

CWRU Cutter IV

Case Western Reserve University's Autonomous Robotic Lawn Mower

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ABSTRACT

The CWRU Cutter family of robots have been designed and built at Case Western Reserve University in Cleveland, Ohio in order to compete in the annual Institute of Navigation autonomous robotic lawnmower competitions.

In 2008, CWRU Cutter placed 3rd at the 5th Annual ION Robotic Lawn Mower Competition. In 2009, CWRU Cutter 2.0 placed 1st at the subsequent 6th Annual ION Robotic Lawnmower Competition. In 2010, CWRU Cutter C placed 1st at the 7th Annual ION Robotic Lawn Mower Competition.

CWRU Cutter IV, pronounced “crew cutter ivy,” is the most recent addition to the CWRU Cutter family of autonomous intelligent ground vehicles. The first three versions of CWRU Cutter tested the feasibility of autonomously mowing grass using commercially available sensors and computational platforms. CWRU Cutter IV focuses on minimization of cost by migrating core computational components to custom built electronics.

CWRU Cutter IV’s primary objective is to compete in the 2011 ION Autonomous Robotic Lawn Mower Competition. The original CWRU Cutter was designed to test the feasibility of autonomously mowing grass with a high quality of cut. The primary objective of CWRU Cutter 2.0 was to improve its ability to accurately and robustly mow predefined paths and perform reactive edging around stationary obstacles.

The secondary objective of CWRU Cutter IV is to provide a robust platform mobile robot platform to enable research for graduate students at Case Western Reserve University.

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TEAM ORGANIZATION

Team CWRU Cut, pronounced “crew cut,” is an ensemble of undergraduate and graduate students that perform research in autonomous mobile robotics at Case Western Reserve University.

The team’s manifesto is to continuously increase CWRU Cutter’s intelligence through improvements in algorithms, software, computational hardware, and mechanical design. In addition to providing general support for the team, each member of Team CWRU Cut team is a specialist in a specific area of the mobile robot’s autonomy. The members converge from Electrical Engineering, Computer Engineering, and Mechanical Engineering to accomplish the interdisciplinary tasks in building an autonomous robotic lawn mower.

The roles and responsibilities of the student team members are as follows:

Bradley Hughes – Team Lead, Positioning and navigation
Henry Snow – Machine vision and obstacle avoidance
Andrew Smith – Mechanical design and fabrication
Jonathan Hall – Electronics design and prototype
Edward Kreinar – Path planning and path driving

The team’s advisor, Dr. Roger Quinn, is the principle investigator of the Biologically Inspired Robotics Laboratory and is the Arthur P. Armington Professor in the department of Mechanical and Aerospace Engineering.

MECHANICAL DESIGN

CWRU Cutter is built around a MTD Products Incorporated walk-behind electric lawn mower deck. The deck has been engineered for consumer applications and features CycloCut technology. The product is sold with a 19 inch blade driven by a 24V permanent magnet motor. The inclusion of an electric mower deck over a gas-powered model provides many benefits – including reduced vibration, noise, and the elimination of a fuel system.

A string trimmer is mounted on the unit’s side. This allows CWRU Cutter to edge effectively, which increases the final quality of the cut lawn. The string trimmer is a commercial trimmer head attached to a 20V motor provided by MTD Products Incorporated. The trimmer is hard-mounted to the robotic platform at a fixed height appropriate for trimming operations.

The drive motors used on CWRU Cutter are sourced from Invacare – an electric wheelchair manufacturer. These powerful motors allow the robot to drive up and down inclines as well as navigate safely over ruts and other obstacles without decreasing speed. This is a vast improvement over previous versions of the CWRU Cutter platform that notoriously struggled to move and pivot over rough terrain and in heavy grass. CWRU Cutter IV’s drive wheels, provided by MTD Products Incorporated, feature a wide dirt tread.

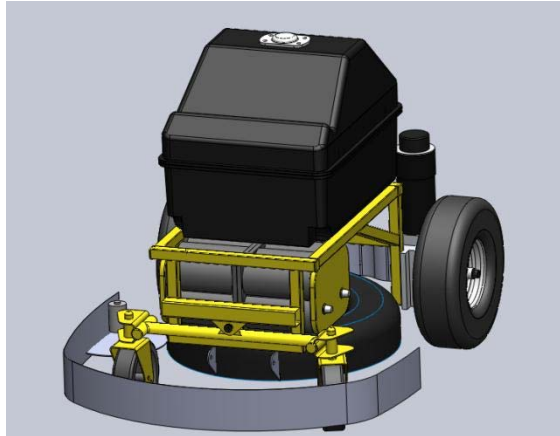


Figure 1: A CAD render of CWRU Cutter IV's robot base.



Figure 2: The resulting implementation of CWRU Cutter IV's mechanical design from Figure 1.

