Workshop on "Satellite Navigation Science and Technology for Africa"

Autonomous Ground Vehicle Guidance, Navigation and Control Using GNSS and Other Navigation Sensor Measurements

April 12, 2010

Dr. Mikel Miller
Dr. Jade Morton

Dr. Mikel M. Miller, Ph.D.

- **Introductions**
- **Overview**
- **Autonomous GNC**
- **Lego® Mindstorms Intro**
- **Lego® Mindstorms Challenge**

- Education:
  - Ph.D. EE (98) & MSEE (87) – AF Institute of Technology (AFIT); Dayton, OH
  - BSEEE (82) – North Dakota State Univ; Fargo, ND
- Experience:
- Current Position: Technical Director, AFRL/RWG, EAFB, FL
- Over 24 years of Pos, Nav, & Time (PNT) Experience
- Published over 40 Technical Papers related to PNT
- USAF Retired after 20 yrs
- Teaching Experience:
  - 5 yrs as AFIT Assistant Prof
  - Over 20 short courses
  - Miami Univ & AFIT Adjunct Faculty
- Professional Societies:
  - Institute of Nav (ION):
    - Fellow
    - Current President
    - Royal Institute of Nav
    - Associate Fellow
    - IEEE, AIAA, TBP, EKU

Dr. Yu (Jade) Morton, PhD.

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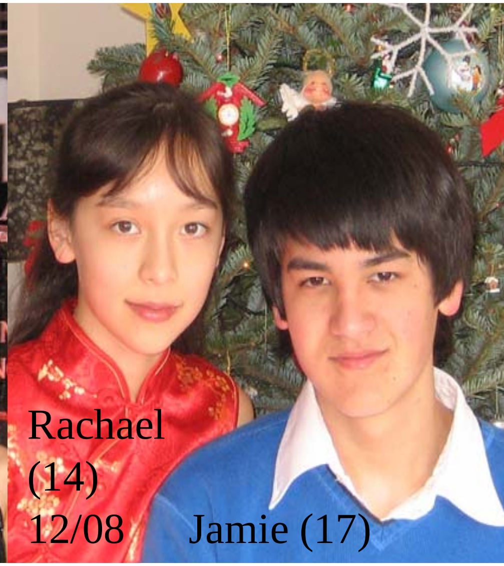
- Education:
  - Ph.D. EE (91) – The Pennsylvania State University, University Park, PA
  - MS Systems Analysis (00) – Miami University, Oxford, OH
  - MS EE (87) – Case Western Reserve University, Cleveland, OH
  - BS Physics (83) – Nanjing University, Nanjing, China
- Professional Experience:
  - Professor, EE, Miami Univ., Oxford, OH. Began tenure track at Miami in 2000
  - Post-doctoral Research Fellow, University of Michigan, Ann Arbor, MI, 1992-3
  - Faculty, Physics, Nanjing University, China, 1983-85
  - Published over 80 technical papers related to PNT and ionosphere physics
  - Mentored over 50 graduate/undergraduate students
- Professional Societies:
  - Institute of Navigation (ION)
  - IEEE: Aerospace and Electronics, Microwave theory & Technology, Signal Processing
  - CPGPS



Carrie New Introduction

Casey Miller Introduction

Overview

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9:00 – 10:00 – Overview (Mikel):
- **Instructors Introductions**
- **Introduce Autonomous Guidance, Navigation, and Control Concept**
    - **Precision Farming Overview**
    - **ION's Robotic Lawn Mower Competition**
    - **Autonomous vehicle operation (DARPA Grand Challenge)**
    - **Mini-Urban Challenge**
- **Importance of Outreach – Next engineering generation**

10:00 – 10:30 – Break

10:30 – 11:30 – GNC issues for autonomous vehicles (Mikel - 30 minutes)
- **ION Robotic Lawn Mower – (Jade – 30 minutes)**

11:30 – 12:30 – MiniUrban Challenge (Carrie and Casey)
12:30 – 1:00 – Mindstorm Robots at De Universite de Cocody

1:00 – 2:00 – Lunch

2:00 – 3:15 – Robotics Laboratory Tutorial (Jade)
•Hardware components, servo motors, sensors
•Software development environment: BrixCC
•Programming: NXC

3:15 – 3:30 – Break

3:30 – 5:30 Laboratory Continued (All)
- **Challenge 1: Color line following**
- **Challenge 2: Use sonar for obstacle detection and avoidance**

Autonomous Vehicle GNC Concept

- **An autonomous ground vehicle is a vehicle that navigates and drives entirely on its own with no human driver and no remote control.**
- **Uses a variety of sensors to carry out the task it has been assigned.**

