pin-hole camera model, this line identified in an image plane can be transformed into actual lines detected in the 3D environment. These 3D points are introduced into the hector for identifying available paths. Figure 10 shows thresholding operations during testing.

Figure 10: Lane detection using color thresholding.

Obstacle Detection

The SICK LMS1000 LIDAR allows Yoshimi to detect object like barrels and small cones. Using a LMSXXX node from the ROS framework, object detection data can be formatted into a usable LaserScan class; this LaserScan class represents one data frame from the laser scanner.

Navigation

For navigation purposes, the team desired a highly reliable algorithm that can virtually recreate the platforms local environment while keeping computing resources to a minimum. Hector mapping was identified as a viable algorithm to meet our mapping requirements. Hector mapping uses a combination of odometry information from the GPS unit and sensor information from the camera and LIDAR systems to create an occupancy grid that accurately represents the environment. The algorithm consumes minimal computational resources while providing accurate environment perception using a similar SLAM-based approach[2]. Figure 11 shows a sample occupancy grid generated from using our hector mapping approach.

Path Planning

In order to provide an accurate path planner with low computational cost, we use a tested and effective algorithm called D* search. This algorithm generates a list of possible path points based off of the occupancy grid generated by our hector mapping approach with each point carrying a weight; this weight inversely represents the relevancy of a point in an obstacle-free path. If a point is found to be non-obstacle-free, its weight is increase. The higher the weight, the less useful the point is along an obstacle-free path[3]. Using a vector path generator, a set of points between two GPS waypoints is generated and used to provide our base motion controller with a command velocity vector that represents an obstacle-free direction of motion for the platform. We represent motion control with a 3-parameter command velocity vector: $\dot{X}$, $\dot{Y}$, and $\dot{\theta}$ representing the two linear and angular velocities respectively. Given these three values, Yoshimi can move in any desired direction generated by the vector path generator.

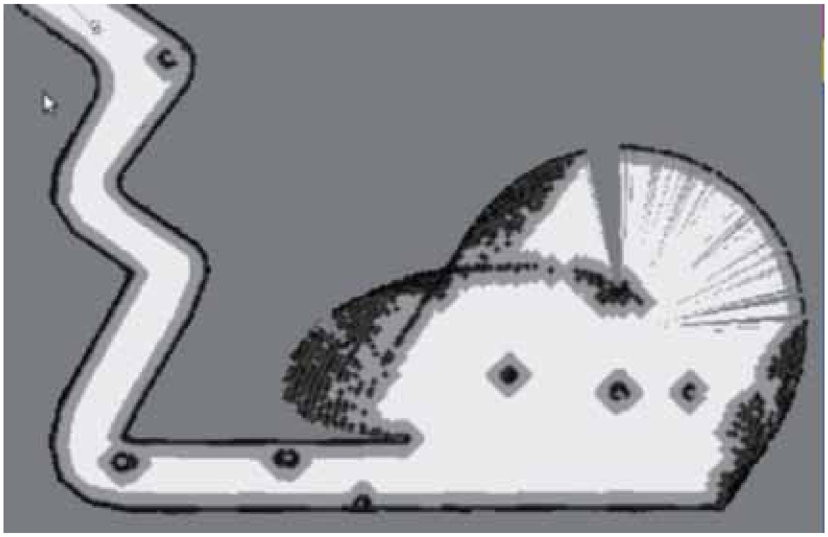

Figure 11: Hector mapping output from simulation.

CONCLUSIONS

Yoshimi is a novel holonomic robotic platform capable of performing flexible high-speed maneuvers while navigating an unknown environment. The Mechanical, Electrical, and Software teams have invested hundreds of man-hours into the design and construction of Yoshimi. We, the UTA IGV Team, are proud of the Yoshimi platform and believe she represents a significant improvement over previous platforms.

ACKNOWLEDGEMENTS

The UTA IGV Team would like thank our sponsors, The University of Texas at Arlington Research Institute (UTARI) and Lockheed Martin Missiles and Fire Controls (MFC), as well as the UTARI staff who have supported the team: Dr. Frank Lewis, Matt Middleton, Stephen Savoie, and Norm Spayd.

BUDGET SUMMARY

	Cost per unit	Total Quantity	Total Cost
Structure and Suspension			
Extrusion Bar	$31.59	6	$189.54
Nuts and Bolts	$75.00	1	$75.00
Shocks	$75.00	4	$300.00
Acrylic Sheets	$400.00	1	$400.00
Wheel Assembly			
Resin	$192.71	5	$963.55
Nuts and Bolts	$25.00	1	$25.00
Aluminum Plates	$155.17	6	$931.02
Al Key	$5.00	4	$20.00
Aluminum Barstock	$700.00	1	$700.00
VCU			
JTAG connector	$1.69	2	$3.38
Status LED	$1.05	2	$2.10
Renesas uC	$75.00	1	$75.00
PCB-VCU	$300.00	1	$300.00
Satellite Receiver	$30.00	1	$30.00
Serial Connectors	$50.00	1	$50.00
Enclosure	$35.00	1	$35.00
Safety Light			
LED Bulb	$20.00	2	$40.00
Driver	$50.00	1	$50.00
Enclosure	$10.00	1	$10.00
E-Stop			
E-Stop Button	$75.00	1	$75.00
RF Receiver	$50.00	1	$50.00
Relay	$20.00	1	$20.00
Misc	$20.00	1	$20.00
Power			
Toggle Switch	$5.60	10	$56.00
Fuse Panel - 8P	$38.33	1	$38.33
Circuit Breaker	$65.00	1	$65.00
Bus Bar	$25.00	1	$25.00
Terminal Connector	$8.00	3	$24.00
Cables & Connectors	$100.00	1	$100.00
DCDC Power Supply	$69.99	2	$139.98
Battery	$62.06	4	$248.24
M4-ATX	$36.68	1	$36.68
Drive System			
Encoders	$75.00	4	$300.00
Quickie Wheelchair Motors	$250.00	4	$1000.00
Motor Mounts	$50.00	4	$200.00
Motor Controllers	$375.00	2	$750.00
Computer &Sensors			
Xsense GPS/IMU	$5,000.00	1	$5,000.00
SICK LMS1000	$5,000.00	1	$5,000.00
Playstation Eye Cam	$20.00	1	$20.00
SBC	$500.00	1	$500.00
Router	$40.00	1	$40.00
Remote Controller	$200.00	1	$200.00
Estimated Cost			$18,107.82
Travel Budget			$10,000.00
Overall Cost			$28,107.82
Sponsors			
UTA Research Institute			$30,000.00
Lockheed Martin Missiles and Fire Control			$3,000.00
Total Sponsorship			$33,000.00

REFERENCES

[1] N. Kiryati, Y. Eldar, and A. M. Bruckstein, "A Probabilistic Hough Transform." *Pattern Recognition*. Vol. 24, Iss. 4, 1991, pp. 303-316.

[2] S. Kohlbrecher, O. von Stryk, J. Meyer, and U. Klingauf, "A Flexible and Scalable SLAM System with Full 3D Motion Estimation." IEEE International Symposium on Safety, Security, and Rescue Robotics. 2011, pp. 155-160.

[3] A. Stentz, "Optimal and Efficient Path Planning for Partially-Known Environments." IEEE International Conference on Robotics and Automation. Vol. 4, 1994, pp. 3310-3317.