The City College of New York

BENDER

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Faculty Advisor Statement:
I certify that the engineering design on the Bender robot by the current student team has been significant and was awarded credit in a senior design course.

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Introduction

The current Autonomous Vehicle Design team of The City College Of New York is a group of the top senior students interested in designing and creating a vehicle that can perform its own navigation functions. This project, to construct an intelligent ground vehicle, required knowledge of electrical, mechanical, and computer engineering as well as computer science. The multidisciplinary team has applied the theoretical knowledge that they have acquired in class to solving real world design problems in a hands-on environment. This is in the form of the annual IGVC competition to build a robot that can self-navigate a complex, randomized outdoor environment. The robot's name, Bender, comes from the name of a robot on the popular animated series, Futurama. Like, its cartoon counterpart, it is autonomous, except it is using gps, an electric wheelchair base, a laser and Player / Stage programming in Linux.

Design Process

The team's design process was geared towards making the most robust robot that it could. The robot would need to be able to work with our algorithm implementation, as well as be able to support multiple sensors. The previous CCNY team's Beaverbot worked to minimal expectations, so an entirely new one was needed.

The new design would have to be adaptable such that improvements to the system could easily be made. As a result, it was determined that a quality platform would be required, on which the sensory system could be mounted and utilized. After reviewing the work done in robotics over the years, both for IGVC and other purposes, it was decided that a wheelchair platform was best suited to the team's needs. Since electric wheelchairs are already controlled through electronics, the team would be able to replace that control mechanism with a customized control system.

Designing a frame to support the sensors, while still being stable and protecting against rain and wind, was challenging. The design took into account the size, weight, mounting method, and compartment arrangement. The minimum length and width of an IGVC robot is 3 feet by 2 feet, so to be on the safe side the bumper extends both of these dimensions by 2 inches (38 inches long and 26 inches wide.) The maximum height is 6 feet, so our design puts the frame at 5 foot 6 inches, giving enough of a buffer to position the GPS antenna on top. There is no IGVC weight criterion, so the only weight considerations were making sure that the center of gravity stays extremely low to prevent rollover. Since the drive unit is 12 inches tall and contains the motors and SLA (Sealed Lead Acid) batteries, this was relatively easy – our two heaviest components other than the drive system are the laser and the payload (a cinder block), and these have been mounted roughly where a wheelchair rider's lower and upper legs would be. The weight of all other components is negligible in comparison and decreases with height. The end result is that in field testing Bender can make a full speed turn on 25 percent grade on grass and not be in danger of turning over (this actually had been an issue for Beaverbot, and the robot was actually flipped trying to get it to competition).

In order to stabilize the mounted frame, damping mounts were placed along with springs, between the frame and platform. As for protecting housed equipment, plexiglass was cut to size and mounted with flip-up action. This allowed the equipment to be safe from wind and rain while still allowing easy access to them.

Bender's aluminum upper frame was designed to keep the desirable features of the previous design – elevation for the cameras and physical isolation for the GPS and heading sensors – while solving some of the Beaverbot's problems. The bumper was designed to meet the size minimums and maximums in the IGVC competition rules. The previous experience of some 2008 team members in robotics competitions is that the best design in the world is nothing if it doesn't allow the team to qualify to enter the competition, and if the design is not created with those qualifications in mind it is easy to get close to the end and realize that the design fails one of the specifications.

The frame material is square one inch tube aluminum, which is welded together. While the P-220 Quickie drive system can handle a 300 pound person plus a significant additional mass in medical equipment, less mass in the frame allows for a lower center of gravity making Bender more maneuverable. High quality aluminum welding was beyond our team's capabilities, so this was done by an outside source who generously donated their time.

All of the sensors to be used on Bender are relatively delicate and could be destroyed if the became the point of contact in a collision (Bender has considerable mass and enough power to move a 300 pound person at 7 mph). The frame was designed so that an aluminum bumper extends out on all sides at least 2 inches further than the rest of the frame at a height of 12 inches. The upright section of the frame should therefore never become a point of contact with walls or doorways as long as nothing is mounted to its sides. Likewise, our most expensive sensor, the SICK LMS scanning laser, is more or less caged by the frame on all sides, even when the frame is detached from the drive unit. The frame, generally speaking, is designed so that if the robot was flipped, no sensors could make contact with the ground, assuming it is close to level.

Suspension

The 2008 team made resolving jitter problems in the machine vision system a high priority. There are certainly mechanical as well as algorithmic solutions to reducing camera jitter (for example Steadicam technology on camcorders) but the best solution is not to create a problem in the first place. The Quickie P-220 wheelchair platform was chosen because of its robustness as an outdoor chair, and one of the benefits of this choice is the large pneumatic tires that provide a much smoother ride than the small tires on Beaverbot.