Autonomous Vehicle GNC Concept

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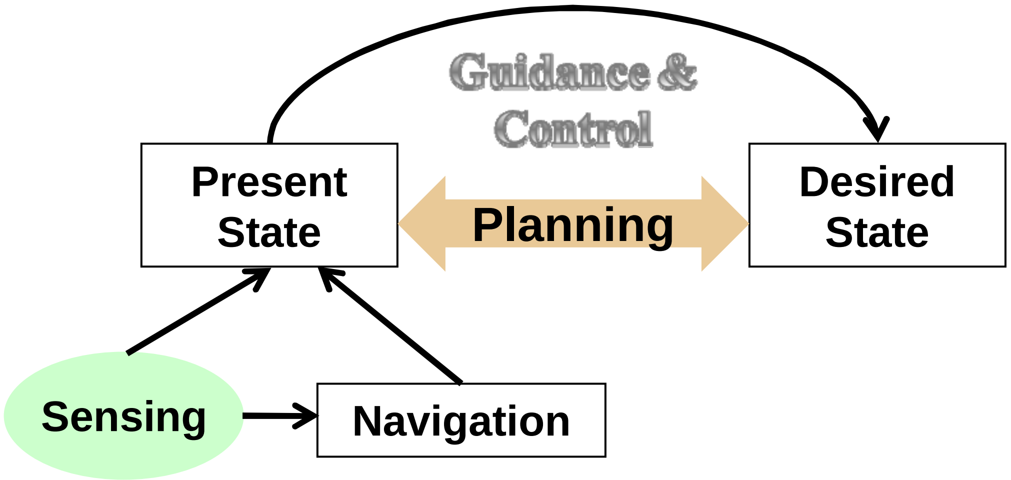
- **What is the mission of the autonomous vehicle?**
  - **Farming, transportation, surveillance, etc..**
- **How does the vehicle accomplish the mission?**



- **What is the Present State?**
  - **Sensing**
- **What is the Desired State?**
  - **Planning**
- **How does the vehicle get from the present state to the desired state?**
  - **Guidance, Navigation, & Control**

Autonomous Vehicle GNC Concept

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Intelligent Vehicle Systems

JOHN DEERE

- **Guiding an intelligent vehicle requires global perception, local perception and vehicle control**
  - **Global perception - localization and path planning system**
    - Identifies the vehicle position with respect to an available global map and the path that the vehicle has to track
    - Vehicle has to know its position and direction with respect to real world and series of positions in order to reach the destination
    - Due to environmental dynamics, global perception system alone is not enough to maneuver vehicle to move to its destination.
  - **Local perception**
    - Real-time sensing system required to perceive vehicle's surroundings
    - Avoid static and dynamic obstacles that block vehicle path – requires localization accuracy to detect small objects and coherently image scanned data
  - **Vehicle control system**
    - Integrates information from the global and local perception systems then determines an appropriate action of the vehicle

RGATOR

Courtesy of
Bob Norris, John Deere

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Autonomous Vehicle GNC Concept

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Intelligent Vehicle Systems

Courtesy of
Bob Norris, John Deere

Precision Farming

Doing the right thing at the right place at the right time in the right way… and without the human interaction

Precision Farming: Concept

- Introductions
- **Overview**
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  - ION Robotic Mower
  - DARPA Challenge
  - ION Mini Urban Challenge
  - Outreach
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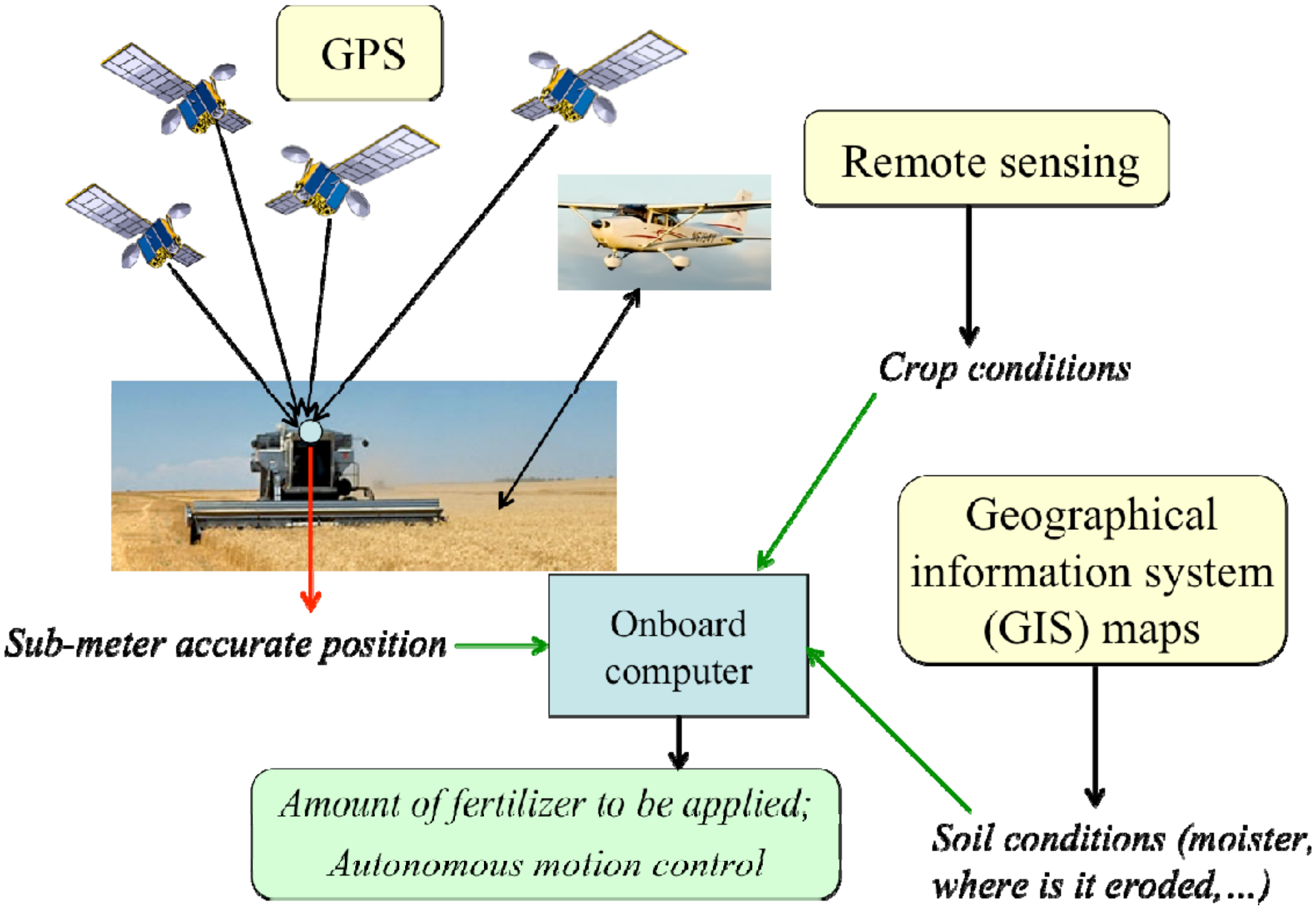

