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# Just Keep Rolling a Lawn

## ION's Autonomous Mowers

You might not know it from your own backyard performance, but mowing a lawn accurately and precisely constitutes a difficult systems problem, requiring centimeter-level accuracy and precision control for straight lines and smooth turns. Three student teams answered the Institute of Navigation's call to produce a smarter-than-the-average lawnmower.

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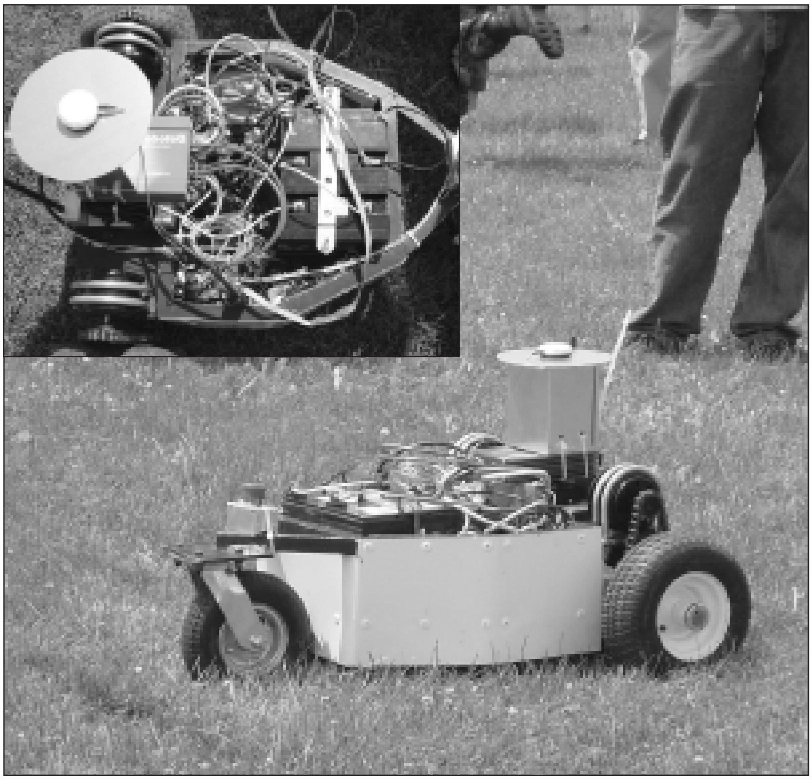
**As industry and society continue to make GPS navigation systems part of daily life, some frontiers remain unexplored. Take lawn mowing, for example. Who has not, while sweating behind a lumbering mower on a hot day, wished that a robot would do the job, while we sat in the shade sipping lemonade? The Institute of Navigation's (ION) Dayton Section, located in southern Ohio — well known for large lawns and hot, humid summer days — did something about this by hosting the First Annual Autonomous Lawnmower Competition. Sponsored by ION's Satellite Division, the event sought to inspire college students to pursue navigation-related research projects and a career in this field.**

**The competition took place June 4–5, 2004, at Ro-**



▲ **THE OHIO UNIVERSITY** entrant took first place, mowing 13 square meters in less than a minute. Inset, a view showing the GPS antenna on top of the motor controller (left), processor and datalink cards (middle) and batteries (right).

tary Park in Beavercreek, Ohio, prior to ION's 60th Annual Meeting in Dayton. The top three teams received cash awards for mowing the most lawn in the shortest time. Teams also submitted detailed reports on mower and navigation system designs, prototype cost, and projected production cost. Judges evaluated mower production costs for reasonableness, and added penalty seconds to the total time score for high-cost designs.

The teams displayed their labor-saving devices during the Annual Meeting and made 20-minute presentations, and ION publications and announcements provided international recognition. Organizers plan to feature all three mowers at ION GNSS 2004 in Long Beach, California, in September.

The Illinois Institute of Technology (IIT), Miami University – Ohio, and Ohio University participated in the inaugural competition. Student teams worked closely with faculty advisors to design and build "smart" lawnmowers that could self-navigate and cut rectangular areas of approximately 150 square meters.

