BENDER
UpTheCreek2018

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Faculty Advisor Statement

I, John W. Peeples, Professor of Electrical and Computer Engineering at The Citadel, the Military College of South Carolina, and Course Director and Instructor for ELEC 421/422, Design I/II, the programs senior design sequence, certify that the design and development of the autonomous vehicle, Bender, by the individuals named on the design team is significant and resulted in award of six semester-hours of college credit for the four of the graduating senior members who chose to pursue the project as their senior design.

May 6, 2018

INTRODUCTION

The UpTheCreek2018 Senior Design Team built an autonomous vehicle, named Bender. UpTheCreek2018 consists of six team members, four who accepted this challenge as their two-semester Senior Design project. Since only one of these four students could be available for travel to the competition, two other students joined the team in a non-credit capacity.

ORGANIZATION

The Senior Design Team

- Connor Fuhrman, is entering full time graduate study in Robotics at the University of Arizona in fall 2018, is the team captain, and will participate in the 2018 competition. Connor led the team and was responsible for all ROS development and simulation.
- Aaron Bahadori focused on the development of image capture and processing, and has accepted employment with a military subcontractor. He cannot attend the competition.
- James French focused on the GPS sensing and navigation and also cannot attend the competition as he entered government service upon graduation.
- Douglas Wattier cannot attend the competition. He is a USAF reservist and was responsible for the chassis, motor drive and feedback electronics.

Conscripted Members

- Josh Widener, a 2018 graduate of the evening BSEE program at The Citadel provided exceptional voluntary assistance the team during the spring term and accepted an invitation to travel to and participate in the 2018 competition.
- Bill Quade, a veteran student rising senior was invited to join the team during the spring term to provide continuity to a planned 2019 IGVC entry. Bill is the third member of the traveling squad.

Connor Fuhrman, Josh Widener, Bill Quade and their faculty advisor, John Peeples will represent The Citadel at the 2018 Intelligent Ground Vehicle Competition.

DESIGN ASSUMPTIONS

The team chose to reuse a vehicle chassis developed for the 2016 IGVC to focus available team bandwidth on the electrical and computing challenges. A few major electronic components, including the LiDAR, and a high-performance gaming laptop computer, were reused to contain costs. There was no Citadel entry in the 2017 IGVC and the 2016 entry, Pablobot, had been cannibalized of most components. Chassis reuse led to a hardware architecture similar to that of the 2016 entry, but electrical and electronic systems, and their software were developed totally anew. Wheel encoders were used to optimize odometry and a microcontroller was integrated in the motor drive implementation to simplify drive and steering. Linux and ROS were chosen as Bender's software foundation.

DESIGN PROCESS

Bender was designed and constructed by one of eight senior design teams of 2018 class of ECE majors at The Citadel. The course focused on conception and design during the fall 2017 term, which culminated with a proof of concept demonstration in December 2017. The spring 2018 term was dedicated to implementation and testing. The UpTheCreek2018 team advisor, Dr. Peeples, was also the course instructor for both terms. As a senior project, Bender's development required many other deliverables including a formal project proposal, scheduling and status reports, a technical paper and presentation, a project demonstration and a final report.

Bender's top-level architecture was devised to use image processing and LiDAR to avoid boundaries and obstacles and GPS for waypoint acquisition. Development of data acquisition methods employing visible light, LiDAR or GPS was assigned to individual team members. The team leader assisted in all areas and had primary responsibility for ROS integration and for simulation activities. As will be detailed, Gazebo was chosen to simulate the vehicular response prior to final implementation.

INNOVATIVE CONCEPTS AND TECHNOLOGY

The senior year flies by, leaving little time to consciously innovate. Hindsight reveals that the use of and dependence on Gazebo in the simulation of Bender is innovative. Not only did this approach provide a flexible and creative development process, but it also eliminated the use of team time for many hard, monotonous hours of effort moving Bender down and back up flights of stairs, and outside for testing. Details of the application and benefit of using Gazebo simulation are covered later in this report.

As detailed later, the choice of Victor motor controllers to replace H-bridges used by prior Citadel IGVC teams enhanced the speed control and steering capabilities without need for a change of other drive train components.