Use of GPS: Example

- **Cm-accurate position solution from GPS is used to automatically steer the vehicle**
- **GPS technology: Real-Time Kinematic (RTK) solution; involves differential GPS and carrier phase positioning concepts**

Image is from www.novariant.com – provider of the GPS RTK AutoSteer

Precision Farming Cycle

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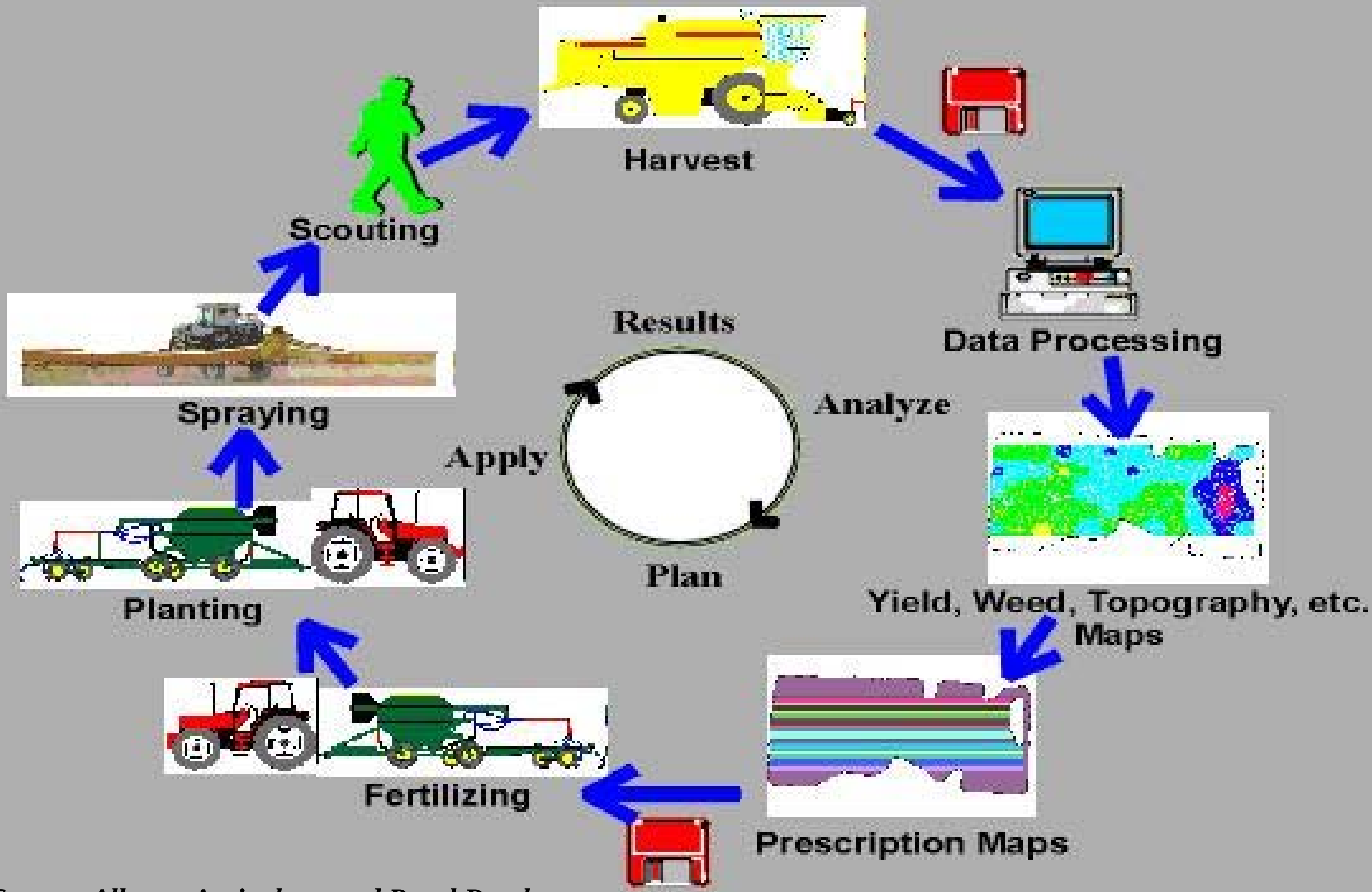

Source: Alberta, Agriculture and Rural Development

- **Yield monitoring**
- **Yield mapping**
- **Variable rate fertilizer**
- **Weed mapping**
- **Variable spraying**
- **Topography and boundaries**
- **Salinity mapping**
- **Guidance systems**
- **Records and analyses**

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ION Robotic Lawn Mower Competition