Overall Width	80	cm
Track Width	63.5	cm
Cutting Width	48.3	cm
Overall Length	1.09	m
Wheelbase	68.6	cm
Blade Height Adjustment Range	5 to 13	cm
Height	81	cm
Weight	72.6	kg
Battery Weight	23.6	kg
Drive Wheel Diameter	31.8	cm
Drive Wheel Width	10.2	cm
Caster Diameter	6.5	cm
Caster Width	5.1	cm
Max Linear Speed	1.618...	m/s
Max Angular Speed	±1.0	rad/s

Table 1: A summary of the physical dimensions of CWRU Cutter IV

CWRU Cutter IV's mechanical model is pictured in Figure 1. The realization of CWRU Cutter's design is pictured below the mechanical model in Figure 2.

ELECTRICAL DESIGN

E-Stop and Safety System

CWRU Cutter has two E-Stop safety chains. If any component in either chain is disabled, the corresponding subsystem is deactivated. The master E-Stop chain controls power delivered to the drive wheels. The master E-Stop is also a dependency of the blade/trimmer E-Stop chain.

The master E-Stop chain requires the following enabled circuits for operation:

1. Main E-Stop Switch
2. Software Controlled Master Enable Relay
3. Remote E-Stop Relay

The robot has a low level safety state machine that governs the software-activated E-Stop circuit. The safety state machine allows the robot to drive only after five seconds of audible alert via a siren. The controller must also provide a continuous "heart beat" monitored via a watchdog timer for the software enable relay to be activated.

The blade E-Stop chain requires the following enabled circuits for operation:

1. Blade E-Stop Switch
2. Master E-Stop Relay
3. Software Controlled Blade and Trimmer Relays

Speed Controller Selection

The selection of speed controllers directly affects several factors of CWRU Cutter including controllability, durability, and safety. A variety of speed controllers have been tested. Victor speed controllers are robust against failure but exhibit a highly nonlinear control response which makes their application difficult. Dimension Engineering Sabertooth 2x25 speed controllers are very linear and have a variety of input options. However, the Sabertooth controllers are less robust and have failed on previous versions of CWRU Cutter. Therefore, we chose to use a Roboteq AX2550 speed controller for the drive wheels. The Roboteq controller includes a variety of input options, internal circuit protection, a robust form factor, and excellent response characteristics. Victor speed controllers were chosen to soft-start the string trimmer and main cutting blade of CWRU Cutter IV.

Battery Selection

All motor and electronics power on the vehicle comes from two 12 V Optima Yellowtop marine batteries. The batteries connected in series provide the robot with a 24V power system and provide 38 amp-hours of power.

Primary consideration was given to power retention and maintenance. Lead-acid batteries are capable of retaining their charge for approximately 2 months. This makes them ideal for lawn mowing applications as a commercial unit would only be in operation two to three times in a thirty day period. Batteries with alternative chemistries can offer more capacity for equal volume and mass, though the lower cost and less complicated charging requirements lead to the decision of lead-acid batteries for CWRU Cutter IV.

Computational Platform

Previous CWRU Cutters featured a single National Instruments CompactRIO programmable automation controller and an Apple Mac Mini computer running Windows XP.

CWRU Cutter C replaced the Apple Mac Mini with a National Instruments Embedded Vision System in order to increase robustness while retaining a significant amount of computational capability.

CWRU Cutter IV replaces the CompactRIO with a National Instruments sbRIO. The NI sbRIO (National Instruments Compact Reconfigurable Input/Output Controller) platform includes two computation subsystems: a FPGA (Field Programmable Gate Array) and a 500MHz RT (Real-Time) processor. The FPGA is a common digital logic device that implements application specific high-speed timing, data acquisition, and control functionality. The real-time processor, using data acquired by the FPGA, implements higher level computations and outputs the subsequent control commands back to the FPGA. The combination of these two devices allow for a robust software platform.

The FPGA on the sbRIO interfaces directly to 110 3.3V DIO pins that are capable of operating at speeds up to 10 MHz. The FPGA also interfaces directly to up to three National Instruments C-series I/O modules that include signal conditioning.

The Embedded Vision System facilitates an interface with standard Firewire and/or Gigabit Ethernet cameras for image acquisition. The EVS-1464 includes an Intel Core 2 Duo processor and runs LabVIEW RT to accomplish machine vision processing in Real-time.

CWRU Cutter IV includes a touch panel for interaction with the user. The touch panel selected is a QSI Corporation QTERM-A7. The touch panel runs Windows Embedded CE 6.0 and executes LabVIEW applications deployed from the LabVIEW touch panel module. The unit selected has NEMA-4X and IP66 ratings which enable its exposure to water, dust, and heat.

A Dell Latitude E6500 laptop connected via 802.11n wireless network switch is used for sensor data logging and GUI (graphical user interface) applications.

SENSORS

Encoders

Encoders attached to the motor shaft of the drive wheels provide wheel speed and wheel position information. The encoders chosen for the application are Grayhill 63R256 256-count quadrature encoders. A 24 to 1 transmission on the output of the motor provides approximately 23,626 ticks/meter. The large number of ticks per revolution allow for backwards differentiation of the position with respect to time. This differenced value can be used directly as a motor velocity for control purposes. The large number of counts per meter also assists with accurate integration of the robot's position over time.

Inertial Measurement Unit

An IMU (Inertial Measurement Unit) is mounted near center of the drive axle of the robot. The selected IMU, a Cloud Cap Technology Christa IMU, is a six-axis unit that provides angular velocity and acceleration in each egocentric Cartesian axis.