The teams received world coordinates for their respective fields' corners. The lawnmowers were to mow assigned areas without going outside a three-meter safety zone. The team that cut the most grass in the shortest time, after taking into account time penalties, was crowned the winner. Any time spent outside the mowing field but within the safety zone was converted to a time penalty.

Each team had a unique design (see following sections), and all mowers cut some portion of the playing field. Ohio University's mower was the fastest and cut approximately 13 square meters of grass in less than a minute before the mower stopped near the center of the field. After observing the mower in this position for more than a minute, the Ohio University team remotely stopped its mower and informed the judges that the team's final attempt was over.

Miami University's mower actually mowed more grass than Ohio University — approximately 18 square meters — before it left the designated safety

## Design Rules

Lawnmowers must be autonomous and unmanned and cannot be remotely controlled during the competition. All navigation equipment (except a GPS differential base station), controls, and power must be carried by the lawnmower.

For safety, the maximum lawnmower speed is limited to 10 kilometers/hour.

Each lawnmower must be equipped with both a manual and a wireless remote emergency stop capability.

Lawnmower dimensions cannot exceed 2.0 meters length, 1.5 meters width, and 1.0 meter height. Cutting width cannot exceed 0.5 meter and weight cannot exceed 250 kilograms.

Lawnmower movement must be accomplished through direct contact with the ground, and power must come from combustible fuel, batteries, or both.

**Safety.** Judges conduct a safety check to test the functionality of each lawnmower's manual and wireless emergency stops, and to verify top speed. Qualifying tests verify each mower's ability to function inside the field of operation.

**Navigation**. The lawnmower can only use any or all of the existing radio-navigation systems, as well as lawnmower-based sensors (for example, inertial sensors, vision, and so on). Systems requiring local installations — besides a local differential GPS base station — are not allowed (for example, buried wires, poles).

**Teams.** Teams consist of undergraduate and graduate students with at least one faculty advisor. Interdisciplinary teams are encouraged (electrical engineering, mechanical engineering, computer science), and business/non-engineering students are invited to participate in marketing, sponsorships, and other program management functions.

buffer area and had to be remotely stopped. Since approximately 5 square meters of the cut grass lay outside the designated mowing area, time penalties were assessed, negatively affecting its final score.

The entrant from Illinois was attributed a symbolic 0.5-square meter for passing the qualifying tests and showing the robust functioning of its system; last-minute difficulties, explained later, prevented the team from demonstrating full vehicle performance.

Based on these scores, Ohio University took first place and a check for $2,500, Miami University received $1,500 for its efforts, and Illinois Institute of Technology won $1,000.

In addition to the mowing competition, each team's technical reports and production plans were judged for technical content, clarity, and format. BearingPoint, a business consulting and systems integration firm and event sponsor, awarded Miami University's team a $1,500 check for first place in the Best Report portion of the competition.

With increasing interest from the navigation community, we expect this event to grow rapidly. The next competition will take place in June 2005, prior to ION's 61st Annual Meeting in Cambridge, Massachusetts, over a slightly more difficult course, with obstacles added to the playing field. Each subsequent year will bring further challenges to the competition with the goal of developing mowers that can navigate any lawn autonomously and safely.

Besides the benefit to all of us in Ohio with lawns, the Dayton Section and the Satellite Division hope that this competition will inspire college students to pursue navigation-related research projects and careers in this field. We look forward to next year's competition, and invite anyone interested to participate or come and watch the festivities.

The lemonade is on us!

The following accounts were drawn from the student reports from each competing team.

