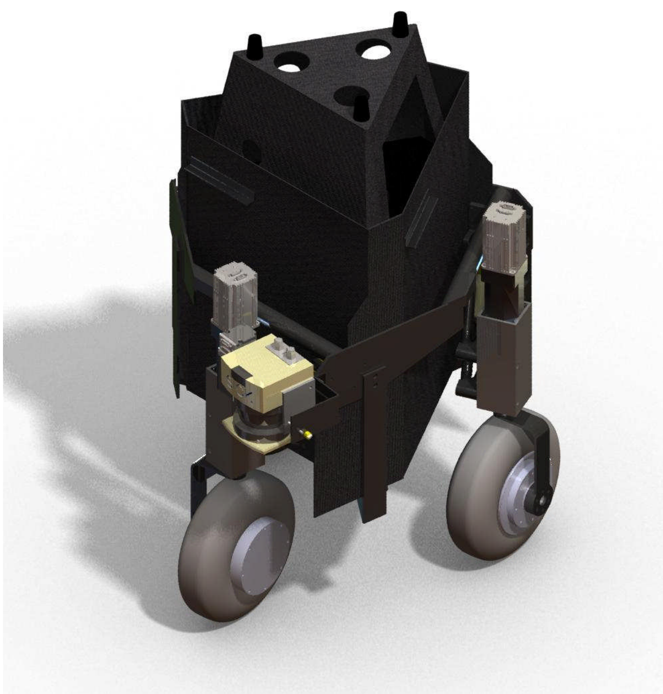
Design of a Hybrid Powered Autonomous Omni-Directional Vehicle

Faculty Advisor: Carl Crane

Center for Intelligent Machines and Robotics

University of Florida, Gainesville, Florida
352-392-0832



CIMAR OmniGator, AUVSI Intelligent Ground Vehicle Competition 2009

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1. Introduction and Motivation

This report describes the design process and implementation utilized to realize the OmniGator, a three wheeled omni-directional autonomous ground vehicle.

The Center for Intelligent Machines and Robotics (CIMAR) at the University of Florida has worked in autonomous ground vehicles since the early 1990s. The lab's autonomous vehicle architecture has evolved in that time to include an active role in development and implementation of the JAUS architecture and was well refined through participation in the three DARPA Ground Vehicle Challenges.

The size and speed capability of the OmniGator vehicle are tailored to allow competition in the Association for Unmanned Vehicle System International's (AUVSI's) Intelligent Ground Vehicle Competition (IGVC). Most other design considerations were chosen to allow the vehicle to serve as a development platform for future work in the CIMAR lab.

CIMAR participated in the IGVC from 2002-2004. The experience gained in these competitions lead to a design effort to develop a vehicle platform capable of addressing the challenges presented in the competitions. The DARPA Challenges intervened in the development process and the OmniGator is the delayed result of this effort.

2. Design Problem

The design problem is to develop an autonomous ground vehicle that is suitable for competition in the IGVC and useful for future research in autonomous ground vehicles at CIMAR. Waypoint traversal and lane following are required behaviors in the IGVC. The challenges presented in the IGVC involve complex obstacles including switchbacks and center islands, dead ends, traps, and potholes. The lab requires an open architecture with hardware support that allows experimental development of ground vehicle autonomy.

3. Design Solution

3.1 Vehicle Mobility

Many conventional wheeled type vehicles have fixed drive wheels and change the direction of the vehicle by orienting the steering wheels. The fixed configuration of the drive wheel constraints the mobility of the vehicle to one as it typically follows Ackerman steering. The omni-directional vehicle platform presented in this paper has three steerable drive wheels allowing the vehicle to maneuver in any direction instantaneously. The steerable wheel mechanism used in this platform is considered as having non-holonomic mobility [7] as it requires a finite amount of time before the steering mechanism can reorient the wheel to the next projected curve. Some special wheel designs such as Mecanum wheels have been introduced [5] to tackle this problem by adding rollers on the wheels. However the rolling mechanism often increases power loss due to conflicts among other actuators [8] and are hard to build for bigger applications, thus we have chosen steerable wheel mechanism for the omni-directional mobility.

3.2 Problem Solution

An omni-directional vehicle configuration was selected as the best mobility platform to address the challenges expected in the IGVC. Power resources were designed to support the mobility scheme and autonomy sensor and computational requirements. Sensor selection and computation resource selection was based on DARPA Challenge vehicle development experience. The resulting system architecture is detailed with consideration of the power system, drive system, and control system.

The power system consists of a modified off the shelf generator-IC engine pair coupled with lead acid batteries. The generator-IC engine pair has been repackaged into the vehicle chassis. The generator produces alternating current that is rectified and conditioned to supply a DC buss. This buss is backed up by lead acid batteries that have approximately 1 KW/hr of storage. The DC buss provides power to the drive motors, steering motors, cooling system, and control system.

The drive system consists of three drive wheels. The drive wheels are of a custom hub driven type and were fabricated for this application. They are propelled by a frameless brushless dc motor that drives the wheel rim via an epicyclic gear train. The drive motors are cooled by a closed coolant loop cooling system that includes a radiator mounted on the vehicle chassis. The drive wheels are mounted on a spindle that is actuated by a steering motor, allowing a minimum of 360 degrees of steering angle for each wheel. The steering motors are sourced from Animatics and include a dedicated controller and amplifier. The steering/drive train is mounted on a sprung swing arm to the vehicle's chassis.