The IMU provides real-time inertial measurement at 100Hz via RS-232 serial.

Differential Global Positioning System Receiver

Two GPS (Global Positioning System) receivers are used to provide the robot with a global estimate of position, velocity, and heading. Differential GPS has been selected to minimize the effects of ionospheric lensing and stratospheric bias. The L2 frequency band, used to receive Omnistar HP corrections, allows for further conditioning of position estimate at the base station.

The selected GPS receivers for our robot are Novatel ProPak-V3 units. The base station GPS antenna, used for real-time differential GPS corrections, is mounted on a fiberglass surveying tripod and is anchored within fifty meters of the operating area. A set of Freewave FGR-115RC RS-232 serial packet radios periodically transmit corrections from the base station's GPS receiver to the rover. The corrections are used by the Novatel receiver

firmware to provide a RTK (Real-Time Kinematic) GPS solution that has 1cm + 1ppm accuracy.

LIDAR

CWRU Cutter IV utilizes a SICK LMS-291 Light Detection and Ranging (LIDAR) unit mounted on the front of the robot. The LIDAR unit delivers a 180° field of view, 8 m range scans with 1° resolution at roughly 10 Hz on a 38.4 kbps RS-232 connection to the sbRIO. The LIDAR allows for accurate detection of the dog and fence obstacles.

Cameras

Two forward facing FireWire cameras are mounted to the top front corners of the robot. These Imaging Source DFK FireWire cameras equipped with CBC America Corporation 1/3 1.8-3.6MM FL.6 lenses were chosen due to their low cost and wide angle. Each camera captures 640x480 RGB color images at a rate of 10Hz for analysis on the Embedded Vision System. The mounting positions and the wide-angle of the lenses allow for at least 180° of viewing area in front of the robot up to a range of about 5 meters.

Cameras have several advantages over LIDAR. First, LIDAR units are only able to detect obstacles in one

plane, as supposed to cameras, which can see objects at any height off the ground. Second, any objects that do not reflect infrared light are invisible to the LIDAR; the cameras can typically identify any visible object. Lastly, the cameras and lenses are far less expensive than a LIDAR unit.

Bump Sensors

A new feature to CWRU Cutter IV is the addition of a contact sensor for obstacle avoidance. The sensor consists of a flexible, strain-sensing bumper suspended from the robotic platform by leaf springs. Strain data is obtained from 15cm long foil gages laminated to the bumper surface. Previous incarnations of CWRU Cutter lacked any means of sensing obstacles for both stopping and trimming operations – the addition of the strain-sensing bumper complements and serves as an ultimate back-up to the LIDAR and computer-vision based obstacle avoidance.

ELECTRONICS DESIGN

Athena Navigation Board

The Athena navigation board is named after Athena, Greek goddess and teacher of navigation. The custom navigation board has been designed in order to evaluate the use of low cost GPS receivers. A RF power splitter is