## Ohio University

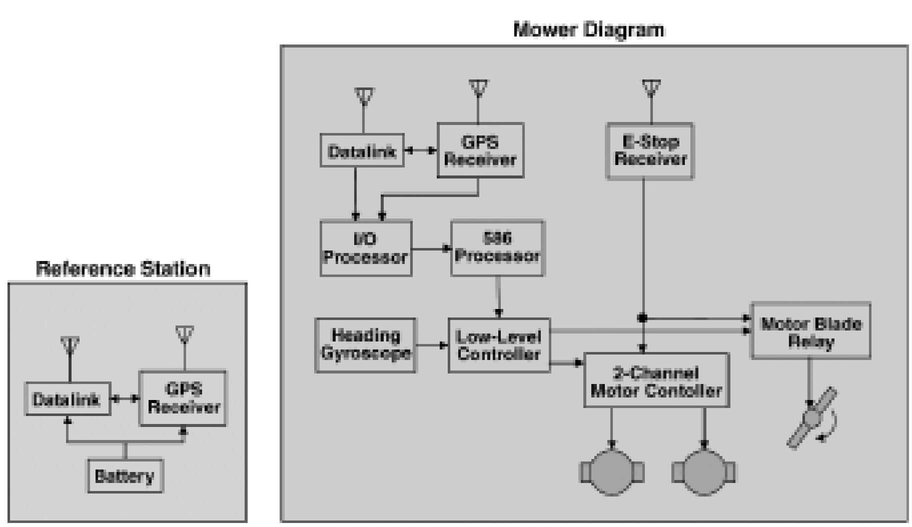
Ohio University's team designed a custom chassis utilizing a 3D computer drafting program. The chassis, constructed of aluminum tubing and plating, optimizes flexibility, space utilization, weight distribution, and the ability to turn at any desired radius. The battery-powered drive system controls both rear wheels independently and can provide up to 1.5 horsepower to each drive motor, more than enough to reach and maintain the 10 kilometer/hour speed limit. A third 0.4 horsepower electric motor turns a 19-inch cutting blade. Two 24VDC batteries keep the mower going for up to 2 hours after charging.

As accuracy is the most-weighted requirement in the competition, the team implemented a relative GPS solution to provide centimeter-level mower navigation with respect to a fixed reference station, installed on a tripod close to a field corner. The reference station consists of a GPS receiver that broadcasts GPS code and carrier phase measurements through a datalink to the mower. The reference station is battery-powered for up to 10 hours of unattended operation on a single charge. Designed as a turnkey system, it broadcasts measurements automatically after power is applied to the reference station. All GPS processing functions are implemented on the mower platform (see Figure 1).

In the mower, GPS measurements from the reference station combine with code- and carrier-phase measurements from the mower's own GPS receiver. Custom software written for the 586 single-board processor tracks the relative position of the mower's GPS antenna with respect to the field coordinates at a 1-second update rate. The relative solution is initialized using pseudorange measurements from both the reference and mower GPS receivers. Following initialization, triple-difference carrier phases maintain the relative position to within a few centimeters.

High-rate path corrections are obtained from the onboard heading gyroscope connected to a low-level microcontroller. Prior to mowing the field, GPS coordinates are input to the 586 processor, which in turn provides an optimal path generation, represented by desired waypoints, headings, velocity values, and positional thresholds for turn executions. While waiting for the assigned start-time, the gyro-

▼**FIGURE 1** Ohio University reference station (below) and mower diagrams (right)



▲ **FIRING UP** Miami University's Red Blade

scope drift is calibrated. As soon as the mower starts moving, occasional gyro drift calibrations are performed using the GPS ground track.

**Cutting Edge.** Upon entering the field, the low-level controller turns on the mower blade, which continues running as long as the mower remains within the field boundaries and the emergency stop command is not activated. The 586 processor performs high-level positioning and heading generation, producing new desired headings every second to adjust and maintain the path of the mower. The low-level microcontroller updates the two independent drive wheels through a motor controller unit approximately 67 times per second. Using differential velocity steering, the mower can precisely follow a commanded heading received from the 586 processor. The low-level controller also gets its
position from the known, commanded velocity, its heading history, and its most-recent GPS position.

A looping sequential-state machine forms the structure of the low-level controls. This state machine consists of ten states in which the mower may exist: initial state, wait and idle, wait and mow, accelerate and track heading, constant velocity and track heading, decelerate and stop, turn, shut down, turn and adjust, and decelerate and track heading. The mower will step through the corresponding state sequence depending on the situation and command given.

