Summary

Michigan Tech's entry into the IGVC known as "Autobot" is a 2 year old project resulting in a robot named "Bishop." The first year of design involved fabrication and software development from the ground up. Bishop was finished in time and successfully competed in the Auto-Nav and JAUS competitions in 2012. This past year was the second year of work and was devoted to polishing issues encountered during last year's competition and improving the software to perform better in the Auto-Nav portion. This report will cover the design of Bishop from the fabrication process up to today.

Design Overview

Bishop uses its mounted sensors to observe the world around it. These observations are sent to the onboard computer where they are processed and a map is constructed. The computer then does path finding and directs the motors to the goal state determined by the GPS coordinates of the next waypoint. The robot has 2 large drive wheels on either side, each with its own motor, centered on a virtual axel. A caster mounted in the front provides stability and allows for zero turn radius.

Sensors

Bishop is equipped with 3 webcams mounted atop the mast for detecting lines. There is also one Ibeo Lux laser range finder used for detecting barrels and other physical obstacles mounted in the front of the central housing unit. A GPS mounted near the cameras allows for accurate navigation to waypoints on the course. An IMU mounted near the E-Stop tracks the robot's local pose for use in navigation.

Computers

The only computer used is a Lenovo ThinkPad mounted with a standard dock and connected to the sensors and motor controllers via USB and Serial connection.

Design Planning Process

Design

Autobot began with a robot from a past team and the task of maintaining and improving the design. After deliberation, it was determined that too many issues were present and that an entirely new robot may be simpler. Design criteria for the new robot were based around shortcomings seen in the previous model. Large turning radius and poor stability were the most prominent issues. Wheel placement began to be the main factor for the new robot design. After modeling, many of the designs began to resemble the old robot in slightly different forms. An idea was given that a 2 wheeled pendulum robot could be created. In this design, 2 large wheels would be used that would leave enough space underneath the axle center to place all the components. To refine and confirm the design, a basic prototype was created using the motors from Autobot and other materials from around the lab. With this prototype the design was confirmed and further modeling was done. Equations were derived that combined an assumed robot tilt and related it to a proper acceleration. The robot moves and balances like a pendulum when it is at rest or moving with a constant velocity.

The drive wheels consist of two 29 inch drive wheels, one on each side of the robot, each driven by a separate motor. This design allows for a zero turning radius. The distance between the two wheels was limited to fit easily through a standard door which also improves maneuverability. A minimum ground clearance is maintained that allows the vehicle to easily traverse sand pits and clear the peaks of hills.

One proposed design feature for the Bishop robot was mounting the wheels with a camber to further reduce rolling. The camber would make the profile of the wheels have an oval profile, which would increase the robot's self-righting properties by increasing the amount rolling would move the center of gravity. The momentum of the robot would be counteracted by the height change by rotation, additional height from cambered rotation, and moment caused by the linear distance from the contact to the center of gravity. This extra force from camber would decrease the amount the robot will roll and shorten the time the robot will take to right itself. The amount of energy necessary to roll the robot to a given angle is equal to the distance the center of gravity will be raised (which can easily be found through trigonometry) multiplied by the weight of the robot (also true without camber). The idea was solid and would have helped with the overall vision of the robot but it reduced already limited ground clearance and was deemed to have insufficient payoff.

Balancing

While accelerating under the two wheel design, the tray does not hang with the center of gravity directly below the motors, as it does while the robot is at rest or constant velocity. Instead, it is suspended at an angle from its rest position proportional to the acceleration. The torque from the motors contributing to the acceleration at that time can be estimated by the weight of the robot's hanging components multiplied by the horizontal displacement of the hanging components' center of gravity. The components' center of gravity is thought of as a pendulum hanging from the motors.

The design of Bishop was based on the pendulum concept explained above. One of the key aspects of the design was that it would right itself after rolling. Rolling here refers to the whole robot turning relative to the ground without the motors rotating the axels of the wheels. The hanging components are fixed to the motors, so rolling would lift them. The robot would naturally roll back so its center of gravity is at the lowest possible point. The magnitude of the self-righting tendency can be estimated as a moment at the point where the wheels touch the ground, with a magnitude equal to the weight of the robot multiplied by the horizontal distance between where the wheel touches the ground and the robot's center of gravity.