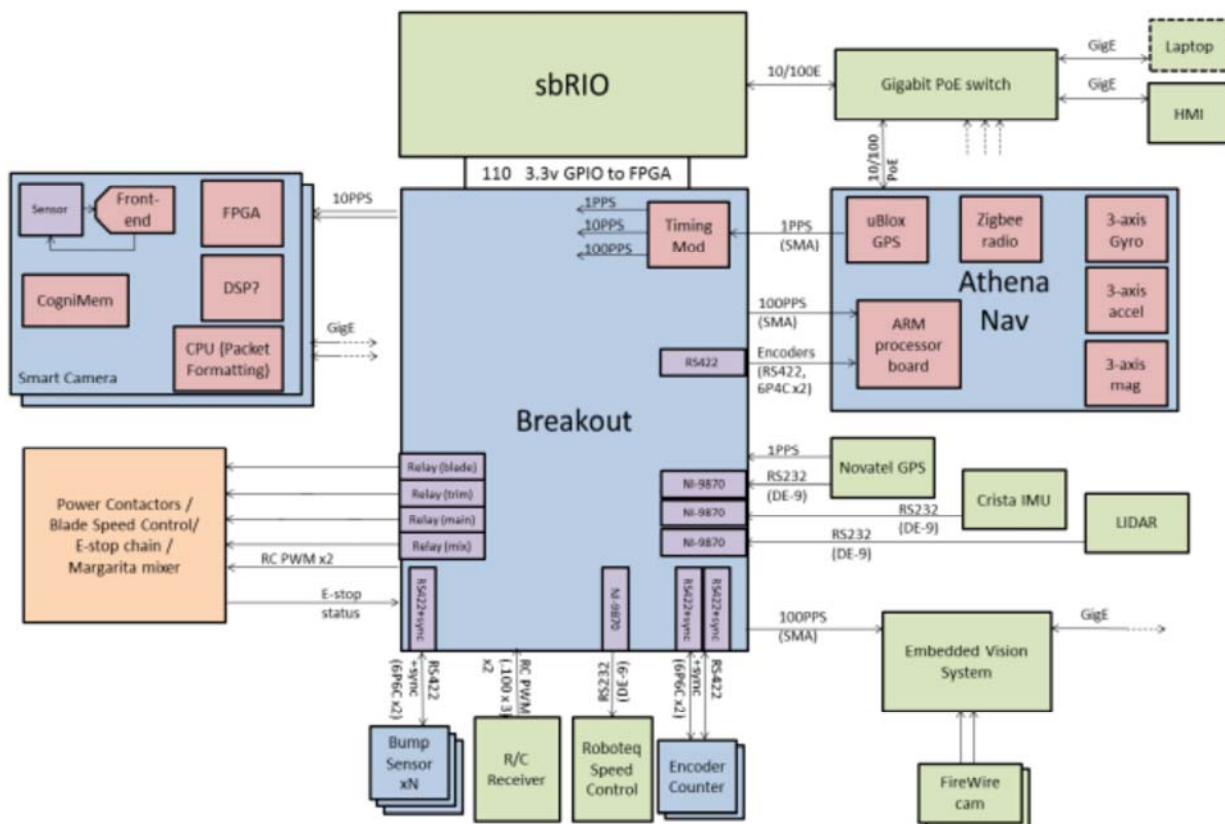


Figure 3: A block diagram representation of the integration of hardware components of CWRU Cutter IV

used to provide GPS signal to the Novatel reference system as well as two on-board GPS chipsets. The two receivers included in the evaluation electronics are the Ublox LEA-5 receiver and the Venus 634FLPx. In addition to the low cost GPS receivers, a magnetometer, accelerometer, and gyroscope are included on-board.

Perseus Control Board

The Perseus control board is named after the Greek god Perseus who killed Medusa. In CWRU Cutter's case, Medusa is a parallel to the messy wiring that is always prevalent in mobile robotics. Perseus' primary function is to provide signal conditioning and interface to the sbRIO controller. The wiring in CWRU Cutter IV is much cleaner than previous members in the CWRU Cutter family.

Palioxis Bump Sensor Board

The Palioxis bump sensor board is named after the Greek goddess Palioxis of backrush & retreat. The bump sensor board includes constant current sources that drive strain gages mounted to flexible metal bumpers. Instrumentation grade op-amps measure the voltage drop of the strain gage. The data is then sent to the sbRIO via a custom serial packet bus.

Phoebe Time Synchronization Board

The Phoebe time synchronization board is used to synchronize image acquisition on the Embedded Vision System. It communicates with both the Novatel GPS receiver and the robot's custom serial packet bus.

SOFTWARE

National Instruments' LabVIEW graphical programming language has been selected as the primary programming language. Ease of use, interactive real-time debugging, and multiple platform deployment options are only a few highlights of LabVIEW's vast feature set. LabVIEW code can be executed on Windows, Mac, and Linux operating system. Further, LabVIEW can be deployed to several embedded hardware platforms including FPGAs. The selected sbRIO PACs (programmable automation controllers) natively run LabVIEW RT on the vxWorks operating system. The touch panel runs LabVIEW Touch panel applications. Finally, the Embedded Vision System natively runs LabVIEW RT on the Pharlap real-time operating system.

The team uses a SVN (subversion) source code control repository to allow for collaboration and integration of independent software components. Redmine, a project management tool with a built in Wiki, is used for a ticket-based bug-logging system as well hub for central

documentation. Successful demonstration of project management using Redmine has led to the university's adoption of Redmine as a campus offered network service.

Architecture

A system-level hardware architecture has been designed to allow for independent development of components and is presented in Figure 3.

A modular architecture with well-defined interfaces allows for independent development of components that can be easily interchanged in order to characterize performance of any one method that can be used to accomplish a particular task.

Each computer will be outlined according to the tasks assigned to it.

CWRUCutter-Spine sbRIO

The main sbRIO PAC ensures safety and low-level autonomy for CWRU Cutter. It accomplishes a variety of tasks:

- 1. Sensor Drivers**

GPS, IMU, and encoder data are parsed in the FPGA. All critical data for low-level control of the robot is parsed at this low hardware level to avoid communication problems and system lag.

- 2. PID Wheel Speed Control**

Wheel velocity is controlled using a PID loop that operates on the FPGA at 100 Hz. Velocity commands are acknowledged at a rate of 10 Hz from the Path Driver in the RT control loop.

- 3. Safety State Machine**

Several safety requirements are checked at a very low level in the FPGA to ensure safe operation. A heartbeat is triggered from the real-time controller at 10 Hz to indicate an error has not occurred and that the main control program is running. If this signal is not received in .25 seconds, the mower is immediately stopped. The states of the E-Stop chains are measured at 10 Hz and are used as signals to pause the robot if required.

- 4. Physical State Observer**

A variety of sensors are available for use in robot state estimation and each sensor has noise and uncertainty. An EKF (Extended Kalman Filter) [2] is used to probabilistically determine the most accurate state estimate. Moreover, the Kalman Filter [1] estimates the state iteratively

in real-time – which constantly drives the uncertainty of the solution downward.