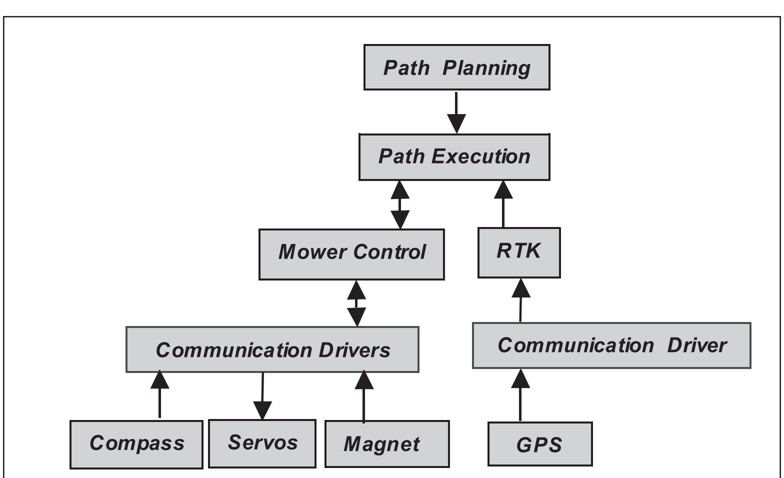
**Team members.** Jidong Huang (graduate student); Ryan Knapp, Doug Hall, Dustin Bates, Brian Becker (undergraduates); Frank Van Graas (faculty advisor).

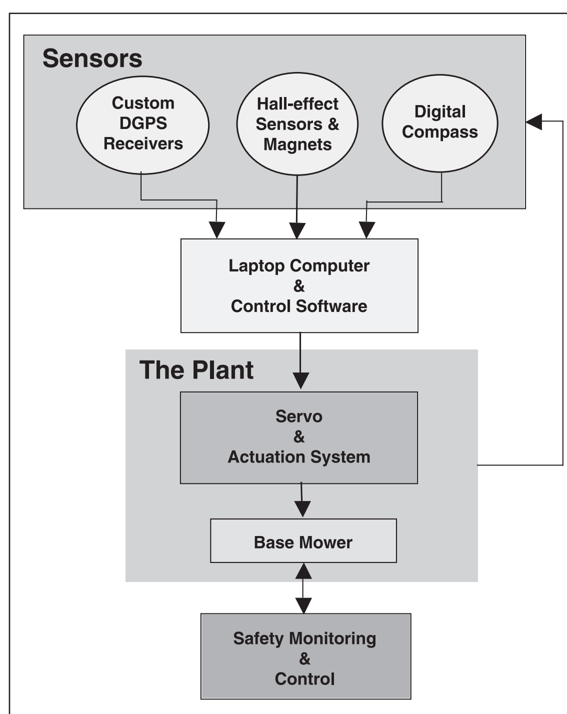
## Miami University

The Miami Red Blade has five major system components: the mower position and orientation sensors, servo actuation systems, control system, base lawnmower, and safety system (see Figure 2).

**Sensing System.** The sensing system uses three major inputs: a differential GPS (DGPS) receiver system, a Hall-effect/magnetic speedometer, and a digital compass. The DGPS system consists of two

▶ **FIGURE 2** Miami Red Blade system overview (below) and control algorithm overview (right)



low-cost consumer-grade GPS receivers and custom carrier-phase positioning calculation software. A set of radio modems transmit receiver data to the controller on the lawn mower. Conventional double-differencing approaches drive the carrier-phase computation algorithm. This custom DGPS system generates precise user location measurements and determines, within 2-centimeter accuracy, the relative location of the lawnmower referenced to the base station as it runs in the field.

The drawback of the GPS system is the 1-second interval between position updates. If the lawnmower moves at a maximum speed of 10 kilometers/hour, the mower will travel 2.7 meters between location updates. This range is not acceptable to provide accurate navigation. For this reason, Red Blade incorporates two more sensors, the Hall-effect/magnet sensors and a digital compass, to help track locations between GPS updates.