The 2008 team built on this first level of vibrational isolation by making the frame a floating platform on top of the drive unit, with springs and motor mount dampeners mechanically isolating the frame.

The first design of our suspension design was simply wobbly. The mounts that were intended to give vibration isolation instead allowed side wobble as well as verticle wobble. This was solved with the addition of springs, which made a complete mass damper system, and milling aluminum support blocks to prevent the mounts moving laterally.

The second iteration using 50 lb load motor mounts also had problems with its time constant which was noticable in machine vision, though much improved from Beaverbot and the first design. After an inadvertent high speed crash test, the team also found that the motor mounts we had first used, which were approximately an inch tall, were highly vulnerable to shear in the event of a collision. In the second iteration of the design these were replaced with smaller denser mounts and the springs were correspondingly shortened, to provide a system more resistant to shear and oscillations.

Field tests have shown that this corrects the vibrational problems that plagued Beaverbot's machine vision implementation. This design should also greatly reduce wear and tear on electrical connections and subsystems due to vibrations, which is always a problem in any motor vehicle design for off-road vehicles.

Sensor Placement

One of the main issues in any autonomous robotics implementation is localization and mapping. These are several distinct issues – determining where the robot is, what its heading is, what its current velocity is, determining how this compares to where it has been, and fitting this data to a more global map of the world.

In designing the frame one of the principles was that the team should attempt to make mapping issues easier by placing the sensors along a common vertical plane. This means that the X-Y coordinates of each sensor will share a common origin, making the math involved in placing each sensors' data in a common map simpler. (IGVC is essentially a two dimensional problem, so elevation is not an issue.) All of the sensors also are mounted on the centerline of Bender (for binocular vision the midpoint of the field of view will be on this centerline.)

The laser was located at a plane near the ground to be able to see shorter obstacles. The laser can be dazzled by glare from the sun, so the team decided that the frame should also be designed to shade the laser from glare (also a consideration for the vision system). In designing the adapters for the Quickie frame, the mounts were made so that Bender has a slightly elevated front. This design decision was made because pneumatic tires will sag slightly under load, and most of the load will be over the front pneumatic tires. It is crucial that the laser have a horizon that does not intersect the ground within a distance of 50 meters. To prevent having to shim the laser's orientation later, we decided to give Bender a slight upwards slope (if the laser is reading 2 inches higher at a distance of 50 meters this will not be an issue.)

The antenna for the GPS system is being placed as high as possible, to give the best possible physical isolation from the motors as well as unobstructed line of sight to satellites. Antennas can have passive reradiation, so the other sensor that is sensitive to fields, the Xsens orientation sensor, is placed at the midpoint of the frame at least a foot from the GPS antenna and above all of the power systems. The choice of an aluminum frame should also help here, since aluminum is a non magnetic material.

At this point in time the 2008 team still intends to implement a sonar system for close range obstacle sensing. Sonar requires many sensors in an arc to provide useful data, and the mounts for this system will be placed on the inside edge of the bumper to protect them. Since sonar sensors use a cone of sound, the Ping transducers will need to be elevated above the bumper so that they don't see the bumper itself.

To aid in localization, the 2008 team decided that it would be crucial to have wheel encoder information. Heading sensors and GPS both are good sources of data, but they are subject to error, and the Pioneer motion algorithms that exist in player-stage count on the position interface returning wheel encoder data. To make this possible, the team removed the failsafe motor brakes that were mounted at the shaft ends are adding shafted 2 channel differential encoders (this will elaborated further in the section on platform modifications.)

Drive System – Adaptations and Modifications

Base Selection

The drive system being used on Bender is a new Quickie P-220 electric wheelchair base with no chair hardware. The base is designed to hold many types of chairs, and is capable of carrying bariatric (i.e., morbidly obese) patients who often have other health issues and therefore can also require additional heavy medical equipment like oxygen to travel with them. In other words, the Quickie is basically unloaded when carrying our frame and sensors.

The Quickie P-220 was selected because it is an “outdoor” chair, robust enough for carrying a patient over an uneven field. The chair also is expected to travel outdoor distances at speed, and has a claimed range of 16 miles with a typical patient at a sustained speed of 7 mph. The power used in carrying a patient again dwarfs the needs of our electronics, and we anticipate that our range and runtime between charges will remain close to the rated range (though this could change with the addition of headlights for the machine vision system.)