- The purpose of this competition is to design and operate a robotic unmanned lawn mower using the art and science of navigation to rapidly and accurately mow a field of grass.
- In the competition the lawn mowers maneuver through a mock lawn:
  - Cutting grass
  - Avoiding static obstacles like a flower bed
  - Avoiding moving obstacles like a pet dog
  - Traveling along a fence line



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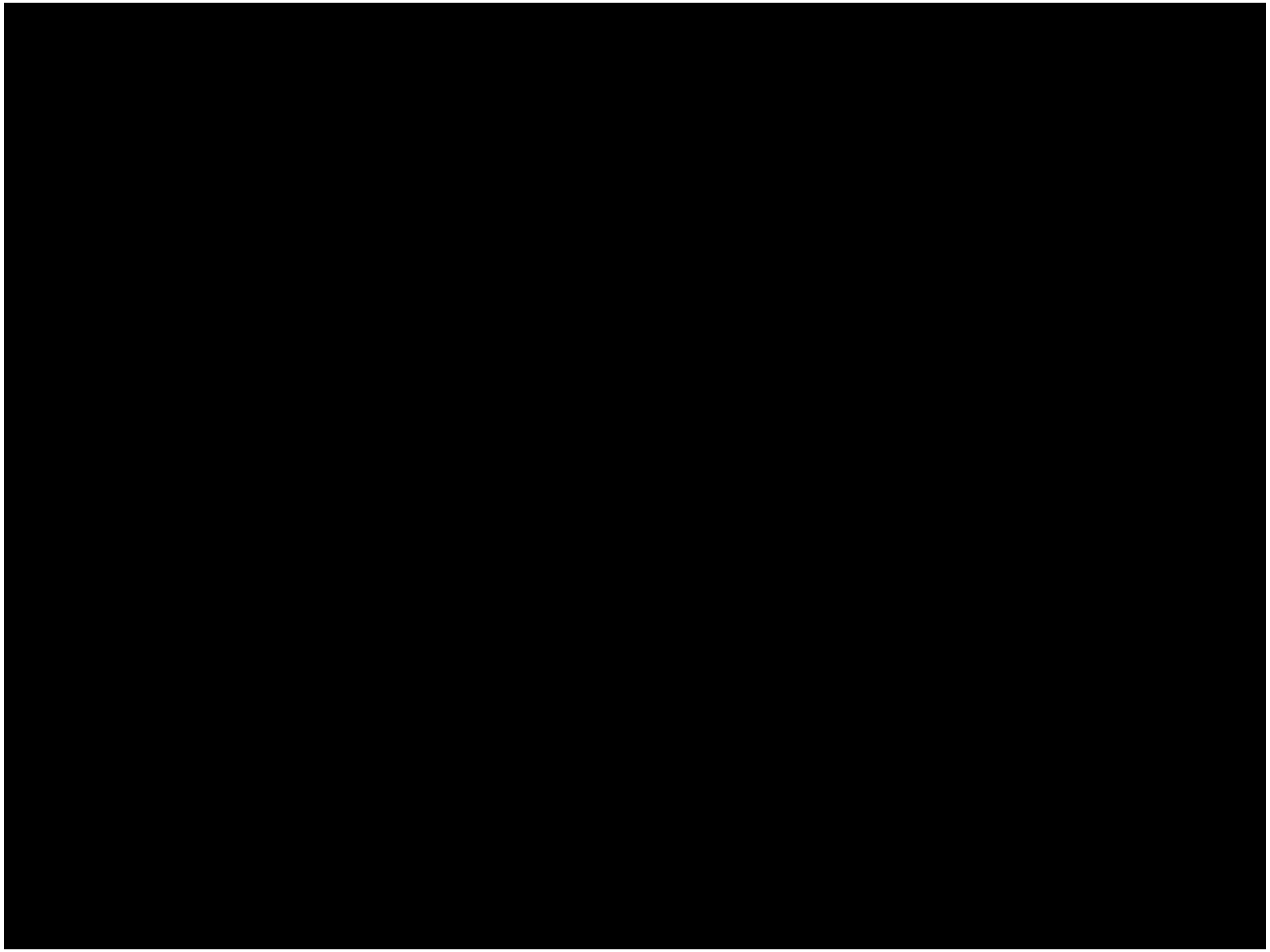

movie

DARPA Urban Challenge

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- The DARPA Urban Challenge is an autonomous vehicle research program developing technology to keep warfighters off the battlefield, out of harm's way.
- In the competition autonomous ground vehicles maneuver through a mock city environment:
  - Executing simulated supply missions
  - Merging into moving traffic
  - Navigating traffic circles
  - Negotiating busy intersections
  - Avoiding obstacles

DARPA Urban Challenge

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Movie Clip from
http://www.darpa.mil/grandchallenge/gallery.asp
called:
DARPA_highlight_preview3.wmv

movie

Mini-Urban Challenge

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  - **ION Mini Urban Challenge**
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- National HS Competition held in conjunction with the ION college Robotic Lawnmower Competition (Dayton, OH)
- Challenge model based on DARPA's Urban Challenge
- HS Students must develop a robotic, autonomous ground vehicle using a LEGO® MindStorms kit to navigate through a LEGO® city
- An autonomous ground vehicle is a vehicle that navigates and drives entirely on its own with no human driver and no remote control.
- Uses a variety of sensors to carry out the task it has been assigned.
- Autonomous vehicles are a focus point of DoD and it has been Congressionally mandated that "It shall be a goal of the Armed Forces to achieve the fielding of unmanned, remotely controlled technology such that… by 2015, one-third of the operational ground combat vehicles are unmanned."