The Hall-effect/magnet sensor system consists of a series of 24 magnets affixed to each lawnmower drive wheel, and a Hall-effect sensor attached to the mower frame near the wheel. As the wheel rotates, the magnets pass the Hall-effect sensor whose outputs are monitored by a microcontroller. The microcontroller sends the magnet count of each wheel to the controlling computer, which calculates travel distance and wheel speed. A digital compass determines mower orientation, updated every tenth of a second. Combining these inputs provides mower position monitoring. The data from these two instruments and from the GPS receivers goes to the control system mower navigation decisions.

**Control System.** The control system consists of an onboard laptop computer and a collection of computer programs integrated into one guidance algorithm. The control software consists of three major parts:

- high-level path planning, coordinate transformations, and field layout interpretations;
- a PID control loop that constantly compares sensor inputs with the ideal path predication provided by the path planning algorithm, and also computes necessary corrections to the mower speed, acceleration, position, and heading; and
- low-level interface programs between the control loop, and the sensors and actuators.

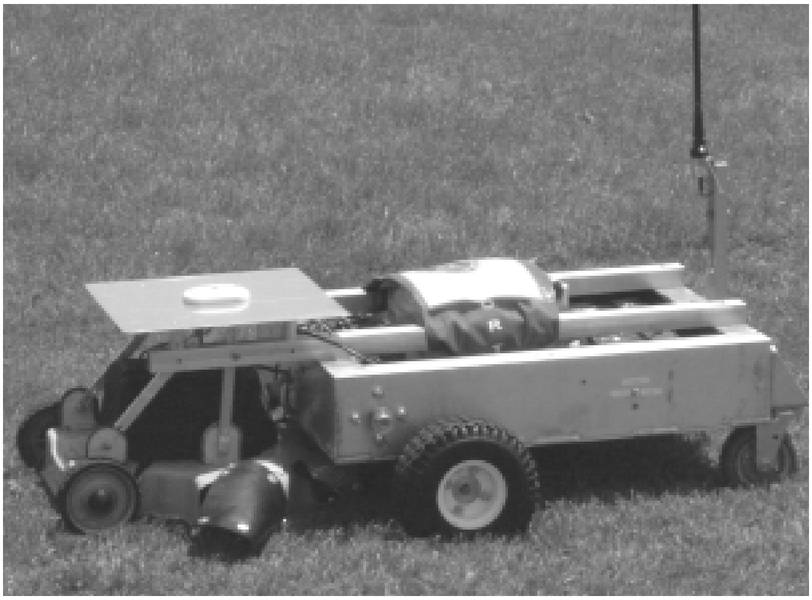
Additional utility software accomplishes fundamental tasks such as forecasting satellite availability and mower state monitoring.

The first two parts of the control software are written in Matlab. The low-level interface programs are written in C and Java. Path planning is performed prior to mower operation. The control loop executes sequentially while the low level interface programs are multithreaded event-driven processes.