The other factor behind selecting the P-220 was that this model line was being discontinued, and was available at a lower price than the newer models. The IGVC team was able to get a deal on the purchase of the base through Gem Mobility Services who discounted the chair in light of its sale to an academic project. Gem programmed the chair on arrival from the manufacturer and also has an agreement to do some future control system tuning if necessary.

Joystick

The base came with a joystick that communicates with a control system in the chair base. Communication between the control system and the joystick are over a proprietary six conductor cable. The connector ends are Redel connectors, but the specific 6 pin configuration on the Quickie is proprietary and these connectors can only be obtained through Quickie (for extensions) or through Penny and Giles Drive Systems, the control system manufacturer (for the actual Redel ports with no conductors attached, which are much less expensive.)

For design reasons that remain unclear, the wheelchair manufacturer made the decision to have the charging port of the chair in the joystick. This makes it necessary to have a very large amperage travel through the line alongside the data, and while this could be quite dangerous for a disabled person with limited arm mobility if there was a short, it is a big advantage in designing a robot, since this single connection gives us data and a clean source of power *(see Control Systems, below).*

The chair base is considered a medical device, and consequently might be required to supply clean power (DC with no back EMF power spikes) to other medical devices. We can therefore be fairly certain that the power system for the motors and the charging system are both well isolated from the power that we will be drawing through the port on the control box *(see Power Distribution Systems, below).*

Brakes Modification

The team has attempted to modify the existing base as little as possible, so that future repairs will be fairly simple. One major modification that has been made is the adaptation of the motor shafts for encoders. The platform came with two motor brakes installed as failsafes - like the air brakes on a truck, the brakes only deactivate when given power. The control system tests for the brakes' existence on startup, and if they are simply disconnected the control system will go into fault mode. After consulting with Steve from PGDT, we decided to try replacing the brakes with 100 kOhm resistors. Experimentation showed that it is crucial that these are power resistors; typical ¼ watt electronics resistors literally burst info flames. When installed with 2 watt 110 kOhm resistors, the chair does not go into fault mode, and functions as if the brakes are in place. This allows access to the ends of the motor shafts, which is where the wheel encoders will be fitted.

Other Physical Fault Modes

The Quickie base is designed with people with multiple disabilities in mind, and so PGDT and Quickie have included many startup diagnostics that will not allow the chair to power up when it is in an unsafe state. One diagnostic that will trigger a fault mode and is not immediately obvious is that the latches to between the base and the upper portion of the base frame (the part that holds the front wheels) must be closed, otherwise the chair will go into fault mode. This is not the case with the rear latches that control the clutch connection between the motors and the drive wheels. Other fault modes can be cause by any deflection of the joystick at power up, or any wires being disconnected on the line between the joystick and the PGDT control system. The system will also go into a fault mode if the power charger is connected to the joystick and an attempt is made to power up.

Control System

PGDT is the control system manufacturer for Quickie, and the control system on the P-220 is from reviews online fairly sophisticated compared with even a few years ago. Without a control loop it would be necessary for the IGVC team to create a feedback system that would prevent discontinuities in signal from the laptop from turning into violent lurching in motion. PGDT uses a “super integrative” control system. The technical meaning of this is unclear, since attempts to get PGDT to elaborate further have been met with explanations of this being intellectual property of PGDT and proprietary information that will not be given to anyone including an academic team. Regardless, the control system seems to be some flavor of PID, perhaps without the derivative component.

The PGDT system communicates with the joystick using a protocol that is also proprietary, for what could only be marketing reasons (I.e., control of replacement parts like the joystick which can run to $500.) Since again, PGDT would not give out the details on this protocol the IGVC team decided to use the pins of the actual joystick itself as the point of entry for control data.

It is possible to create a new control system with connectors to the batteries and motors (all proprietary through PGDT) but this would lose two of the largest advantages in selecting an off the self wheelchair – the battery charging and tending system, and the electrical isolation of the motors and charging system from the electronics.

Software

The team chose to design its software around the Playerstage architecture because of its design, robustness, flexibility and community support.

Motion System

The team elected to use Player/Stage on our onboard laptop, which runs Ubuntu Gutsy Gibbon (version 7.10). Player/Stage was selected for its built-in support of many devices and algorithms that the team used, and for its ability to provide simulation that closely matches the actual environment that Bender will face during the competition. However, the software has a steep learning curve, and much time was spent figuring out the architecture of the code and adapting it to meet the challenges of the IGVC competition.

There are two modes of operation, one based on data from the GPS for the Navigation Challenge, and another based primarily on data from the laser and vision system for the Autonomous Challenge. All programming was done in C++ using Player's libraries. The team implemented the Vector Field Histogram (VFH) method of obstacle avoidance using data from the laser and sonar range finders. In this method, the robot is considered to be in a force field in which the obstacles or lanes exert a repulsive force and the destination exerts an attractive force.