DARPA Urban Challenge 2007

Mini-Urban Challenge

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- The purpose of this competition is to challenge high school students to design and operate a robotic unmanned car built from a LEGO® MindStorms kit that can accurately navigate through a LEGO® city.
- In the competition the LEGO® cars will maneuver through a mock LEGO® city:
  - Driving along the roads
  - Following traffic signs (stop signs, speed limits, etc.)
  - Stopping at stores
  - Avoiding pedestrians

Outreach – Next Generation Engineers

Large need for more students to pursue engineering degrees

- Baby boomer retirements will deplete the science and engineering workforce by 50%
- “Over the next 18 months, 27 percent of the engineering work force will be eligible for retirement”
- Fewer than 6% of high school seniors plan to pursue engineering degrees
- One-third drop in the number of U.S. students interested in pursuing engineering degrees throughout the past decades

Outreach – Next Generation Engineers

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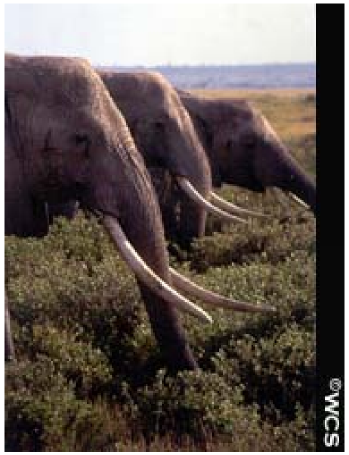
- To encourage the use of navigation technologies for societal and economic development and environmental protection
- To provide a knowledgeable engineering workforce in Africa
- To initiate international scientific collaborations

Disaster Relief

Air Navigation

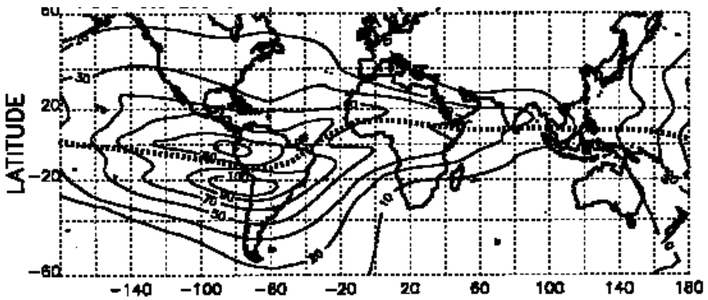
Land Navigation

Water Navigation



Wildlife Conservation

Precision Farming



Scientific Exploration

Autonomous Vehicle GNC

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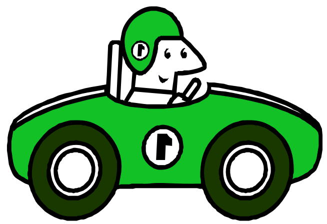
- GNC issues for autonomous vehicles
- Basic Control (Mikel - 30 minutes)
- Sensors description
- Outer Loop
- Inner Loop

- ION Robotic Lawn Mower – (Jade – 30 minutes)
- Miami University's Approach

- MiniUrban Challenge (Carrie and Casey – 1 hour)

- Mindstorm Robots at de Universite de Cocody (30 min.)

An Example of Control System: Open-Loop Control

Throttle position →  → **Speed**

Input → **System** → **Output**

How much input is needed to get the desired output?

Input ↔ **Output**

Calibration

Problems with open loop control:
Calibration results are invalid when environment/system changes

Slopes, vehicle mass, wind, tire pressure, gas quality, road surface, engine wear, ...

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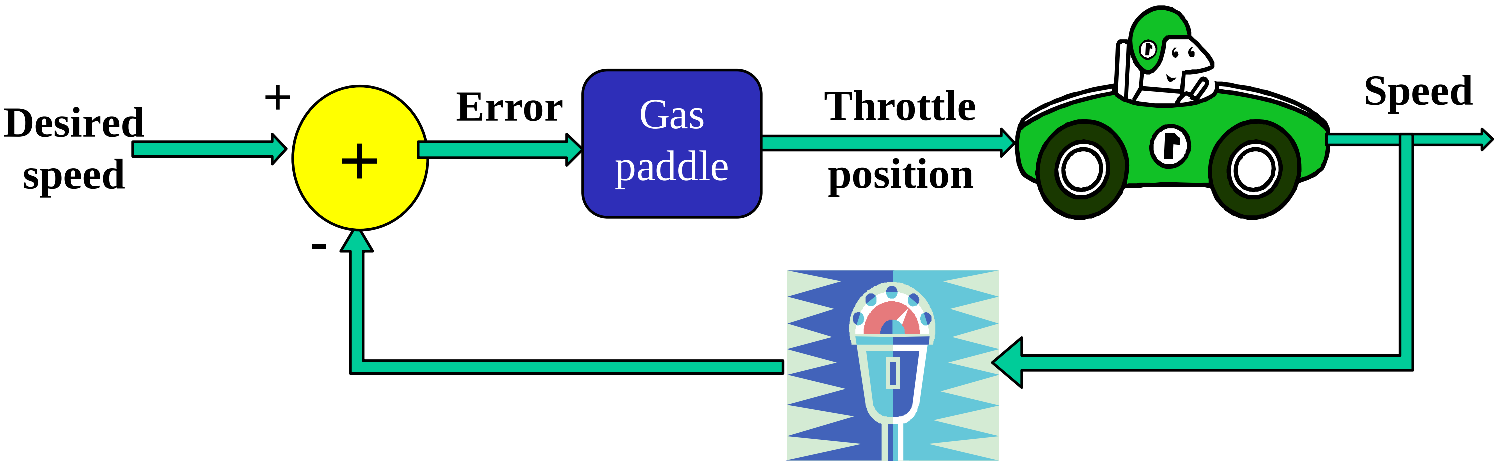