This is a useful way to think of the self-righting tendency because it can easily be compared to the robot's tendency to roll. The primary contributing factor to rolling will be a moment at the point of contact with the ground with a magnitude equal to the *vertical* distance from where the wheels contact the ground to the robot's center of gravity multiplied by the inertial force (which itself is the robot's mass multiplied by its acceleration at that moment).

The design necessitated the use of an active balancing mechanism to keep the robot upright and stable. To this end, it incorporated a linear actuator to swing the mass of the batteries and payload relative to the robot's axis of rotation. In this way, the robot's center of gravity could be shifted to keep the robot upright at all times.

In practice, the actuator did not move fast enough to keep the robot balanced, so another solution was sought. Instead of moving the weight of the robot to compensate for changes in acceleration, the robot could be accelerated to compensate for a shift in its mass. The control theory was then similar to a Segway, with the added control variable of where the robot's mass should be placed.

To keep the robot upright, a simple PID filter was written. No special adaptations were used, as the system responded fairly well to a textbook PID implementation. The angular displacement of the robot was measured by an inertial measurement unit mounted on the robot's mast. The PID filter set point was configurable at runtime to allow for small shifts in the robot's static mass without recompiling.

A Ziegler-Nichols approach was used to tune the PID filter. The robot's angular displacement was measured and plotted with motor commands and current speed against time. The proportional gain was increased until the robot oscillated stably with the integral and derivative terms set to zero. The oscillatory period was measured, and the resulting critical gain and period were then used to calculate the final P, I, and D gains according to the formulas in **Error! Reference source not found.**. The resulting filter was fairly responsive, and performed well in indoor testing.

When the robot was taken outside, the small humps presented by the grassy surfaces presented an issue. The robot did not have enough rotated mass to account for the step in energy needed to roll over grass mounds. As such, when encountering a lump of grass, the robot would sit and oscillate, occasionally destructively. As a result, the team resorted to their backup plan and mounted a pneumatic caster on the robot. The caster provided ample stability without severely compromising maneuverability or maintainability.

Obstacle Avoidance

The method of line detection in the original robot took raw camera data, applied a Hough transform, and attempted to find a line in both the left and right cameras. By knowing that the robot was between two white lines, the software assumed that the robot was in a safe state. When a line was detected only on one side, the software would turn to attempt to compensate.

It was identified that this would fail when no white lines were present. Also, the image was not perspective corrected, misrepresenting the robot's state.

To rectify these issues a new set of image transforms were applied to the camera data in order to view the data as if it was sourced from an overhead view which allowed for several improvements. Instead of having to determine an actual "line", the software could instead just treat any sufficiently outstanding white object in the image as an obstacle, to be handled by the standard path planning algorithm. In addition, the software was now presented with an image whose coordinates could be made to correspond to those of the laser rangefinder, the two sensor data sets could be trivially combined into one world view. Path following is now an obstacle avoidance problem. Even dashed lines are handled by enforcing the robot's size during path finding.

Path Planning

Ray casting was the method decided upon to determine the longest path available to the robot in the current sensor data frame. This technique is adopted from the early days of computer graphics, wherein modeling and rendering every vertex of a 3D scene was far, far too processor intensive. Essentially, all the sensor data is composited onto a single map. Every few tenths of a degree, a ray is projected out on the composited sensor data to find the first data point detected, and the longest options are recorded. This method runs in a constant time, giving the added benefit of predictable latency, always a benefit in real-time software.

Mapping

The software in the previous robot disregarded sensor data after using it; preventing it from making more informed decisions. This proved especially annoying with the cameras, which had a limited field of view. Since the software didn't remember observations it made mere seconds ago, it never had good understanding of its immediate environment, preventing it from making intelligent decisions. Mapping helps eliminate this problem, and makes it simple to generate complex paths using Dijkstra's Algorithm. Now, backing out of a dead end becomes trivial and controlled, where the old software would have to resort to guesswork in order to safely navigate out. Switch backs, center islands and dead ends are non-issues.

Power

In contrast to the electrical systems of previous robots which ran on 24 volts, Bishop was designed to run on 12 volts. This was done with an eye to safety. The motors in the design operate happily at 24 volts, but turn at 230 RPM when running without load. With the 29 inch wheels mounted to Bishop, this translates into a speed of approximately 20 miles per hour. This is absurdly fast by any standard and defies the mandated hardware speed limit of 10 miles per hour. While this top speed is not possible to achieve under load, the larger supply voltage still presented a danger. With a 12 volt bus, the robot was inherently limited to less than 10 miles per hour.