The control system is composed of a hardware control component and an Autonomy component. Two COTS Micro-ATX motherboards and an embedded microcontroller are utilized to implement the control system. The motherboards host a quad core and dual core processor and are used to run the higher level hardware control and the autonomy. The embedded micro-controller manages the drive motors and hardware system control. The autonomous control of the vehicle is implemented utilizing the JAUS 3.3 standard. The architecture is a derivative of past CIMAR work utilized in the DARPA Grand and Urban Challenges.

4. Hardware Platform

The vehicle's hardware subsystems are illustrated in figure 1. System Components include:

Outer Cover: protects compute resource

Inner Cover: Mounting surface for compute resources

Nodding LADAR: Obstacle and Terrain detection

Chassis: Enclosure and structural

"Omni" Bumper: Structural integrity

Steering Motor: Steers drive wheel

Drive wheel: Drive motor, tire, and gear train

Power system: Generator, batteries, and power conditioning/conversion.

4.1 Drive

CIMAR undertook the design and development of a drive wheel for omni-directional use. Fulmer [3] successfully demonstrated the performance of a hub drive wheel for the omni-directional vehicle in his paper. The hub drive wheel developed consists of a brushless motor embedded in the hub of a wheel with a two stage epicyclic gear train. Active cooling of the motor is integral. Figure 2 shows the dynamometer test set-up for the drive wheel done by Fulmer. Figure 3 details the results of the dynamometer testing with seven forced cooling rates. The performance of the drive is consistently better than 280 in-lbs of torque. This converts to a propulsive drive force of approximately 46 lbs. The vehicle is required to traverse a 15 degree slope and accelerate to and maintain a speed of 5 mph. The weight of the vehicle is estimated at 250 lbs. The drive is adequate for these requirements. See Fulmer[3] for complete performance estimates.

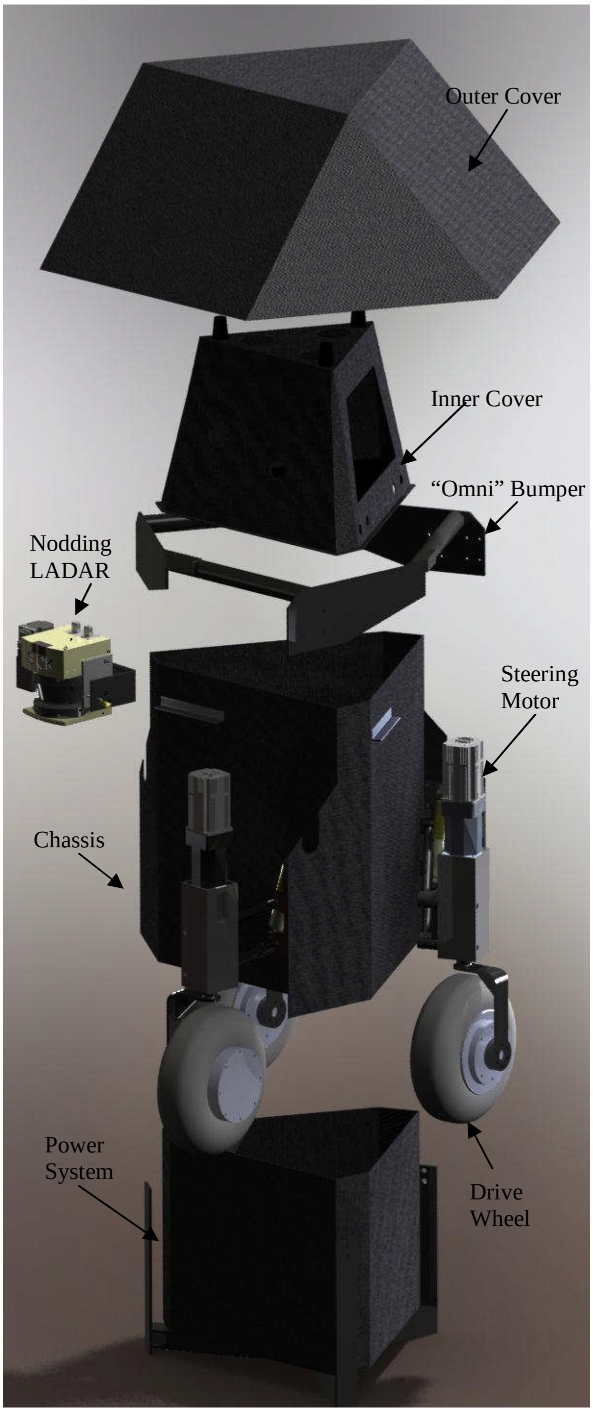
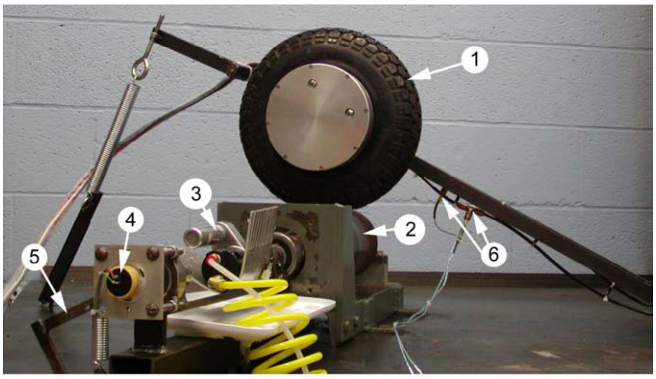


Figure 1. System Components



1. Drive wheel
2. Dynamometer roller
3. Air brake
4. Potentiometer
5. Torque reaction arm and linear spring
6. Coolant inlet and discharge thermistors