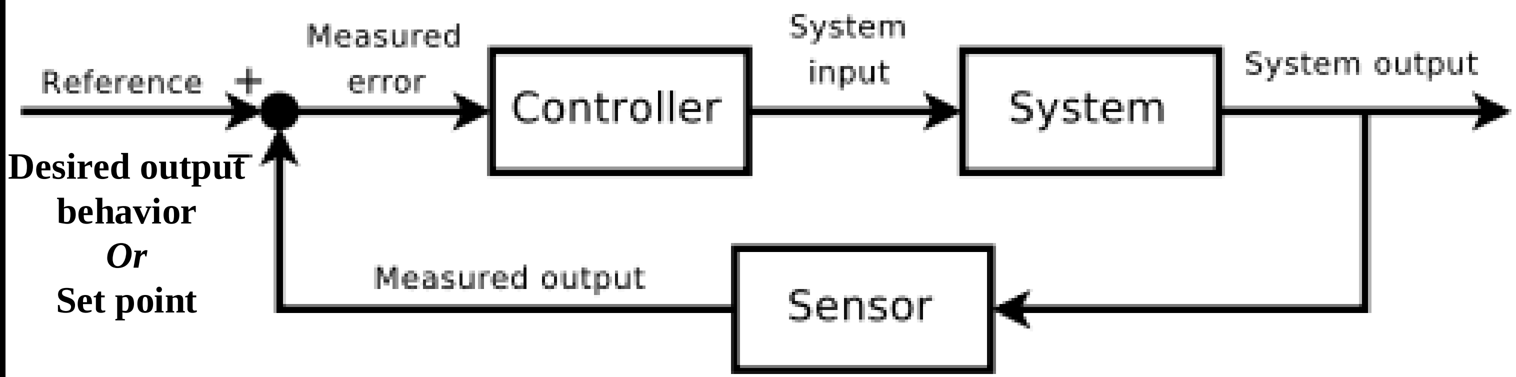

Can you think of a closed-loop feedback control system in practice?

Basic Feedback Controller

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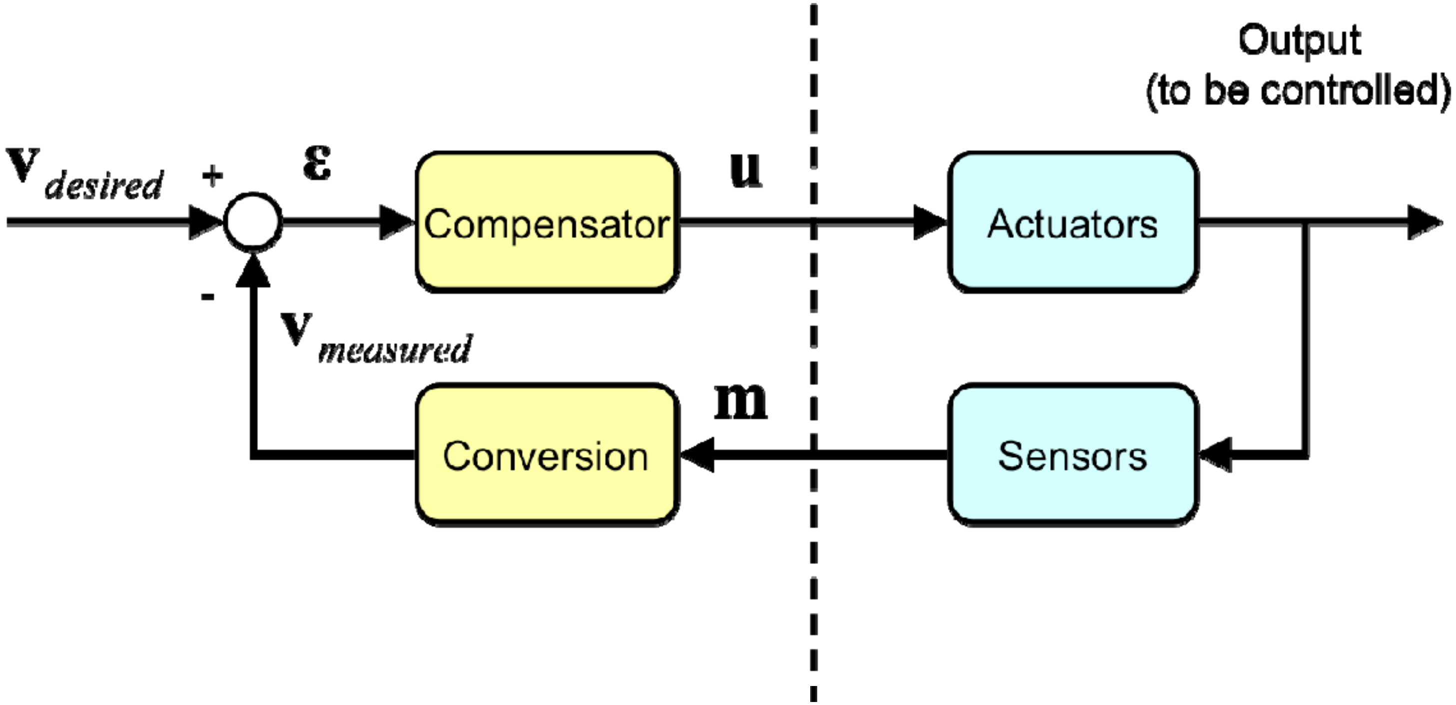
In general