The sensors that are used in estimation of the robot's physical state are defined:

a. **GPS Position Measurement**
The GPS receiver's latitude and longitude estimates as reported in the WGS84 datum are translated into a local coordinate frame centered at the location of the base station. These local coordinates along with the receiver's reported height measurement is used as a (x,y,z) triplet to update position. The GPS receiver transmits uncertainty information in its standard positioning message and is used to formulate an estimate of the sensor's covariance.

b. **GPS Velocity Measurement**
The GPS receiver's North, East, and vertical velocities are used to update the robot's local coordinate frame velocities. A constant covariance matrix has been assigned to this sensor measurement and has been empirically tuned to provide smooth and accurate velocities.

The GPS receiver's heading estimate is reported within the velocity message and is used to update the robot's heading. A covariance measure with respect to heading is generated as a function of robot velocity in order to reject heading updates from GPS while the robot is traveling slowly. The piecewise function converges to a constant covariance estimate at velocities greater than 1 meter/second.

c. **Wheel Speed Measurement**
The left and right wheel speeds of the robot are used to update the robot's local coordinate frame velocities. The previous

state's attitude vector is used to project the left and right wheel speeds into the local coordinate frame. A constant covariance matrix has been assigned to this sensor measurement and has been empirically tuned to provide accurate velocity estimates.

d. **IMU Measurement**
The IMU's accelerations are integrated for one control cycle to provide a differential velocity update. The IMU's angular rates are integrated for one control cycle to provide a differential attitude update. A constant covariance matrix has been assigned to these sensor measurements and has been empirically tuned to provide accurate and smooth state estimates.

5. Path Driver

A design goal for CWRU Cutter is to mow straight and parallel paths as opposed to random paths. Other commercial autonomous mowers only demonstrate the ability to follow a buried guiding cable or drive sporadic, random paths.

The path driver supports a variety of path primitives:

- a. **Line**
The line segment is defined by its start and end points.
- b. **Arc**
The arc is defined by the center point of the arc and the exit point's Cartesian coordinates.
- c. **Pivot**
The pivot is defined by a pivot direction and an exit heading.
- d. **Linear Velocity and Angular Rate Pair**
A linear velocity and angular rate pair can be used to navigate for a given duration.

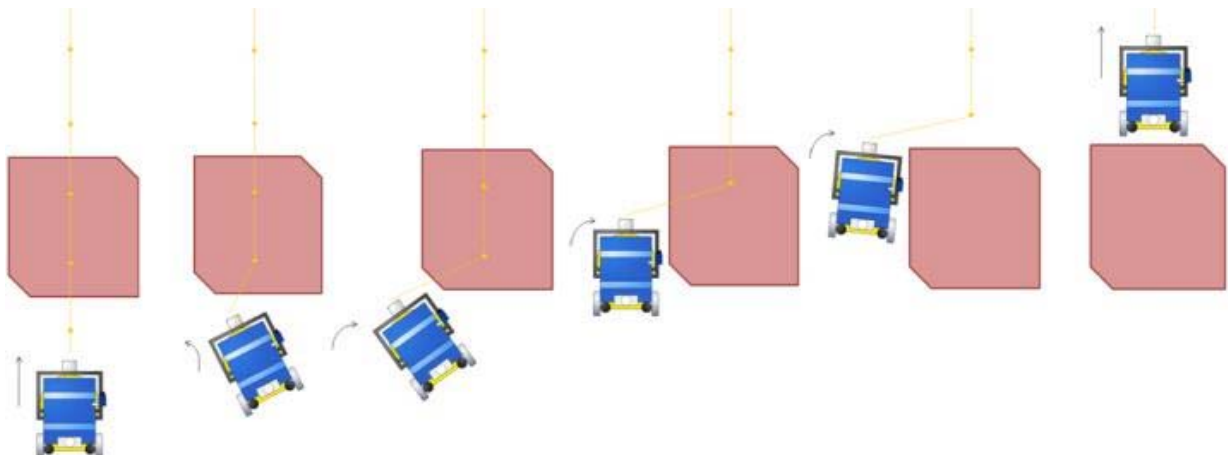


Figure 4: The resulting behavior of CWRU Cutter's reflexive obstacle avoidance. At the left: CWRU Cutter encounters an obstacle. The Veer Left reflex engages, turning the robot to the left. The path driver continuously tries to drive the robot back to the path segment. After the obstacle is passed, the path driver converges back to the path primitive.

- e. Stop
The stop command disallows the robot to move for a given duration.

The path driver uses three control terms:

- a. Heading difference error
- b. Perpendicular distance to path error
- c. Damping on curvature

[3] formally introduces the path driving algorithm chosen.

6. Polar Freespace Observer

The Polar Freespace observer acts as a filter on obstacle field observations as reported by the Embedded Vision System and the LIDAR unit. Subsequent scans are projected forward in time by the backward difference of the robot's physical state estimate. This removes noise in obstacle detection. Figure 5 illustrates the behavior of the Polar Freespace Observer.

7. Reflexes

Local reflexive obstacle avoidance has been implemented to provide CWRU Cutter with a "hand on the wall" obstacle avoidance behavior.

In order for this process to occur at a rate of 10 Hz, configuration spaces of the robot, indexed by linear and angular velocity, are pre-computed in the same representation as the Polar Freespace.

Figure 6 illustrates CWRU Cutter's local body definition and a pre-computed configuration space for a positive linear velocity and positive angular velocity.