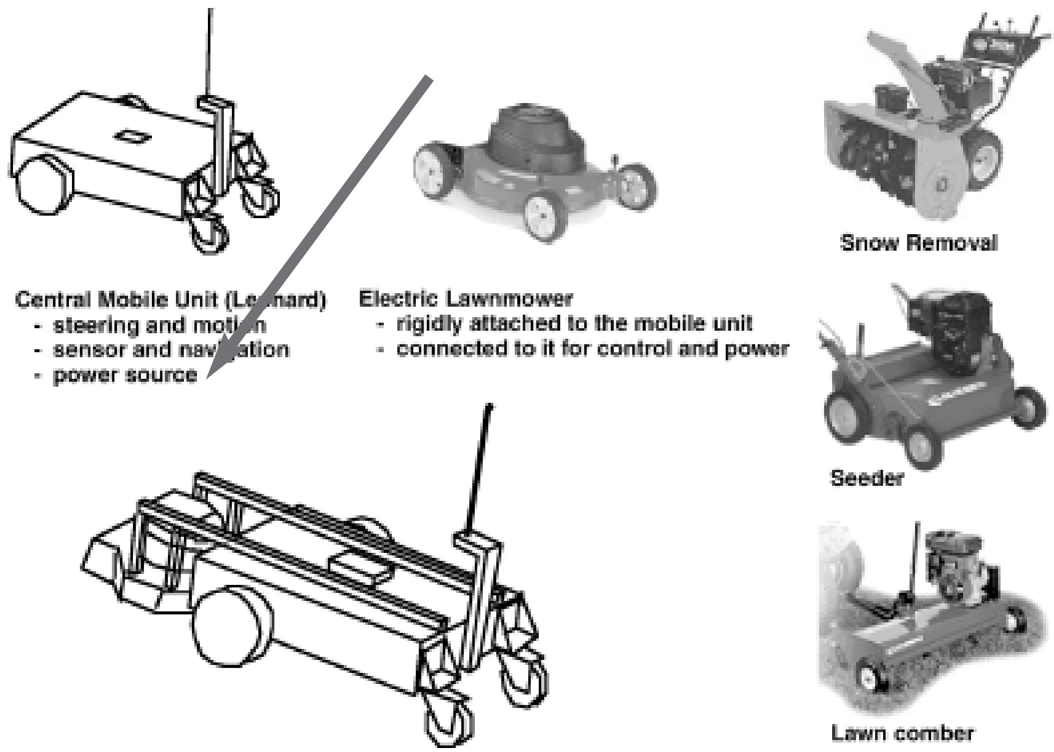
**Servo System.** Two servo motors and controllers are used on the lawn mower. The servos are attached to the control shaft of the hydrostatic pump on each wheel. The position of the control shaft determines how fast each wheel moves and in which direction (forward or reverse). The servos are linked to the control shaft through a gear system, where they convert voltage inputs into physical movement. Controlling the position of each servo controls and/or predicts the speed and location of the mower.

**Base Mower.** A 42-inch hydrostatic lawnmower served as the base unit for the Red Blade. The major reason to choose the hydrostatic mower was the capability of controlling each drive wheel independently. Many other mechanical features added to the mower make it self-sufficient and user-friendly. These modifications provide Red Blade with the proper structure, support, and protection for all of its components. Other modifications added safety and ease of use when operating. Specific modifications include the servo support system, the protective Pelican electronics case and stand, the dash board, a kick stand, the GPS and compass stand, the magnet sensing system, and the wiring.

**Control Panel.** A custom dashboard contained the appropriate user operating devices such as the throttle, ignition, and blade control, previously located on the handlebars. Initially, the handlebars did not meet ION specifications for mower height. They also inhibited autonomous control and were



▼ **MEET LEONARD,** a modular control device from the Illinois Institute of Technology, shown here with companion mower



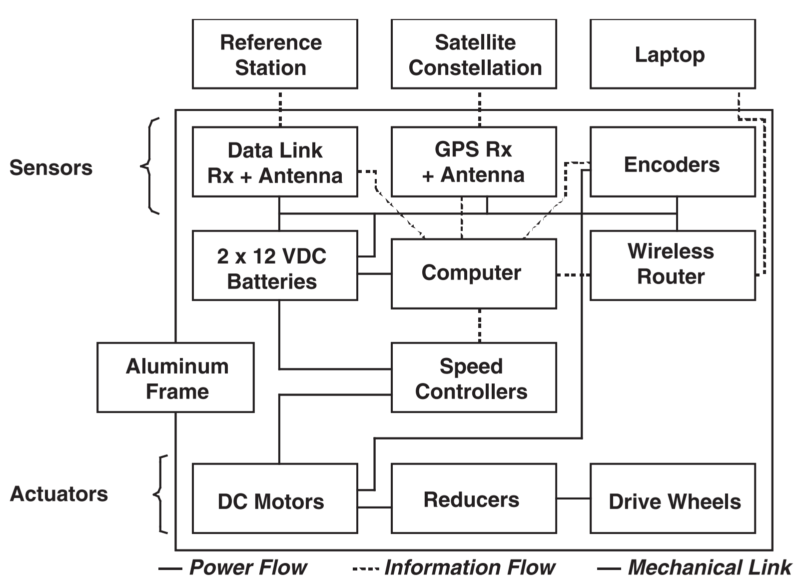

◀**FIGURE 3** Illinois Institute of Technology modular design

therefore removed. An emergency stop switch, hardwired into the kill switch of the ignition, was placed on top of the dashboard. A remote control E-stop was also mounted on the back side of the dash.