Figure 2. Dynamometer testing of drive wheel

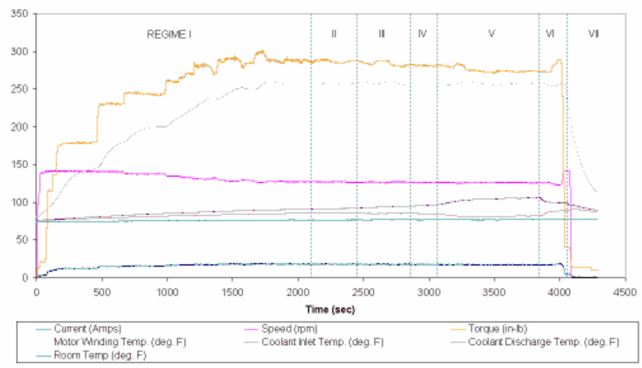


Figure 3. Dynamometer testing results

4.2 Power System

The power system architecture for the omni-directional vehicle is illustrated in figure 4. The system is a serial hybrid approach with a gasoline powered Honda eu2000i generator for electrical power generation. Lead acid batteries serve as power storage. The primary DC buss is 48 volts. Secondary busses are sourced from the primary via DC-DC converters. A common ground is maintained for all DC busses. The generator can be replaced with wall power to facilitate static testing in the lab without the internal combustion engine running.

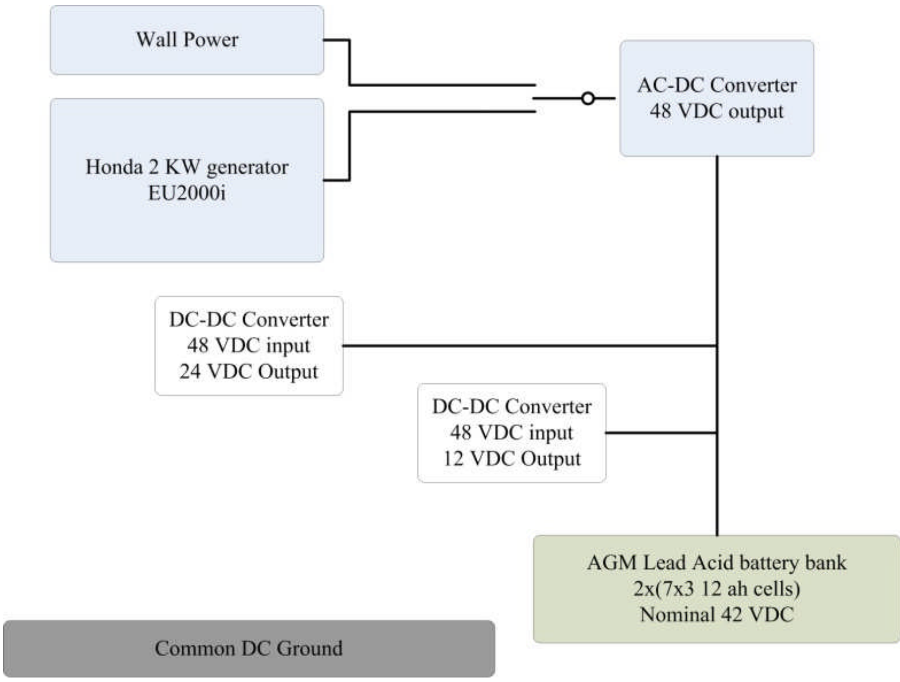


Figure 4. Power system layout

4.3 Computational Resources

The omni-directional vehicle autonomy is implemented on two COTS motherboards. One motherboard supports a quad core Intel Q9400 and the other a dual core Intel 8200 E8200. Both systems are powered by dc-dc atx power supplies. Inter system communication is facilitated with a gigabit router.

5. Sensors

The environment of the autonomous vehicle is explored using several types of sensors. A single LADAR is utilized for terrain classification and obstacle detection. Two cameras are used to find lines and obstacles. An inertial measurement unit, a GPS with RTK correction, and wheel odometry are utilized for localization. A data base called a Knowledge Store is implemented to augment situational awareness.

5.1 Localization

Localization of the autonomous vehicle is critical for our implementation of the Smart Sensor concept and the reactive planner. The architecture requires that the sensor data be placed in a common reference frame for fusion. We use the global frame for this purpose. Several sensors are utilized to estimate the current position and orientation of the vehicle in the global frame. A MicroStrain 3DM-GX1 Inertial Measurement Unit (IMU) uses an internal microprocessor to filter raw acceleration data into gyro-stabilized roll, pitch and yaw angles dynamically accurate from 0.5° to 2° up to a tested 30Hz. This heading feedback comes with almost negligible design impact due to the very low current draw, large supply voltage range, small enclosure construction, built-in magnetic field compensation and RS-232 interface. To compliment the IMU, a Novatel Propak V3 is used to acquire high precision GPS information. The Novatel unit is equipped with an RTK subscription capable of producing global coordinates with 10cm accuracy at 20Hz. When high precision mode is not available, CDGPS can provide 60cm accuracy – still good enough to properly locate the desired IGVC waypoint goals with the IMU and wheel odometry. To maximize the GPS's ability, the antenna was mounted on the very top of the robot – limiting the amount of avoidable service interruptions (as high precision mode can take as long as twenty minutes to reacquire). Together, these sensors provide a healthy location that enables the system components to work intelligently placing objects in the environment more accurately.

5.2 Obstacle Detection

The CIMAR architecture implements reactive autonomy. This requires characterization of the environment local to the vehicle. Detection of objects and classification of drivable areas are needed.