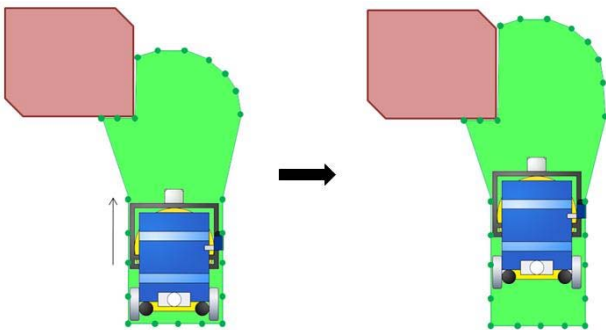


Figure 5: CWRU Cutter's Polar Freespace Observer filters subsequent obstacle observations. The robot's physical state estimate is used to project forward previous polar freespaces. The above graphic shows the inherent behavior of the Polar Freespace Observer. On the left, the robot observes the obstacle. On the right, the robot remembers its past polar freespace – behind the robot – and continues to filter the observed freespace in front of the robot.

Two reflexes use the robot's local body definition and an interpolated velocity dependent configuration space to constrain the path driver's linear and angular velocity commands. The two reflexes are the "veer left" reflex and the "stop" reflex.

a. Veer Left Reflex

The veer left reflex, detailed in Figure 4, performs an element wise comparison of the most recent Polar Freespace Observation and a scaled variant of the most recent interpolated velocity dependent configuration space. This scaling factor creates a safety buffer around the robot. If the obstacle field intersects the scaled configuration space, an iterative search is performed to decrease linear velocity and increase angular velocity. This causes the robot to slow down and turn to the left of observed objects.

b. Stop Reflex

The stop reflex performs a comparison of the tight body configuration space with the most recent Polar Freespace Observation. If an intersection is found, the robot is decelerated along a constant curvature path until it is stopped. This causes the robot to slow down along the commanded path (while continuing to avoid any obstacle the veer left reflex is obeying) while saving the robot from a collision.

The resulting behavior of the reflexes and path driver is illustrated in Figure 7. More details on the reflexes for CWRU Cutter can be found in [4].

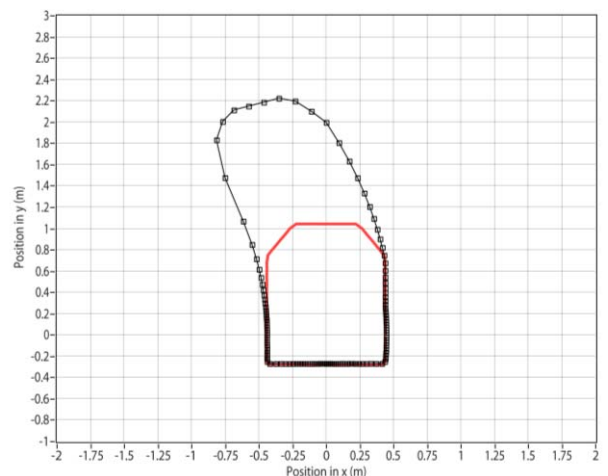


Figure 6: An example pre-computed configuration space (in black) given CWRU Cutter's local body definition (in red.)

CWRUCutter-Eyes Embedded Vision

CWRU Cutter IV utilizes two FireWire cameras and a National Instruments EVS-1464 Embedded Vision System to perform obstacle detection. The EVS captures images from the two cameras at 10Hz and processes them in real-time using SVM Feature Classification. When obstacles are detected, their locations and sizes are passed to the Mapper.

The cameras are located at the top left and right front corners of the robot and are angled down and in so that at least 180° in front of the robot can be observed. The cameras have been calibrated to allow for conversion of pixel (x,y) coordinates to real-world (x,y) coordinates in meters. The calibration routine also removes the fish-eye effect the wide-angle lenses add.

The vision control loop governs the acquisition of images from the camera. Several concurrent loops run in parallel inside it: timed triggering, camera acquisition and processing (x2), and logging. The timed triggering loop waits for a timestamp from the GPS unit, which acts as the system clock. When a signal is received, it triggers the camera acquisition loops. The acquisition loops (one for each camera) run in parallel and are responsible for acquiring the image at 640x480, scaling it to 320x240, running the processing algorithm, and sending the results to the mapper.

The support vector machine (SVM) feature classification algorithm (diagrammed in Figure 7) is a supervised learning algorithm with two components: a one-time training set and a real-time classification process. A training set of images is built ahead of time containing all possible variations of the texture to be found. From there, they are passed through a wavelet feature detecting filter and statistically classified. Using this information, a threshold on incorrect texture detection can be determined. The real-time process uses the same wavelet

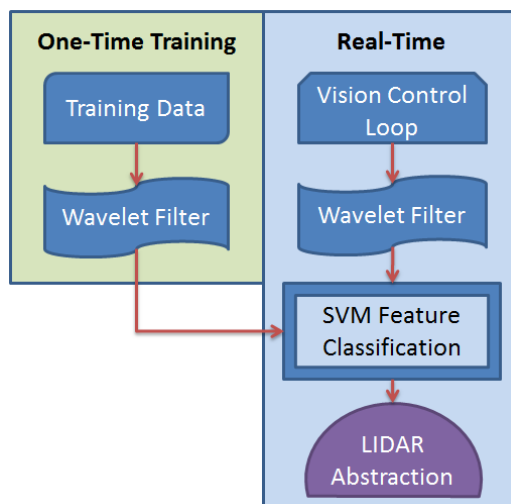


Figure 7: SVM image processing flow diagram

feature detecting filter on the live images and passes them through the SVM to classify them based off of the aforementioned threshold. If the SVM detects an incorrect texture, it will add its coordinates to an array of identified obstacles. These coordinates are then translated to real-world coordinates and an obstacle object is generated to be passed to the polar freespace observer.