The GPS and compass stand (made of PVC, unistrut beams, and t-joints) provide the compass and GPS receiver with a safe and sturdy location for operation. The GPS receiver/antenna was raised above the stand to help eliminate potential multipath errors as well as provide the antenna with an unobstructed view of the sky. Further, the compass was positioned directly over the central axis of the lawnmower to provide accurate orientation readings.

**Team Members.** Brett McNally (team leader), Micah Stutzman, Collin Koranda, Chris Mantz, Jeff Macasek, Scott Miller, Andrew Walker (undergraduates); Jade Morton, Scott Campbell, and James Leonard (faculty advisors).

▼**FIGURE 4** IIT conceptual design




## Illinois Institute of Technology

The IIT lawnmower prototype consists of two units: the vehicle ("Leonard"), containing the navigation sensors, computer, and power supply, and providing motion and steering; and the grass-cutting device, a standard off-the-shelf electric lawnmower.

The mobile platform was not specifically built for mowing missions, but was designed with flexibility to accommodate various tools and sensors. This modular structure provides the advantage of use not only for lawnmowing, but also spreading fertilizer and seeds, sweeping concrete surfaces, or removing snow. From a marketing perspective, this versatility becomes a decisive asset (Figure 3).

Leonard, an automated ground vehicle (AGV), performs trajectory-tracking operations. Carrier-phase differential GPS (CDGPS) measurements are fed back to the controller, which sends optimal correction commands to the motors.

IIT opted for a differential-drive vehicle concept for its simplicity and robustness. Steering is performed by differencing angular velocity measurements from two opposing driving wheels. The actuators consist of two DC motors with gear-and-belt type reducers. The power is delivered by two 12V DC batteries that provide up to four hours of autonomous operation. All components except the antennae and wheels are enclosed in a waterproof and dustproof rugged aluminum frame. Two floating casters ensure vehicle balance and stability.

The lawnmower is a separate module rigidly mounted on the mobile platform. It carries its own 12V DC battery that powers a motor directly linked to a 15-inch cutting blade. The mower can operate for up to 45 minutes.

**Sensors and Computer.** The DGPS sensor is composed of a GPS receiver and a spread spectrum data link in communication with the reference station. The GPS patch antenna is fixed at the center of an aluminum plate to minimize the effects of multipath reflections. Also, low cost optical encoders are integrated to the motor driving shafts.

An embedded computer equipped with a data acquisition card processes the sensor data and sends commands to the motors via speed-controller interfaces. The speed controllers, or motor drives, provide the necessary amperage to the motors at the computer's request. A wireless system enables remote control, and can provide real-time monitoring.

**Control System.** The navigation and guidance control system is based on a detailed dynamic model. Linearized along the desired trajectory, at a constant velocity of 2 kilometers/hour, the equations of motion for the vehicle result in a fifth-order state space representation.

The control system, a discrete closed-loop feedback algorithm, uses a linear quadratic regulator (LQR) whose controller performance index weights are distributed to minimize cross-track error and avoid drive-motor saturation regions.

A seventh-order Kalman filter using CDPGS sensor inputs provides the basis for state estimation. Optimal performance of the estimator requires that process and sensor noise be accurately modeled. The team derived and implemented detailed random process models in terms of vehicle design parameters to account for disturbances such as ground slope and rugged terrain. The correlation of the GPS measurements due to multipath reflections is modeled with a first-order Markov process.

The controller's time constant (here 0.5 seconds) is limited by both the actuator's bandwidth and the DGPS update rate, and determines the frequency per unit distance of the cross-track-error corrections, for a given vehicle velocity.