5.2.1 LADAR

The decision to include a laser range finder as part of the perception element was based on CIMAR's many years of experience developing autonomous vehicles. The accuracy and range of the Ladar lends itself to be an excellent sensor for mapping the geometry of the surroundings. Since a Ladar only detects a two dimensional cross section of space, the decision was made to create an actuated assembly that fanned the Ladar up and down to capture range data in a broader three dimensional manner. This feature is critical for generating a realistic image of obstacles as well as for determining the slope of the ground plane. Using a fixed Ladar configuration would make detection of smooth sloping areas such as hillsides or bridges likely to be indistinguishable from obstacles; the actuated configuration allows for these cases to be correctly classified as traversable regions.

A Sick LMS-291S05 laser range finder is mounted to the front of the vehicle with an actuator to continuously adjust the pitch angle of the sensor. The purpose of using a ladar for mapping the vehicle environment is twofold: obstacle detection and terrain traversability estimation. Obstacle detection is possible by extracting objects from the surrounding ground plane point data while terrain traversability is evaluated by applying a heuristic method to the slope and curvature of the terrain. Figure 5 shows the configuration of the sensor.

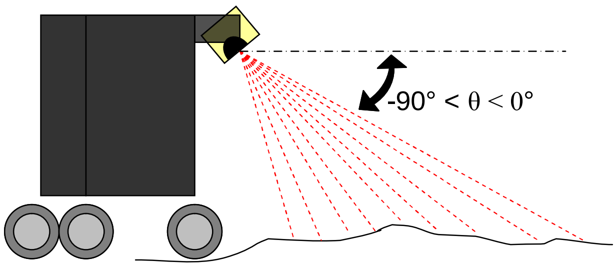


Figure 5. Ladar mounting configuration

The process of recreating the environment from the Ladar data involves first transforming the polar data to the vehicle's reference frame and then transforming these points to the global reference frame. The advantage of storing and processing the time persistent data in the global reference frame is that the point data transformation is only required once whereas keeping the data in the vehicle reference frame would require transforming old data points as the vehicle moves and rotates. The data is stored as z-heights in a regular grid structure as opposed to an irregular network so the points must be snapped to the nearest grid point before being stored. Since the data is kept persistent over time, new data must be merged with this older data. A weighting factor based on age is used so that older data has less confidence than newer data. If two points are merged that are close (i.e agreement

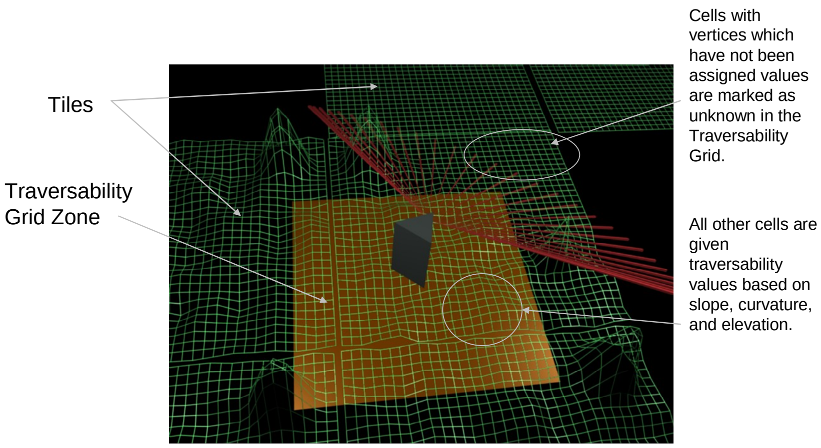


Figure 6. LADAR local fusion scheme

between old and new data), their weighting factor becomes higher. Figure 6 below illustrates the usage of addable and removable tiles that store the point data as well as the local region that will be processed shown in yellow.

A 30 m by 30 m region of the point data is selected and processed at each time step in order to evaluate traversability and obstacle boundaries. This region of the laser range data is processed and a traversability grid is formed. The traversability grid is a 121 by 121 element grid that is mapped to this region, yielding a 0.25 meter resolution. Each entry in the traversability grid is scalar value that represents that area's traversability based on smoothness, slope, and elevation. This general value can be interpreted by the planning element based on the vehicle type, that is, a region which should be avoided by one vehicle type might be safely covered by a larger vehicle. This architecture permits reactive path planning within a 30m by 30m zone around the robot. Sending the latest traversability grid at a rate of 10-20 Hz provides ample reaction time for a robot limited to 5 mph. Finally, the objects that have been extracted from the ground plane based on their height above the surrounding ground space is vectorized into a polygon and stored in the knowledge store as an obstacle.

5.2.2 Vision

The Line Finding Sensor is a vision based component which extracts line information from the local environment. For the OMNIGATOR, we use two mvBlueFox 120aC cameras which perform the roles of finding lines as well as obstacles. The extraction of lines is performed by using Hough transform. This is implemented using openCV libraries.

BlueFox cameras have a capture rate of 100Hz, which provides a lot of scope for fast image processing. Also it is USB 1.1 compatible. The driver software together with the FPGA reduce the PC load to a minimum during preprocessing. The automatic gain control and exposure control of the BlueFox is also advantageous. The Tamron lens chosen for the OMNIGATOR, has a variable focal length and can be used as both telephoto and wide angle lens.

Detection of painted demarcations is accomplished by considering multiple environment cues which include intensity, color, shape and orientation. These points of interest are searched for and linear dominant elements are reported. The input image which is a three channel image is reconstructed into a single channel image and the Canny algorithm is applied to it in order to detect the dominant edges. The Canny algorithm computes first derivatives in x and y, which are then combined into four directional derivatives, where each of the maxima are assembled into edges.