CWRU Cutter Laptop – Dell Latitude E6500

A Dell Latitude E6500 Laptop is connected to the mower via an 802.11n wireless network during operation. It performs tasks that are computationally intensive and less critical to the lawnmower's operation than the real time subsystems in CWRUCutter-Spine sBRIO.

1. Logging

The laptop receives relevant information from the CWRUCutter-Spine sBRIO. Subsystems that are logged: Physical state observer, polar freespace observer, sensor input (GPS, IMU, LIDAR, images). Logging allows for post-run playback of data for ease of debugging as show in Figure 8.

2. Dynamic Path Planning

The path planner implements a cellular decomposition which creates paths that cover an entire area while avoiding obstacles. The particular procedure is fashioned after the algorithm described in [blah]. In order to avoid obstacles in an unknown environment, the general path planning strategy is as follows:

- Given a boundary, edge the perimeter.
- According to the mapper, edge all obstacles detected inside the boundary.
- Once the obstacles have been determined, perform the cellular decomposition for the entire boundary.
- Follow the complete-coverage path.

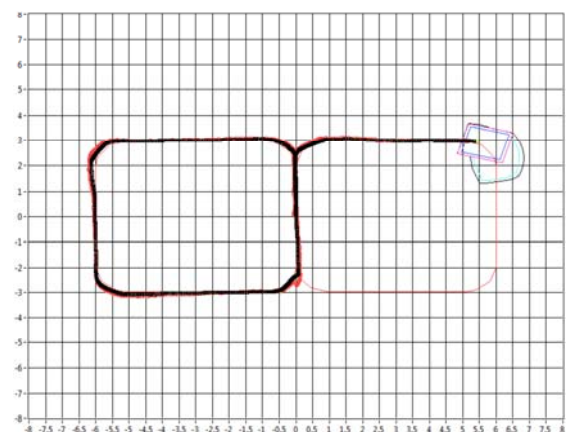


Figure 8: Playback of a test course showing the planned path and driven course

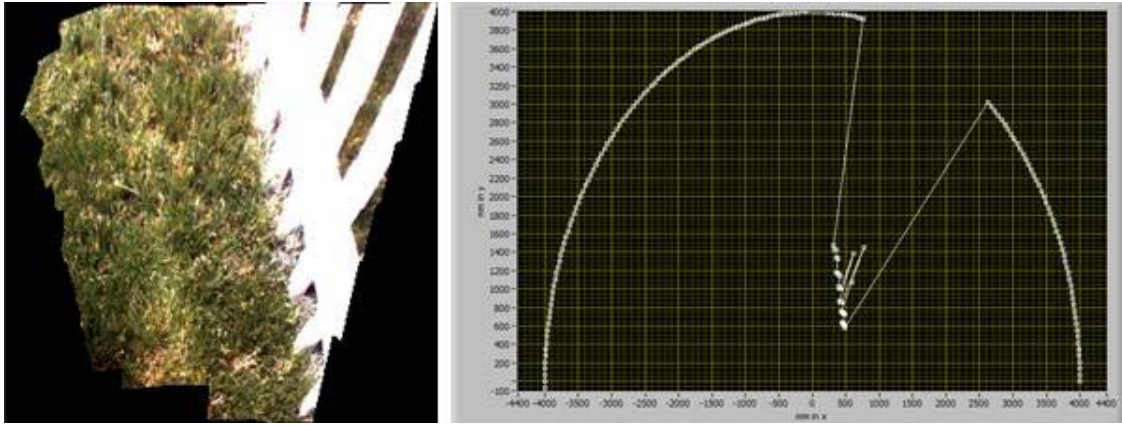


Figure 9: (Left) A calibrated image of a fence. (Right) The Polar Freespace, plotted in Cartesian coordinates, after texture analysis and calibration is performed.

Dynamic paths can be passed into the path driver to be executed, provided that every path through the current location is considered “locked” and does not change. Further work into dynamic path planning is ongoing.

RESULTS

This article presented the technical specifications of the fourth iteration CWRU Cutter – Case Western Reserve University’s autonomous robotic lawnmower platform. Emphasis on this iteration was the replacement of expensive hardware with more cost effective options that still provide robust performance. Navigation for the robot is accomplished via differential GPS, an IMU, and wheel encoders. These sensor measurements are combined using an Extended Kalman Filter to provide an accurate estimation of the current state of the robot. Obstacle avoidance is accomplished using two cameras. Vision processing software has been developed specifically for CWRU Cutter that utilizes both color and texture measures. Reflexive local obstacle avoidance is implemented using pre-computed configuration spaces and is, as a result, computationally efficient. Additionally, special care was taken this year to increase the overall robustness of CWRU Cutter.