Another innovation was the use of a stereo camera. All past Citadel IGVC entries have used single lens cameras. Bring perspective "into the picture" allowed for a totally new approach to line imaging and processing. The avoidance of simulated potholes was dramatically simplified with the new scheme, detailed later in this report.

MECHANICAL DESIGN

Overview

Bender utilizes a frame designed and assembled in 2016 for a differential drive wheeled robot, which competed in the 2016 IGVC. Bender's two mid-chassis drive and steerage wheels sport rubber studded tires for traction on rolling grass terrain. Front and rear casters provide stability and tight turning radius.

Frame and Structure

Bender's open aluminum frame and its appendages complies with all competition rules. Riveted angle-aluminum construction of a symmetrical chassis, shown in Figure 1, proved to be both lightweight and strong. Platforms over the forward and rear casters are designed in size and strength to accept payload and battery. The mid-section of the chassis is taller and hosts not only the drive electronics and drive-train, but also the camera, LiDAR and GPS sensors. Bender is steered via independent modulation of the two motors steer.

Suspension

Dynamic loading is reduced by velocity limitations and weight containment. Pneumatic tires are sufficient suspension for the otherwise rigid design.

Weatherproofing

Team bandwidth and the scope if the IGVC project relegated weatherproofing to the "hope for the best" category. Team "planning for the worst" is tactical, rather than strategic, and will unfortunately rely on duct tape and garbage bags.

ELECTRONIC AND POWER DESIGN

Overview

A 12 V DC deep cycle marine/RV battery that accommodates multiple discharge/charge cycles anticipated and has threaded terminal posts to simplify electrical connection powers all systems aboard Bender.

Power distribution

All components are connected to the common ground, and either directly to the battery's 12 VDC rail or to 5VDC provided by the laptop computer's USB ports.

Motive Power

Two VIX FR801-001 motors, produced by CCL Industrial Motor Limited produce a nominal 64 Oz-In of torque at 27 A of current. These motors provide maximum power is 2655 rpm[1], and drive 12.76 to 1 gearboxes which reduce axle speed and enhance torque. This approach allowed moderately priced motors to deliver the torque, speed, energy consumption and ground clearance needed for this competition.

Electronics

CPU. An ASUS Republic of Gamers (ROG) with Intel 3rd generation Core™ i7 processors and an NVIDIA GeForce ® GTX 670M Graphics Processing Unit (GPU) is Bender's CPU. This computer's performance and configuration is ideal for our vehicle. Four USB3.0 ports power and communicate with collateral components, eliminating the need for a 5VDC source. The ASUS ROG includes optimized thermal management, allowing it to remain at peak performance over a wide environmental range. A small power inverter has been added to constantly charge the laptop from the 12VDC battery, rendering laptop-only recharge unnecessary. Strategic partition of software across the of the laptop's rotating hard disk and internal solid state drive dramatically impacts processing performance of selected systems.

Motor Control. An Arduino Zero receives data from various sources and produces a Pulse Width Modulation (PWM) signal to drive the vehicles two motors via Victor 888/Victor SPX motor controllers. The controllers recognize duty cycles between 1% and 60% as reverse rotation while duty cycles between 64% and 100% impart forward rotation.

Any duty cycle between 60% and 64% translates to no movement, or neutral. The microcontroller also powers the safety light and encoder measurements.

The microcontroller provides for multi-protocol communicating with the GPS, wheel encoders, and motor controllers, and is integrated into ROS through an Arduino node capable of subscribing to and publishing multiple topics.

Sensor Hardware

Bender's autonomy relies on an integrated set of sensors to allow for navigation. The vehicle must detect multiple obstacles and move accordingly to reach the destination.

Imaging: The Intel Realsense D415 camera is a stereo imaging camera developed for robotics applications. The camera uses RBG cameras and infrared to generate information about the color and depth of an image. This is translated to a ROS PointCloud2 message containing RGB-d (RGB with depth). This image is then processed to detect the lines.

Obstacle Detection. Bender detects obstacles using a Hokuyo URG-04LX-UG01 2-D planar LiDAR, optimized for semi-predictable objects such as traffic cones of varying color, but also capable of detecting bushes, trees and man-made obstacles.