The Probabilistic Hough Transform is applied to the binary image, which is a slight variant of the Standard Hough Transform. The Standard Hough Transform calculates the ρ and θ value of all the lines present in the frame, where ρ and θ are the distance and angle respectively, of the line from the origin (0, 0). In our case the starting position was the top right of the frame, which indicates a negative value of ρ meant the line was on the right half of the frame. The Progressive Probabilistic Hough Transform is a variation as it accumulates only a fraction of the points in the accumulator plane. This results in line segments with starting and ending points instead of an infinitely long line with the given slope. This was chosen over the Standard Hough transform as the first derivative of the set is more accurate than the ones derived by Standard Hough Transform.

For the line finding algorithm, we set an initial slope value and then perform a constant comparison with the previous slope to see that there is no major deviation from the previous slope, thus following the same line though it may have slight changes in slope as in the cases of curves. Once these points are extracted, the information is sent to the Knowledge Store. The points are packed in a particular order to indicate that one side of the line is traversable while the other is not.

Obstacle detection with the cameras has been reduced to a polygon recognition and reporting one. The obstacle in the path is found by detecting the contour. This is implemented using openCV libraries. The binary image with the edge pixels is classified into positive and negative regions. Depending on the intensity, the area is classified as either a contour or a hole. The contour is the approximated into an approximate polygon. This is done by taking the extreme ends of the contour and drawing a line between them. The point which is farthest from this line is taken as the third point and so on. The iteration stops when the distance between the point and the line is lesser than a specified value. Also while finding the polygons, noise may interfere with the data capture, so we assign another condition that the area of the contour detected must be greater than a particular value (to indicate that there is a polygon).

The points are found in a random order which is packed into a predefined clockwise order and sent to the Knowledge Store.

5.2.3 Knowledge Store

The Knowledge Store component functions as a repository of vectorized data and information for any system components. The Knowledge Store is designed on top of a Postgresql 8.3 database with Postgis1.3 spacial extensions. Both were chosen for their wide usage in industry and are open source. The Postgis library of predefined geometric functions and types was chosen to facilitate rapid integration with the overall system. The Knowledge Store allows any number of client components to create, query, and delete instances of vectorized objects in the database. Once the component receives and parses a message by using dynamic cues set in the structure of the message, a SQL query string is built using definitions that are predefined within the system. The query is then sent to the database and depending on what type information was in the message; the Knowledge Store compiles the desired data from the database return or queries the database again depending on the results. Vector objects stored in the database can have any number of predefined properties. These properties can be merged into sets that describe an object. For example, a cone on the field would hold a geometry that describes its shape as classified by sensors, a time stamp of when it was last classified, a traversability value assigned by the client, which component classified it and so on. Three basic geometric types are supported: points, lines, and polygons. Messaging functionality is built off of the AS-4 standard. This allows the knowledge store to run on any JAUS compatible system.

6. Control

6.1 Low Level Control

As an omni-directional mechanism, three hub drive BLDC motors are attached to an L-shaped bracket. Each wheel bracket is connected to the steering servo motor with a 48:1 gear head. Figure 7 shows the physical arrangement of the mechanisms.

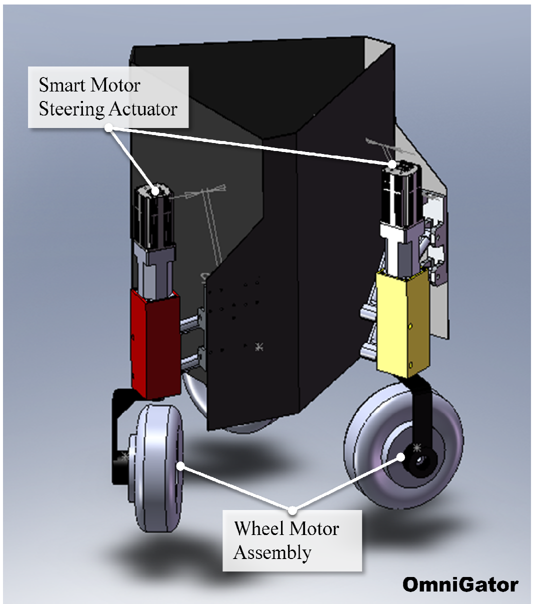


Figure 7. Drive Configuration

In order to control the vehicle platform, certain inputs have to be converted to a power to drive the actuators. In the hierarchy of the JAUS architecture, the primitive driver (PD) provides the method of interpreting plans to actuator command. PD requires low level or hardware level control system. Figure 8 shows the architecture designed to interface with actuation systems.

A SmartMotor SM3440D from Animatics is used for the steering actuator. It is a complete servo system equipped with individual embedded motor controller, amplifier, and an encoder. Each SmartMotor is commanded through RS-232 serial communication. Physical alignment of the drive wheel is very important in controlling the steering angle of the omni-directional wheel. If any of the wheels are not correctly aligned towards the omni-directional motion, abnormal forces will be applied to the mechanism and that can potentially damage or destroy it. To prevent such a catastrophic event from happening, every time the device is turned on the SmartMotor must be initialized prior to operation. This initialization process includes homing and alignment. An optical sensor switch is mounted on one side of the gear head block looking down to the wheel bracket. A reflective tape is placed on top of the bracket which enables the sensor to detect the light emitted from its source and find the home.