Basic Feedback Controller

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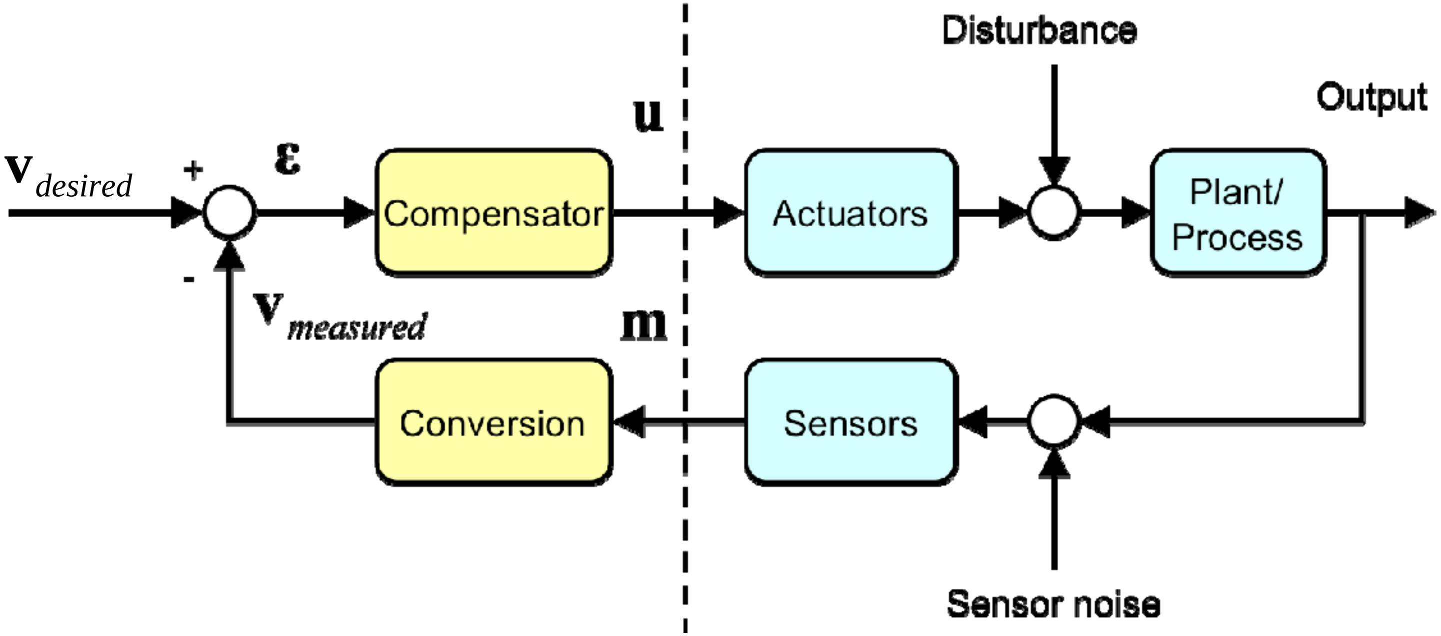
However, in reality



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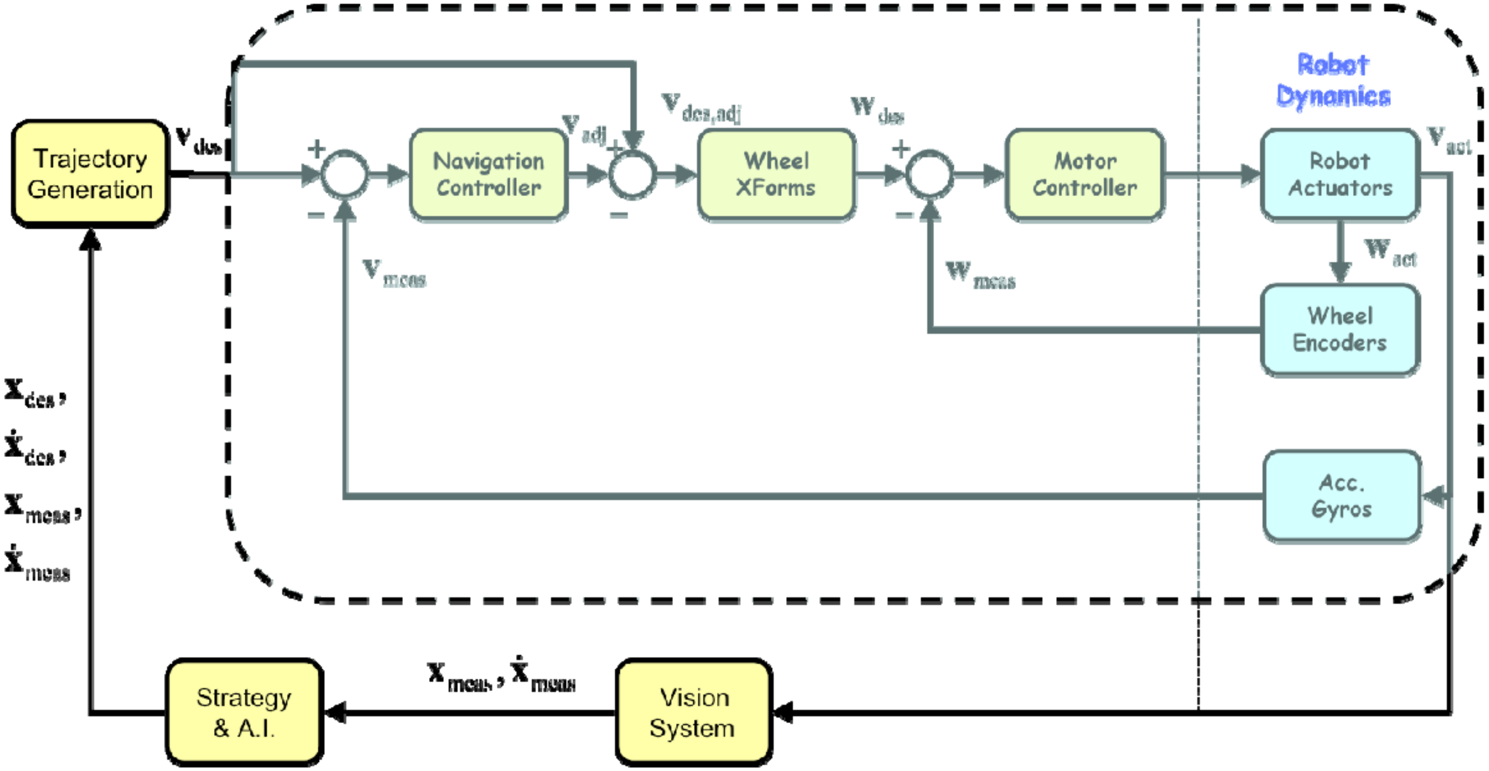
The Control Loop