CWRU Cutter’s robustness and technical strengths should yield a competitive autonomous robotic lawnmower entry in the 2011 ION Autonomous Robotic Lawnmower Competition.

A video overview of a previous CWRU Cutter mower demonstrating obstacle avoidance can be found in [7], [8], and [9] subsequently.

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REFERENCES

- [1] Kalman, R.E. "A New Approach to Linear Filtering and Prediction Problems." Transactions of the ASME--Journal of Basic Engineering D ser. 82 (1960): 35-45.
- [2] Grewal, M., et. al. Global Positioning Systems, Inertial Navigation, and Integration. 2. Hoboken, NJ: Wiley, 2008, pp. 394.
- [3] Kanayama, Y. and Fahroo, F., "A New Line Tracking Method for Nonholonomic Vehicles," Proceedings of the 1997 IEEE International Conference on Robotics and Automation, Albuquerque, New Mexico, April 1997, pp. 2910-2911.
- [4] K. Daltorio, A. Rolin, J. Beno, B. Hughes, A. Schepelmann, J. Green, M. Branicky, R. Quinn. "An Obstacle-Edging Reflex for an Autonomous Lawnmower" Proceedings of IEEE/ION PLANS 2010. Palm Springs, CA.
- [5] A. Schepelmann, et al. "Vision-Based Obstacle Detection for the CWRU Cutter Autonomous Lawnmower," In Proceedings of the IEEE International Conference on Technologies for Practical Robot Applications (2009 IEEE TePRA), Woburn, MA, Nov. 2009.
- [6] Schepelmann, A. Identification & Segmentation of Lawn Grass. Case Western Reserve University, Mechanical and Aerospace Engineering. Cleveland: Case Western Reserve University. 2010.
- [7] Hughes, B., Snow, H. (Producers), & Hall, J. (Director). (<http://www.youtube.com/watch?v=ToTkpbWwIk>). "CWRU Cutter C 2010." [Motion Picture].
- [8] Schepelmann, A. (Director). (<http://www.youtube.com/watch?v=vt-F5bMRSYQ>). "CWRU Cutter C Vision-Based Obstacle Avoidance" 2010. [Motion Picture].
- [9] Schepelmann, A. (Director). (<http://www.youtube.com/watch?v=58JtPdrRPF4>). "CWRU Cutter Reflexively Avoids Obstacle" 2010. [Motion Picture].
- [10] Choset, H., Pignon, P.; "Coverage path planning: The boustrophedon cellular decomposition." Int. Conf. on Field and Service Robotics. 1997.

Description	Unit Cost	Quantity	Total	Retail Total
Mechanical				
Remington 19" Side Discharge Electric Mower	\$0	1	\$0	\$169
Invacare Wheelchair motor, hub, wheel, and tire	\$0	2	\$0	\$2,400
Materials for robot chassis	\$0	1	\$0	\$100
Pelican case	\$250	1	\$250	\$250
Beverage Blender	\$25	1	\$25	\$25
Computational Platforms				
NI Single Board RIO sbRIO-9602	\$524	1	\$524	\$1,499
NI-9401 DI DIFF/TTL High Speed	\$242	1	\$242	\$269
NI-9870 4-Port RS232	\$521	1	\$521	\$579
NI EVS-1464RT Embedded Vision System	\$4,499	1	\$4,499	\$4,499
Netgear WNDR3700 Wireless-N Router	\$129	1	\$129	\$129
Sensors				
Imaging Source IS-1CI Firewire CCD Camera	\$350	2	\$700	\$700
Crista IMU	\$1,950	1	\$1,950	\$1,950
Novatel GPS System	\$3,800	1	\$3,800	\$18,000
Athena Navigation Board	\$600	2	\$1,200	\$1,200
Encoder Boards (Qty. 4)	\$400	1	\$400	\$400
Phoebe Time Synchronization Boards (Qty. 2)	\$100	1	\$100	\$100
Palioxis Strain Gage Sensor Boards (Qty. 5)	\$600	1	\$600	\$500
SICK LIDAR LMS-291	\$3,500	1	\$3,500	\$6,000
Safety Subsystems				
Remote E-stop system	\$410	1	\$410	\$410
E-stop buttons and switches	\$140	1	\$140	\$140
Power Subsystem and Electronics				
Optima D51R Yellow Top Deep Cycle Batteries	\$155	2	\$310	\$310
Battery Chargers	\$90	1	\$90	\$90
DE Sabertooth motor controller	\$125	1	\$250	\$250
Victor speed controller	\$149	2	\$298	\$298
Roboteq AX2550 motor controller	\$495	1	\$495	\$495
Circuit Breakers	\$20	5	\$100	\$100
Wiring Supplies	\$500	1	\$500	\$500
Blade motor/Drive motor contactors	\$30	3	\$90	\$90
Drive motor enable/trimmer relays	\$120	2	\$240	\$240
			\$21,363	\$41,692