The 2-D planar sensor is accurate to ±3% for distances beyond 1m and scans 240° to 5.6 meters. The sensor consumes a small amount of power and is lightweight, making it ideal for a mobile vehicle. Unfortunately, the Hokuyo URG-04LX-UG01 is designed for indoor use and can be saturated by outdoor lighting. Bender utilizes filtering and strategic shading to minimize the interfering solar noise[2] in order to allow use of this lower cost LiDAR component.

Positional Sensing: The Garmin GPS 76 is a handheld GPS unit that outputs NMEA strings via a USB adaptor connection. The NMEA string is interpreted by ROS to generate a positional fix. This information is then used in the path planning algorithms.

Safety Devices. Bender is equipped with manual and wireless emergency stop (E-stop) systems. A manual E-stop switch is in series between the battery's positive terminal and the motor/motor controllers, and immediately interrupts all motive power when engaged. Though Bender can be stopped using the wireless Xbox 360 controller to send a neutral PWM signal, a 12V 10A Relay with RF Remote Control is integrated to disrupt power as the software-independent remote shutdown required by IGVC rules..

SOFTWARE AND MAPPING

The Robot Operating System (ROS) is used to connect all sensors through an open source library database with hardware drivers and algorithms.

Robot Operating System (ROS). ROS totally controls the vehicle. This middleware from the Open Source Robotics Foundation, first developed at Stanford University in 2007, contains many useful tools and libraries to simplify the robotics development process. Being open source, ROS encourages collaboration between uses through various forums and wiki pages. ROS provides tools developed by expert laboratories to address the complex tasks such as mapping environments and navigating autonomously.

Bender relies heavily on the partitioned nature of ROS. The vehicle operates on a series of nodes communicating with each other through a publishing and subscribing protocol. This is contrary to most other development environments where all code is interconnected regardless of intent. For a node to communicate with another within ROS the user must initiate a publisher command in the publishing node and a subscriber command in the subscribing node. This generates a ROS topic holding the published information. These topics are like C++ structures in their architecture since they contain both header information and pertinent data. The ROS graphical interface allows the user to know exactly what topics are within what nodes. The node architecture also allows the reuse of variable names without conflict.

The node architecture also allows C++ and Python code to be used together. Since each node is independent of another, one node can be written in C++ while the other is written in Python. The passing of topics through publishing and subscribing is handled through ROS specific protocols and therefore is not affected by a specific node's language.

Linux Ubuntu 16.04 LTS. Ubuntu 16.04 LTS Xenial Xerus is an open source operating system based on the Debian Linux architecture, and distributed by Canonical Ltd. Importantly Ubuntu fully supports ROS. The team utilized many open source software packages available for Ubuntu. An adaptation of QT Creator designed specifically to work with ROS was used as an IDE to develop proprietary ROS content efficiently.

Lane Following. Bender uses the Intel Realsense camera and the Intel-provided ROS node to create a PointCloud2 topic containing color and depth information. This is then sent to MATLAB for processing.

MATLAB is used to process the received images and pick out the white lines. MATLAB is ideal because it contains thousands of complex and stable algorithms for robotics applications. Bender relies on a sponsored MATLAB license for explicit use in robotics and autonomous vehicle development.

The Robotics Systems Toolbox bridges the gap between MATLAB and ROS. This toolbox creates a MATLAB node within the ROS master node that communicates using the standard ROS protocol. Data can be published and subscribed using MATLAB commands. In certain applications, this simplifies the communication process within ROS.

Image processing is intensive and not within the capabilities of this team using C++ and open source libraries such as OpenCV. MATLAB's Image Processing Toolbox makes lane detection feasible. Data is received by MATLAB from ROS. The photo is thresholded against a certain whiteness criteria, a value from 0 to 255, to create a logical image array displaying only white objects. This process marks the white lines as a Boolean True value.