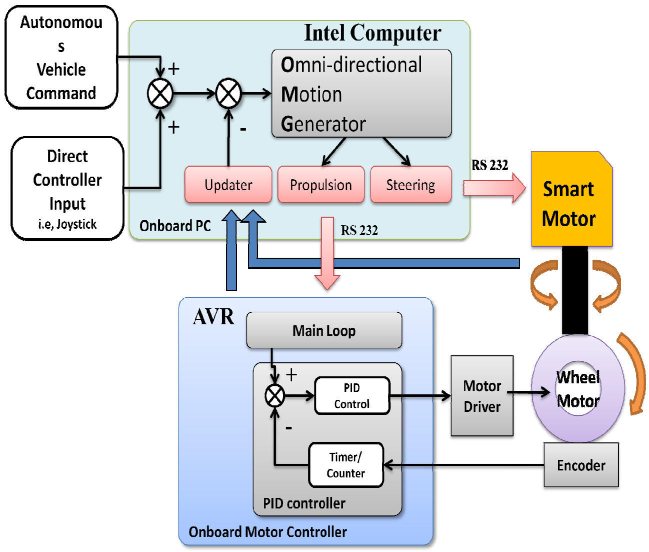


Figure 2. Lowlevel control

Controlling the three wheel motor requires different techniques as it lacks both motor amplifier and controller. A BE40A8 BLDC motor driver from Advance Motion is used to power the motor. This motor driver converts analog reference input to switching currents for the brushless motor. An embedded controller is used to complete the motor feedback control system. An ATmega128 provides an economical and reliable solution with enough computing power (up to 16MIPS at 16MHz [1]). The wheel motor contains an optical encoder with 1000 counts per revolution (CPR) attached to the motor shaft. Each pulse out from the encoder is fed back to the controller by its embedded timer/counter. A discrete PID control algorithm is implemented in the microcontroller to compensate the errors with newly updated encoder counts. The error obtained here can be expressed as

$$E = GoalRPM - CurrentRPM \qquad (1)$$

Where GoalRPM is desired velocity of the motor and CurrentRPM is the latest encoder count measured during a sampling time. The sampling time in this case is set to 8ms, a sampling rate of 125 Hz. With this feedback system, the discrete-time PID control law is shown as follows:

$$Output_{PID} = K_P E + K_I \sum (E \cdot \Delta t) + K_D \frac{\Delta E}{dt} \qquad (2)$$

Where K_P, K_I and K_D are the controller gains of proportional, integral and derivative terms respectively. Figure 9 shows simplified diagram of the PID control system developed for the omni-directional wheel motor.

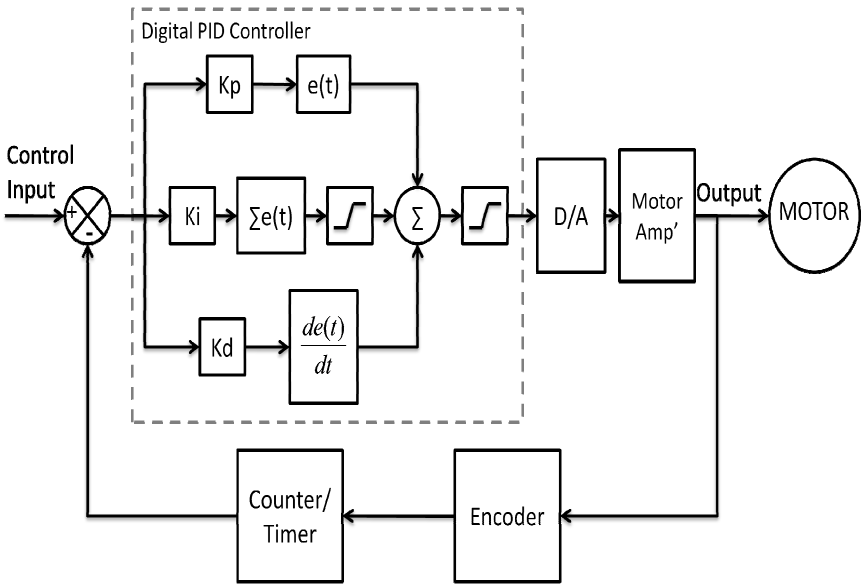


Figure 9. Control system block diagram

Adjusting the gains used for the PID controller often becomes trial and error especially when trying to control motors with unknown characteristics. Since the nature of the omni-directional mobility requires synchronous motion, tuning of the PID motor controllers were focused on ensuring paralleled motion. The step responses of all three motors are shown in Figure 10. This result shows the performance of the newly implemented PID motor controller.

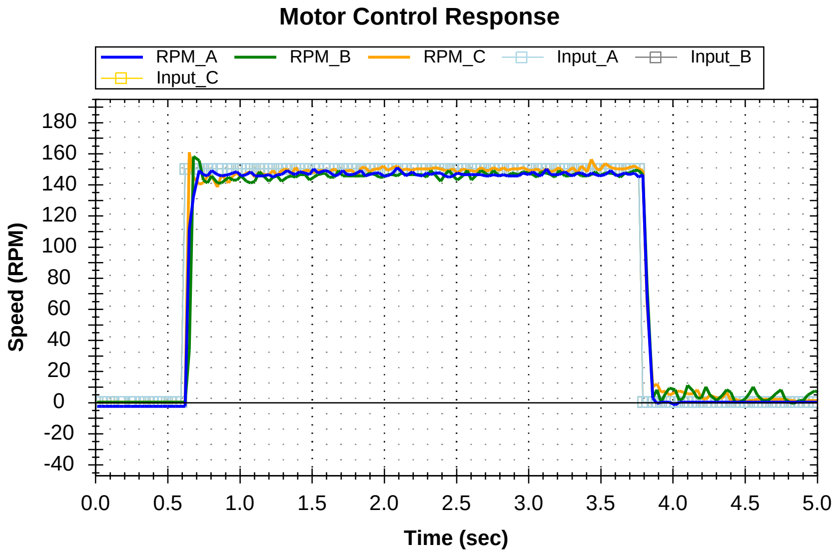


Figure 10. Step response

6.2 Autonomy

The autonomy deployed on this omni directional ground vehicle is derived from the CIMAR architecture that was developed over the course of the DARPA Ground Vehicle Challenges. The architecture implemented traversability grids in the second Grand Challenge[2], and multiple behavior modes were implemented in the Urban Challenge. The development of the architecture is ongoing. The current work focuses on improving situational awareness through utilization of a knowledge store.