The 12v system bus satisfied the needs of all components save the SICK LMS-291, which required a 24v source. This power requirement was met with a 12-24 volt step up module sourced from Murata-PS. Several other devices on the robot required 5 volt supplies, such as the wireless e-stop receiver. These were provided using simple linear regulators, as the devices had relatively small power requirements.

The switching system on the robot uses standard rocker switches wired to automotive relays for all large system loads. The hardware emergency stop is wired in series with the relay coil supplies for all of the locomotive components on the robot, ensuring that a hardware stop will cause the robot to stop moving immediately.

The robot is wired such that the frame is isolated in order to increase fault tolerance. While in a standard vehicle the frame is typically grounded, the extra ground wiring was deemed a worthwhile tradeoff to increase the number of tolerable chassis wiring faults from none to one.

An effort was made to increase maintainability over previous robots. Connectors were used wherever a component swap would be feasible in the field, with heat shrink reinforcement to ensure that accidental disconnect was not possible.

Useful instrumentation was also added. A current shunt was wired in series with the ground return wire in order to monitor the robot's power consumption over time. A panel voltmeter was also fitted to facilitate easy battery level observation.

Alteration History

As problems with the original design arose, they had to be addressed and the robot refitted.

No Balancing

When balancing was deemed infeasible, a caster was mounted to the front of the robot providing 3 stable points of contact without interfering with turning or navigation. While it was originally a quick fix for the competition last year, it is now a permanent feature.

Mounting System

When balancing was eliminated, the swinging tray became obsolete and cumbersome. Instead of modifying this tray, the team decided it was more viable to fabricate a new system of securing the batteries and payload. In the design search, the team determined that the best placement for the payload and batteries was still below the motors and batteries. In this position, the weight increases the overall stability of the robot and the close proximity to the center of gravity keeps the rotational momentum low for turns. With the batteries further forward, the weight on the caster is increased and the amount of "bucking" when the robot starts suddenly is decreased.

In order to create the most flexibility in the designs, the battery and payload hangers were created with separate attachments and do not rely on each other. The batteries were placed just forward of the motors and hung from the bottom edges so that they could each slide in from the ends. The payload was hung directly behind the batteries by 2 "J" type hooks welded out of Aluminum. The hooks had enough space above them that the payload could be loaded by holding it in the center and simply placing it in the hangers. Besides being much easier to load both the batteries and being more secure, locating the batteries and payload in this fashion increases the overall ground clearance of the robot. This increased clearance also solved an issue with the robot drawing too much power when driving through tall grass.

Wheel Base

As the testing was done before the competition, the robot was unable to drive through a normal residential doorway and had to be carried. The robot was also slightly wider than initially planned. To correct these navigation issues, the robot was narrowed 1.5 inches overall by moving the mast forward and bringing the motors closer. This alteration coincided with the new mounting system so that the tray width was not an issue.

Rangefinder

The robot originally used a SICK LMS rangefinder. During competition last year, it broke and a back-up was used, but left the team in a fragile position. Combined with noticeable performance issues regarding hills, the decision was made to change the rangefinder used. An Ibeo Lux provided by our sponsor is now used.

Filtering

The Ibeo projects on 4 parallel planes simultaneously allowing for a 3d view of the world. The possibility of upgrading the mapping system was explored and rejected on the grounds that the 4 planes were not sufficient to gain substantial information to outweigh the increase in complexity. Instead, we can determine the angle made between an obstacle and the robot. With this, we can distinguish between a real obstacle that should not be driven on and the gradual incline of a hill or ramp which is still navigable. One issue was the increased noise of the rangefinder. The returned distance can vary by as much as 10cm; too much for reliable mapping and potentially too much to accurately distinguish inclines. To combat this, neighboring points can be grouped together, ideally representing a discrete obstacle. Then, regression can be used to find the best fitting curve for that group and those values over written, reducing the noise.

Mounting

Along with the new rangefinder, the placement was changed; moving into the central housing unit for a higher vantage point. This change coincided with the permanent integration of the front caster allowing for the removal of the cage protecting the old rangefinder and a larger caster than the one used last year. This has resulted in easier navigation over rough terrain due to the larger radius and greater stability due to the caster being mounted more directly to the chasis.