The control strategy for mowing a rectangular field takes advantage of the forward/backward motion capability of the vehicle. It aims to simply to go back and forth straight along the field, each trip offset by the width of the cutting blade. More elaborate tactics are considered for future work. In particular, Leonard has the capability to operate at various speeds (that could change depending on the proximity of the mower to the field's edges), and can per-

## Marketing Analysis

(Excerpts from the University of Miami's report)

**Target Market.** We intend to appeal to the young and middle-aged homeowner. We feel this lawnmower could be targeted to men and women alike. We foresee a particular niche with families on the go and parents with tight schedules.

**Advantages.** Most current models work similar to a pool cleaner. They run random patterns and avoid objects as they work. This often results in areas of uncut grass and drastically increased cutting time (days). Today's products require a wire to be run around the perimeter of the lawn, similar to an invisible fence for dogs. This limits the travel of the mower but also creates excess cost for the homeowner. It will also cause inconvenience when a homeowner decides to change landscaping or home additions.

**Tactics.** We will concentrate our marketing on the promise of more free time and ease of operation. No longer will people need to slave under the hot sun during their time off, just to do it again in a week. Family life and the joys of good weather will be used to induce guilt and eventually create even more distaste for lawn care.

"Would you change your mind if we told you that every year you spend 24.4 hours of your life guiding a lawnmower. An entire day each year! This may not move you, but when you think that most of your time spent with a lawnmower is on your weekend under a cloudless sky, that day looks much more valuable. Shall we begin to mention the time spent cleaning grass clippings out of your hair or sweat off your back? If mowing a lawn provided a health benefit, sweat and sore arms would be a welcome sacrifice, but for most people the process of mowing a lawn is dull, time-consuming, non-beneficial, and boring.

Are we far off in our assumption that you share this sentiment?"

form zero-radius turns.

**Subject to Murphy's Law.** Leonard successfully passed tests in Chicago and demonstrated cross-track control accuracy of less than 10 centimeters (standard deviation) at a nominal velocity of 2 kilometers/hour. IIT expected similar performance for the competition in Ohio — that is, until the main board of the small customized computer failed 36 hours before the start of the competition!

In a couple of sleepless days, the team redesigned the computer system (including power supply and interfaces) using off-the-shelf equipment. They also reinstalled and reconfigured the operating system, and rewrote part of the navigation program that they could not recover from the former hard drive. The last lines of codes were written at 5 a.m. in the parking lot of the Holiday Inn in Beavercreek, Ohio.

In a final twist of fate, after setting everything up on the competition field, IIT realized that in its haste to reach Beavercreek in time, the team had forgotten the rack hard drive for the DGPS reference station's computer back in Chicago. Obviously they were disappointed because this prevented them from demonstrating the results of their hard work. Nevertheless, IIT maintains a very positive impression of the whole experience, having successfully completed the qualifying safety tests and demonstrated the robust mechanical functioning of the system.

**Team Members.** Scott Bachmann; Mathieu Joerger (team leader), Moon Heo, Fang Chan, Livio Gratton, and Samer Khanafseh (graduate students); Boris Pervan (faculty advisor).

## Manufacturers

Ohio University employed two NovAtel (Calgary, Alberta, Canada) *Allstar* GPS receivers, a set of FreeWave Technologies (Boulder, Colorado) OEM radio modems, a *3DM Gyro-Enhanced Orientation Sensor* from MicroStrain (Williston, Vermont), and a two-channel *AX2850* DC motor controller from RoboteQ (Scottsdale, Arizona).

Miami University used two Garmin (Olathe, Kansas) *GPS 16* receivers, custom carrier-phase positioning calculation software, a set of Freewave Technologies radio modems, a Honeywell (Plymouth, Minnesota) *HRM 3200* digital compass, Parker Hannifin *Compumotor OEM 770X* servo motors and controllers, and a Snapper *Pro Hydro* mower.

The Illinois Institute of Technology used a NovAtel *ProPakII* containing L1/L2 *OEM 3* GPS receivers.