Although the laser provides accuracy up to 80 meters from the robot, we only used data within 8 meters of the robot, which is sufficient for local obstacle avoidance. This data is synchronized with data from the vision system and sonar sensors to compose an occupancy grid. The value 1 is assigned to a cell considered to be obstacle-free, -1 to a cell considered to be an obstacle, and 0 if the status of the cell is unknown. The data from the sensors is combined probabilistically, with the laser being weighted more strongly than the others.

Robustness

The team chose to use Playerstage because it acts as a hardware abstraction layer; it takes care of the communication between the hardware and the computer, allowing the programmer to focus on the decisions that need to be made once that link is established (tasks such as data processing and decisions that need to be made given any piece of data.) Playerstage was used as the hardware abstraction layer because it is very robust-designed for the pioneer robot and tested on many others, the code has gone through rigorous testing and is very well maintained (both through a team of people on the project and contributers to the open source project.)

Flexibility

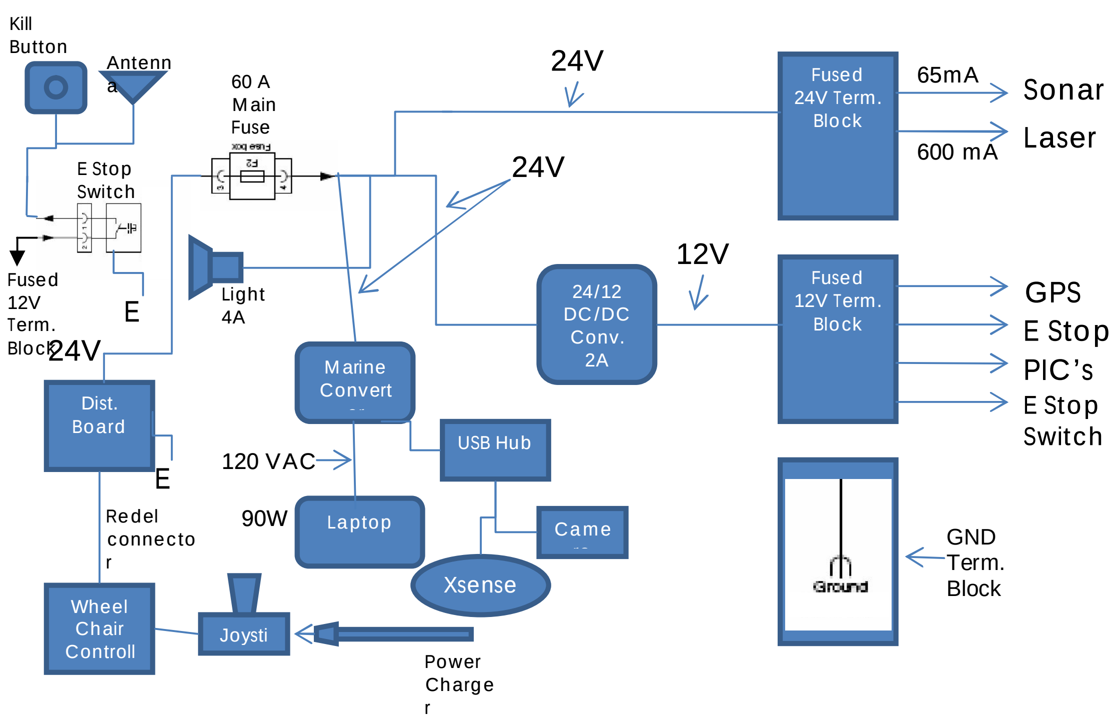
Playerstage's modular design makes it an incredibly flexible system. Playerstage treats everything (from localization functions to lasers to vision systems to logs) as a device with a unique driver, and even has options for blank drivers and writing new drivers if the user wants to use something not already in the library. Playerstage also has utilities for mapping and testing, and interfaces in multiple programming languages. Since much of the vision coding was done using Intel's OpenCV library. it was crucial to use an architecture that easily integrated outside libraries-which is something Playerstage does easily, in part because it is written in the same programming language (C,which is one of the best languages to use for real time programming because of it's speed).

Support

Playerstage was also chosen because there is a large, accessible, knowledge bank on its use. According to the playerstage website, the Player robot server is probably the most widely used robot control interface in the world. It is very widely used at CCNY and has the mailing list is also very active and full of helpful posters, both of which provided much need help when questions or problems arose, a necessity because of the inexperience of the team.