The architecture is implemented in a JAUS 3.3 compliant manner. JAUS defines a component as a collection of software that performs a defined task. JAUS specifies a group of messages that allow components to communicate. The standard leaves room for custom messages and experimental components. Some of the architecture is experimental.

The Smart Sensor Concept developed for the Second Challenge takes raw data from the sensor level and converts it into a format that is fusable with other sensor data, whether the sensor is of the same type or not[2][6]. The traversability grid provided the means for this fusion to happen. Tested heuristics were utilized to fuse the data to allow planning based on multiple sensor input with varying time and space resolutions. The addition of a knowledge store required modification of the Smart Sensor output. We have maintained the traversability grid and the appropriate representation of the reactive environment in which we plan in. We have the Smart Sensors extract terrain data and represent it as a traversability grid. Obstacle data is reduced to vector representation and stored in the Knowledge Store. This data is fused with the traversability data in a process call the Arbiter.

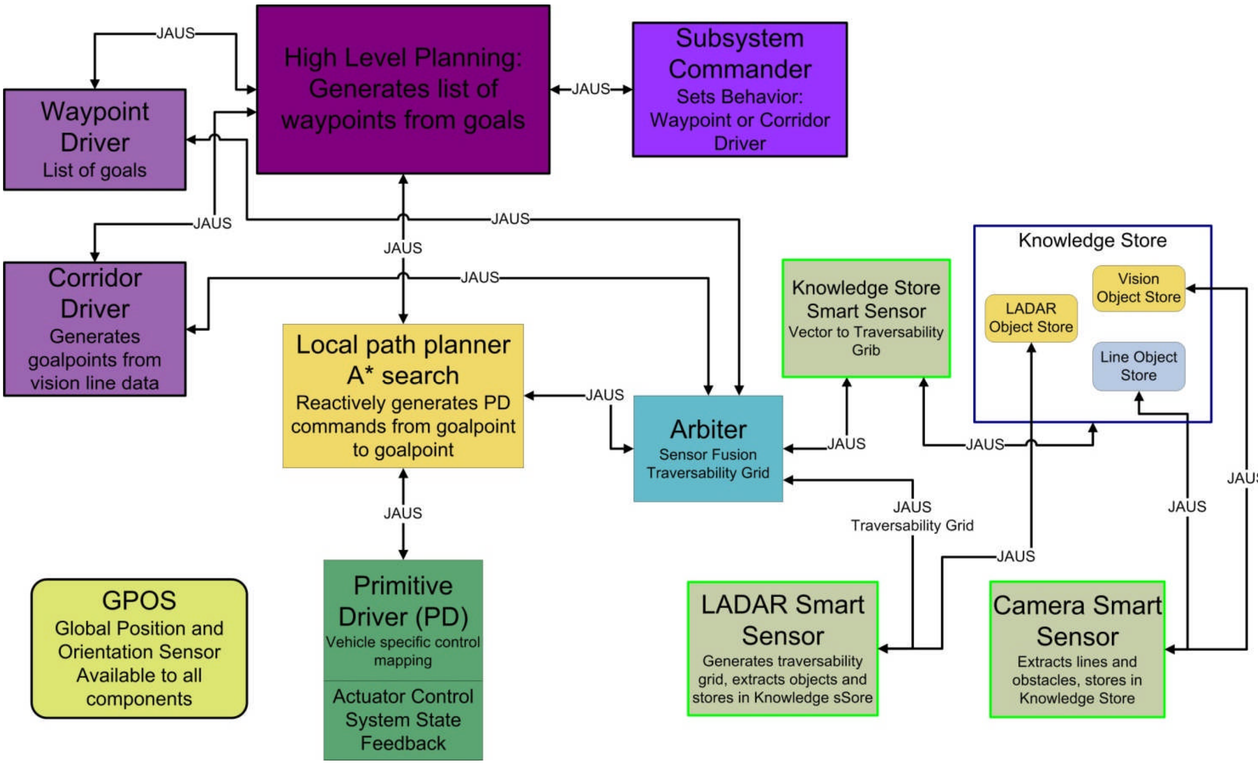
The fused result is then used in a receding horizon planner based on an A* search [4] combined with a receding horizon control strategy to generate motions for the OmniGator. A goal state is determined according to the operating state of the vehicle, either considering a list of waypoints to visit or corridor center estimations coming from visual sensors. The A* algorithm expands and evaluates nodes which represent potential future states of the vehicle in an attempt to reach this goal state. These future positions are estimated using a kinematic vehicle model of the platform, which allows for translation in any direction. The vehicle model uses a unique, prospective steering command associated with each potential state to calculate a position in the vehicle frame of reference. These future states are then evaluated based on a number of different factors, including the value of the cell of the traversability grid within which they fall, as well as their distance to the vehicle's goal state. The evaluation of each node is broken down into two parts and takes the form:

$$f(n) = g(n) + h(n) \qquad (3)$$

where f(n) is the total cost of a particular node, g(n) is the known cost to get to that node, and h(n) is a heuristic estimate of the cost to get from that node to the goal state of the vehicle. According to the A* method, the evaluated nodes are placed in a queue where the least costly node is always first in line to be expanded. This provides for optimality in terms of path cost. When a search node reaches the desired goal state, the algorithm traces back the sequence of connected nodes to the first state change and uses the steering command associated with this search node as part of the next control input to implement. This heuristic algorithm was selected for its reactive planning capabilities. Objects present in desired travel direction are represented as areas with high traversal costs in the traversability grid. These high costs will lead to the search algorithm expanding nodes that avoid these areas and seek out lower cost paths.