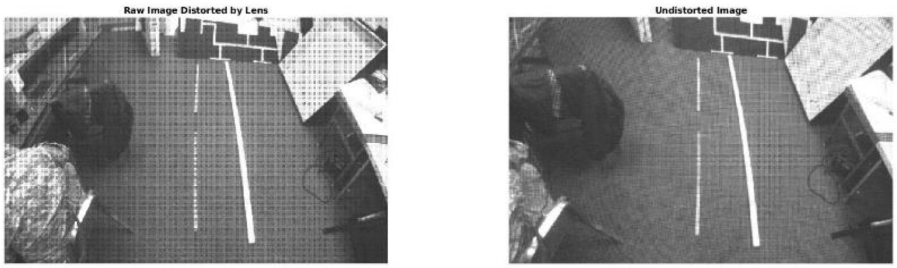

Figure 1: Raw Camera Image and Processed Image

Figure 1 shows a raw image and an undistorted image. MATLAB allows for lens distortion correction through a built in function.

MATLAB code translates the processed PointCloud to a ROS message. This message is passed to the navigation stack as an obstacle to be avoided. Thus, the vehicle will stay between the lines.

Obstacle Avoidance. LiDAR illuminates a target with laser beams and measures the return time and signal wavelength to provide information about physical surroundings. LiDAR systems can detect a range of materials including non-metallic objects, rocks, rain, and cloud[3].

LiDAR communicates to ROS via the "urg_node". This is a ROS node designed specifically to take data from Hokuyo LiDARs. The data, published in the LaserScan format contains intensity data and a vector of distance measurements, one for each angle increment. This data is utilized in the ROS Navigation Stack. ROS's built in data visualization tool, Rviz, allows LiDAR data to be seen in relation to the vehicle's position as shown in Figure 2.

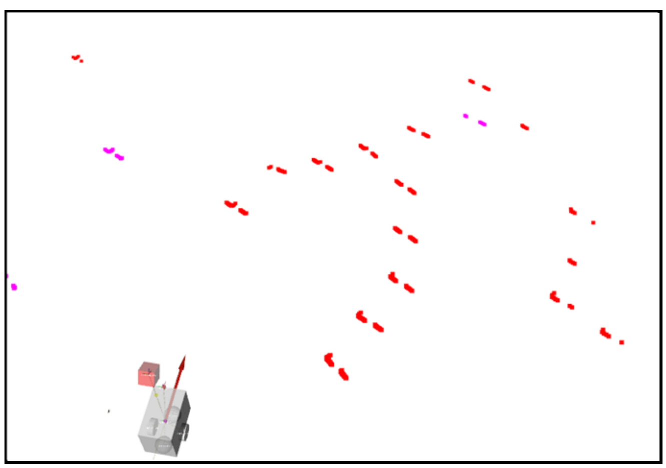

Figure 1: LaserScan Data Visualization in ROS

Mapping via Navigation Stack Path Planning. Bender uses the Navigation Stack, set of nodes parameterized and customized by the user to manipulate a differential drive robot. LaserScan, PointCloud (a 3-D collection of data), and Odometry data can be employed.

Bender utilizes two LaserScan topics and one Odometry topic. A LaserScan is an ROS data type used for passing device specific information, distance data, and light intensity data received from a LiDAR. Odometry data gives information about the robot's distance traveled and current velocity. Their use allows the robot to localize itself in a known or unknown map. The Navigation Stack, using Odometry and LaserScan data, marks for the robot to avoid. ROS then employs path planning algorithms to execute the most efficient route to a given location. The movement commands are given as an x, y, and z velocity that are translated into PWM signals by a vehicle-specific node.

The main component of the Navigation Stack is the "move_base" node. This initializes two costmaps, a global and a local. A costmap is a representation of the vehicle's perception of obstacles to be avoided. This map is marked and cleared by the LiDAR and camera data. The user defines a radius around each obstacle for the vehicle to avoid. This provides a margin of error in measurement and localization of each obstacle.

Odometry. Odometry is employed in vehicle path planning. Information is provided by optical wheel encoders and an inertial measurement unit to provide robot position and current velocity.

The US Digital E4T Miniature Optical Encoders utilize differential measurements to track wheel rotation[4]. Arduino code transforms this into the odometry information needed for path planning and obstacle avoidance. The encoders connect directly to a specialized shaft turning at the same rate as the wheels. An encoder measures motion or position using optical sensors that generate pulse trains. A and B channel signals are generated to allow calculation of both speed and direction, by using phase differences and number of pulses on the two channels. Wheel encoders are inherently inaccurate because they measure shaft rotation and not vehicle movement. Since Bender operates in an outdoor environment, it is possible that the wheels will lose traction and turn without translating into actual vehicle movement. An Inertial Measurement Unit and an Extended Kalman Filter compensate for wheel slippage.