Electric Power Distribution Systems

Bender's Power System Diagram



The power distribution system feeds off of its own Redel connector into the control system. The control box has two female ports for joysticks, and one of them will continue to be used for the joystick, and therefore for controlling the robot. The spare connector which has turned out to be useless for control is instead going to be used for providing 24 VDC to all of the other electronics.

The main power source for the robot comes from the wheel chair batteries which supply 24V/80A, for a total power of 1920W. The power system is charged through the joystick which is connected to the wheelchair controller. The wheel chair controller assures that the system's batteries are equally charged and consumed.

A power line connects the wheelchair controller to a distribution board which goes through a 60A fuse/ kill switch. The line connected into the fuse diverges into four lines. Each line feeding the following components: a 24V distribution board, and 24VDC in/ 120VAC out marine inverter, a 24Vto 12V DC/DC converter, and the lights' circuit.

- The 24V distribution board will be used to power the Laser and possibly the Sonar ping sensors.
- The 120VAC line coming from the marine inverter will be used to power the laptop and a USB hub.
- The 12VDC line coming from the DC/DC converter will be connected to a 10 terminal fuse, with max terminal amperage of 1 mA, those terminals will be used to power the GPS, the Sonar and speed controller PICs and the wheel encoders, the kill button and the antenna.
- All ground lines of the power system are connected at one terminal.

The amperages of this system's elements are as follows:

Component	Amperage
1. Laser	800 mA start, 500 mA run
2. Laptop	1060 mA
3. USB Hub	
4. GPS	300 mA (at 12VDC)
5. Sonar PIC	65 mA
6. Speed Controller PIC	65 mA
7. Wheel Encoders	≈ 215 mA
8. Lights' Circuit	4 A

Safety Cutoff System

The safety cutoff system was designed to quickly and effectively shut off Bender's power supply. There are two emergency stops, one mounted on the exterior of the frame, and the other is wireless. This is to guarantee that, in case of malfunction or any unseen problems, the robot can be stopped before any damage is done to itself or objects in the vicinity.

Both the wireless and physical switch emergency stops make use of a safety feature of the wheelchair, which is that in case of any fault condition the chair will stop its motors, but will continue supplying accessory power to lights or medical equipment that are attached. Both the switch and the remote operate by opening the circuit to ground, which prevents the robot from moving again until the joystick has been physically turned off and on again. In addition, the emergency stop on the back of the robot has an additional safety feature that once switched, the circuit remains open until the switch is pressed again. Likewise, if the remote is activated, a user must hit a different button to allow the motors to run again. Testing has shown that due to reverse EMF effects the motors stop the robot from moving in less that 2 meters at full speed.

Mechanical Design

Previous experience in robotics competitions (FIRST as well as IGVC) has shown that typically when multidisciplinary teams work together on a robot, the mechanical team often finishes so late in the overall competition timeline that many important electrical, programming and general system integration issues don't receive sufficient time to get properly resolved. One of the early decisions for the 2008 team was to not have the CCNY's 2008 IGVC be a multidisciplinary effort. If mechanical students were involved for their senior design class, they would probably feel compelled to make the mechanical systems complex enough to justify their senior design credits – and this seems to be why Beaverbot had a chain drive system. The limited mechanical work on Bender has been done by the electrical engineering team working with Ghaith Abdullah and Bill Morris (both mechanical engineers) where more technical mechanical knowledge was necessary.

IGVC is supposed to be a multidisciplinary competition, however, and in designing the frame for this year's robot one consideration was that in the future a CCNY IGVC team might want to have an mechanical group design a new drive platform. The current frame was designed with this in mind, and if a new drive system is built to fit a fairly simple mounting system the entire frame should be easy transplantable (the drive system would also have to provide clean 24 volt DC power). This design will allow future electrical, programming and mechanical teams to work in parallel, and to switch over late in the process without interfering with each other's progress.

Project Parts and Costs

Item	**Retail Cost**	**Team Cost**
Electric Wheelchair	$5400	$5400
Ping sonar sensors	Already acquired	$0
Sick LMS scanning laser	Already acquired	$0
PIC 18f4550 Dev Boards	Already constructed by team	$0
Novatel GPS	$9000 - donated to last year's team	$0
3G Gyro and Heading sensor	$3000 – donated to last years team. May need replacement.	$3000?
Bumblebee stereo camera	Already acquired	$0
Laptops for programming and running robot	Already acquired	$0
Speed controller	Already acquired	$0
Tools	Some already acquired, some needed	$200
Power bus	$100	$100
Software	Open source	$0
Remote control and emergency cutoff, JAUS controller	$200-500	$500 (estimate)
Travel	$2000	$2000
TOTAL		**$11200** (high end)