The omni-directional vehicle's kinematics are theatrically unrestrained in the plane (3 degrees of freedom). As mentioned in section 2, the steering and wheel velocities cannot be controlled instantaneously, so the vehicle has slightly non-holonomic behavior. A ray based kinematic model is utilized as the kinematic model for omni-directional motion at the reactive planning stage, and the low level control is scheduled to compensate for the non-holonomic behavior by retarding linear velocity in favor of correct heading.

The vehicle is expected to complete two primary behaviors: waypoint following and corridor following. In waypoint following, the vehicle is given a list of waypoints in Latitude and Longitude. The vehicle is then expected to navigate from point to point, avoiding obstacles. In corridor following, the vehicle is put in a corridor defined by lines on the terrain, and expected to follow the corridor avoiding obstacles until the corridor ends. Both of these navigational behaviors can be implemented by driving the optimization scheme of the receding horizon planner. A desired path is imposed on the traversability grid that the Arbiter produces, leading to the desired path being found by the planner provided no environmental factors (from sensors) restrict the plan. Figure 11 illustrates the system diagram. The perception elements consist of the LADAR and vision smart sensors and the GPOS component. The LADAR component utilizes the input from a LADAR sensor and the GPOS data to define the traversability of the terrain local to the vehicle. It also detects obstacles and commits



them to the knowledge store component. The vision component extracts line objects and obstacles from the field

Figure 11. Autonomy Diagram

of view of two cameras. This information is vectorized and stored in the knowledge store. The GPOS component produces a current estimate of the vehicle's global position and pose.

The subsystem commander establishes which navigational behavior is active and monitors system health. The corridor driver queries the knowledge store for line data to define a corridor. It establishes a series of goals for any instant in time based on the line data. These goals are sent to the high level planner which directs the local path planner. The waypoint driver takes an a priori list of waypoints and sends them to the high level planner in a similar manner.

7. Team Contributions

The team is composed of numerous Mechanical and Aerospace students at the University of Florida. Both undergrad and graduate students have participated. The initial omni-directional vehicle design was begun in 2002. The most significant contribution at that time was the design and fabrication of the hub driven drive wheels. Chris Fulmer was the principle contributor to this development.

The next significant work was performed in 2006. The vehicle configuration was changed from four wheel to three wheel. Previously fabricated drive wheel components were assembled. Previously designed suspension components were modified for the new configuration. The chassis was fabricated. Steve Velat and Gregory Garcia contributed to this effort.

The current effort was begun in the late Fall of 2008. This stage includes the completion of the hardware, leading to an operational OmniGator. A large group of students have participated in this stage.

The software has undergone continuous development since CIMAR's first participation in the IGVC.

Table 1 details individual contribution. All of the current team members are noted, and several historical contributions are included.

Table 1. Team Members

		Software			
Team	Hardware	Control	Planning	Sensors	Localization
David			30		5
Owen Allen	50				
Ryan	20			40	
Chris	250				
Gregory	40				
Greg Haley	20				
Jonathon	100				40
Jean-		30			
Bob Kid	30				
Drew Lucas			40		
Brandon			20		
Darsan R	20				
Premchand				70	
Shannon	100	10	10		
Eric Thorn		10	40		
Steve Velat	40				
Vishesh		10	20		20
Kyu Hyong	120	40	10		

8. Costs

The design and fabrication of the OmniGator is spread out over several years. Many of the components were fabricated by team members. Costs are estimated based on material costs and constitutive component costs. The wheel drive components are detailed in Fulmer's paper[3]. Table 2 gives estimates for material and component costs for the OmniGator.

Table 2. Cost Estimate

Component	Quan.	Cost ea.	Sub total
Wheel Drive, BEI frameless motor and custom transmission	3	$2,000.00	$6,000.00
Steering Motor, Smartmotor 3440 D with Gearhead	3	$2,000.00	$6,000.00
Chassis/Covers and power cell structure	4	$450.00	$1,800.00
Suspension	3	$400.00	$1,200.00
Honda Ei2000u Generator	1	$1,600.00	$1,600.00
12 Amp/hr 6 VDC SLA lead acid battery	14	$22.00	$308.00
Power Conditioning, 115 AC -> 48 VDC, 48 VDC -> 24 and 12 VDC	1	$1,200.00	$1,200.00
Misc wiring	1	$700.00	$700.00
SICK 291 LADAR	1	$7,200.00	$7,200.00
Nodding Mechanism, Smartmotor 1770 with custom gearhead	1	$2,700.00	$2,700.00
Matrix mvBlueFox 120aC Camera	2	$1,000.00	$2,000.00
Micro controller	1	$350.00	$350.00
Compute Resources	1	$1,800.00	$1,800.00
MicroStrain 3DM-GX1	1	$1,500.00	$1,500.00
Novatel Propak V3	1	$6,000.00	$6,000.00
		Total:	$40,358.00

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