The Sparkfun Nine Degree of Freedom (DoF) Inertial Measurement Unit (IMU) uses a SAMD21 microprocessor in conjunction with a nine DoF sensor to provide 3-axis accelerometer, gyroscope, and magnometer information[5]. The accelerometer measures the vehicle's actual motion in the x, y, and z direction.

Filtering is accomplished with the "robot localization" node. This node subscribes to raw odometry data generated by the wheel encoders, the IMU data generated by the Sparkfun IMU, and a visual odometry package generated from the camera and various ROS packages. The filter generates an ROS topic, "odom_combined", that loosely couples all three odometry sources together to create a much more realistic representation of the robot's special movement.

FAILURE MODES, POINTS AND RESOLUTIONS

Failure analysis of the overall vehicle system and sub-systems was limited by a compressed development schedule over a very busy school year. None of the team members had any IGVC knowledge prior to choosing the competition as their senior project in September 2017. The vast majority of testing has been via Gazebo simulation, as explained in the following section of this report. Vehicle safety concepts are those set by the competition rules. No other safety strategy was developed.

SIMULATION

Gazebo

Gazebo, an Open Source Robotics Foundation simulation product with ROS interface was utilized to simulate Bender's design and interactions with the virtual competition courses. Gazebo, first developed in 2002 at The University of Southern California for simulating robots in outdoor environments, employs the Open Dynamics Engine, a high-performance library for simulating rigid body dynamics. It interfaces with ROS in the same manner as physical hardware. The use of Gazebo allowed rapid implementation of navigation algorithms without the need for physical hardware. This radically compressed development time and ultimately, made competition in the 2018 IGVC possible.

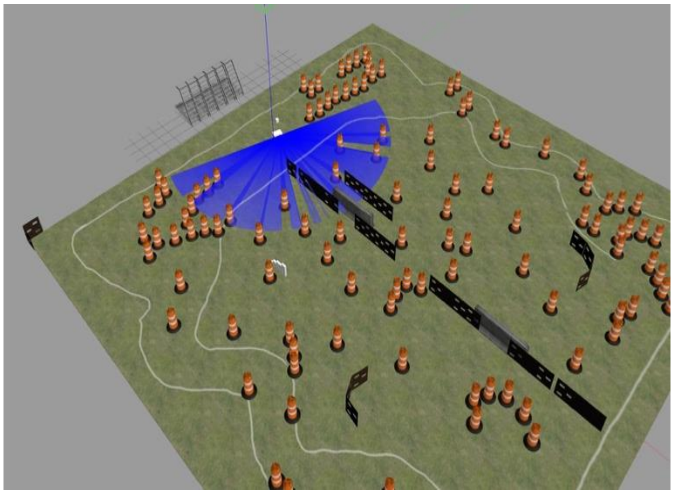

Figure 32: Gazebo Model Bender on an Outdoor Course

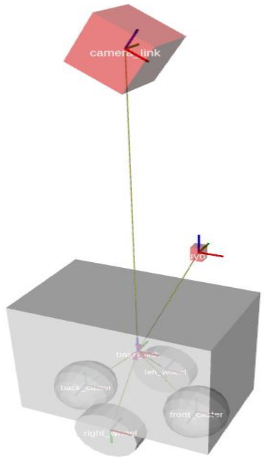

Figure 4: Simulated Model of Bender

Figure 3 shows Bender in the simulated environment. Figure 4 is of Bender within the simulation. The robot model is implemented in the Unified Robot Description Format (UDRF). The barrel cones and white lines are similar to those expected in actual competition. This is extremely useful as construction of a scale practice course is not possible at The Citadel. "Gazebo Bender" can navigate any course from any computer, allowing algorithms to be rapidly tuned.

Simulation Advantages

Most importantly, the simulation translates to real hardware. Except for timing parameter, the algorithms used in ROS are unaware that a simulation is occurring. LiDAR is simulated to exactly match the Hokuyo model. The camera models the TIS camera in resolution, focal length, mounting point, and orientation. This allows direct interchange of ROS code between simulation and physical hardware.

Bender navigates the simulated course autonomously through the Navigation Stack but can also be controllable by an Xbox 360 controller. Doing so, using the ROS joy node and the teleop_twist_joy node allows the user to map the environment and simplify navigation development.

PERFORMANCE TESTING TO DATE

At the time of this report, Bender is untested in fully autonomous mode. This is in part due to the simulation-dependent design approach adopted by the UpTheCreek2018 team but has also been delayed due to decisions affecting imaging and odometry. The deployment of stereo cameras and new wheel encoders came late in the spring 2018 term due to discoveries made during simulation. Testing has been confined to the following:

Automation

Bender motive capabilities have been extensively tested since early in the spring 2018 semester. It has been driven using a wireless X-box controller many times without payload. Testing with payload has not been accomplished but is not anticipated to be a problem due to the reuse of the 2016 chassis.

LiDAR

Data acquisition with LiDAR has been extensively tested since early in the 2018 spring semester, culminating with a detailed mapping of the third floor of Grimsley Hall at The Citadel. Bender was driven through all hallways collecting LiDAR data and building a visual map of the hallways and doorways. Successful compilation of this detailed visual map served as a portion of the team’s senior design project demonstration. Full sunlight testing remains and is expected to present problems. A sunshade like that used by the 2016 team has been installed in anticipation of these problems.

Image Capture and Processing

The binocular camera was the most recent addition to Bender’s arsenal. Images have been captured and processed, and resulting boundaries established and treated as obstacles. Image capture and processing are proven capabilities.

GPS

The GPS approach has recently been simplified. NMEA strings are parsed for location use. An earlier, similar but different approach proved too clumsy. This is an unproven capability.

Autonomy

Autonomy is unproven as of the date of this report, but is an expectation prior to the team traveling to the competition.

VEHICLE COST

As detailed earlier, some key components from prior IGVC vehicles were reused on Bender to defray costs. The following Bill of Materials documents the complete material costs.

Description	Qty	Part Number	Supplier	Unit Price	Extended Price
Robot Chassis	1	001	Citadel	$250.00	$250.00
LIDAR	1	URG-04LX-UG01	Hokuyo	$1,040.00	$1,040.00
Camera	1	RealSense D415	Intel	$149.00	$149.00
GPS	1	Venus638FLPx	SparkFun	$45.95	$45.95
GPS Antenna	1	Venus816	SkyTraq	$12.95	$12.95
Battery	1	HP24DC	Duracell	$86.99	$86.99
Arduino Microcontroller	3	Uno Rev3	Arduino	$22.00	$66.00
Laptop	1	ROG GL5 Series	ASUS	$1,500.00	$1,500.00
Laptop Power Supply	1	A32NI405	EBK	$299.00	$299.00
RGB Light Sensor	1	ISL29125	SparkFun	$8.00	$8.00
Inertial Measurement Unit	1	Atmel SAM D21E	SparkFun	$45.95	$45.95
Encoder	2	E4T	US Digital	$24.81	$49.62
Encoder Breakout Board	1	LS7366R (TE-183-002)	SuperDroid Robots	$45.68	$45.68
Molex Connectors	2	CA-MIC6-SH-NC-1	US Digital	$35.50	$71.00
Wireless Controller	1	Xbox 360-JR9-00011	Microsoft	$45.61	$45.61
Controller Receiver	1	Xbox 360-882224248495	Microsoft	$5.99	$5.99
Motor	4	FR801-001	CIM Robotics	$27.99	$111.96
Motor Controller	2	Victor 888	Vex Pro	69.99	$139.98
Wheels	2	490-325-0012	Lowes	$39.98	$79.96
Wheels (Caster)	2	GACK04KDSX	Lowes	$49.98	$99.96
				TOTAL	**$4153.60**

INITIAL PERFORMANCE ASSESSMENT

Bender's steering and speed are proven capabilities, as are LiDAR and image data acquisition and processing under interior lighting conditions. A dedicated push is underway to complete integration. A successful qualification run, per competition rules is required prior to travel to the 2018 IGVC in just a few short weeks. Much work remains.

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