Autonomous Vehicle Navigation & Control Loop



Note: x = position
xdot = v = velocity

Controller: Inner Loop

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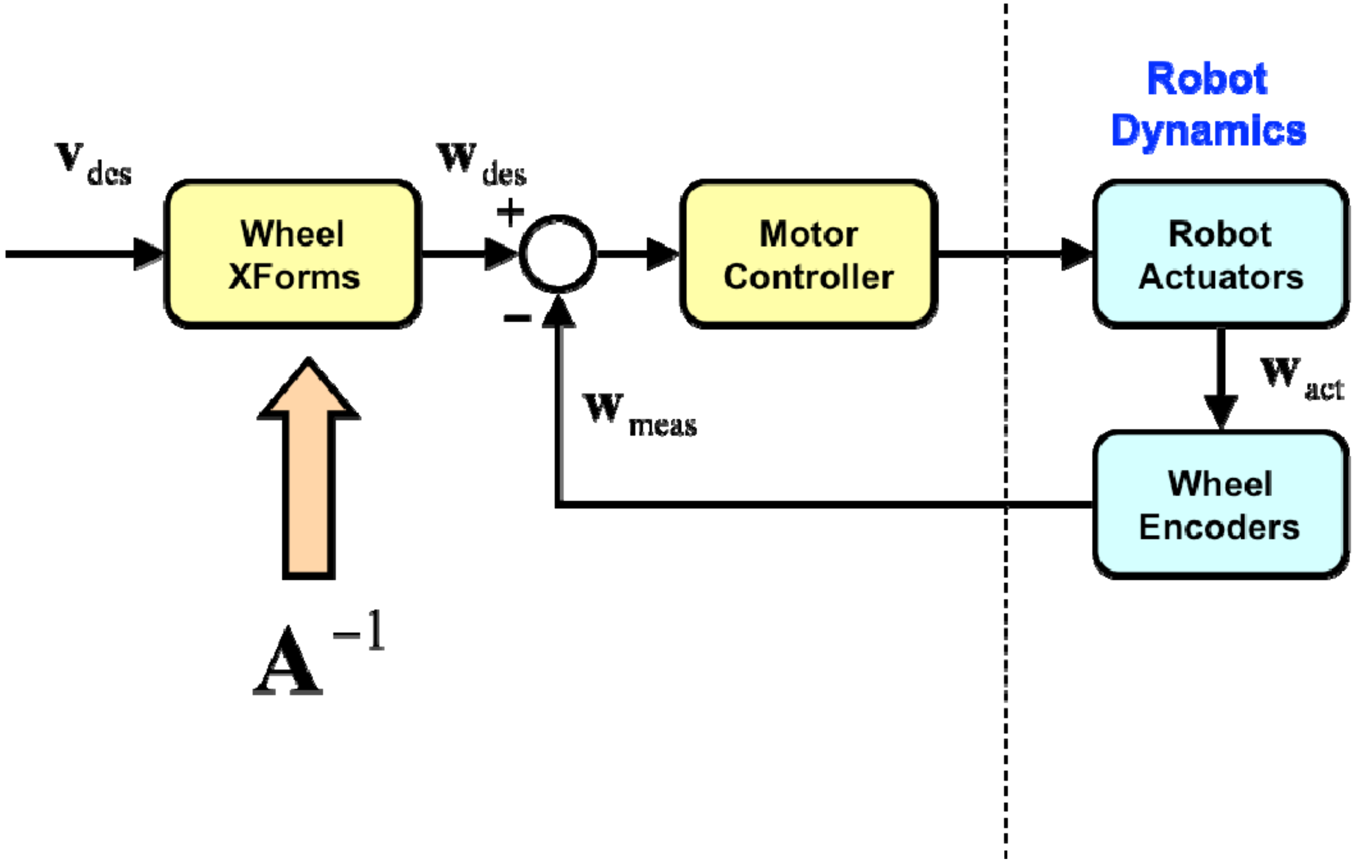
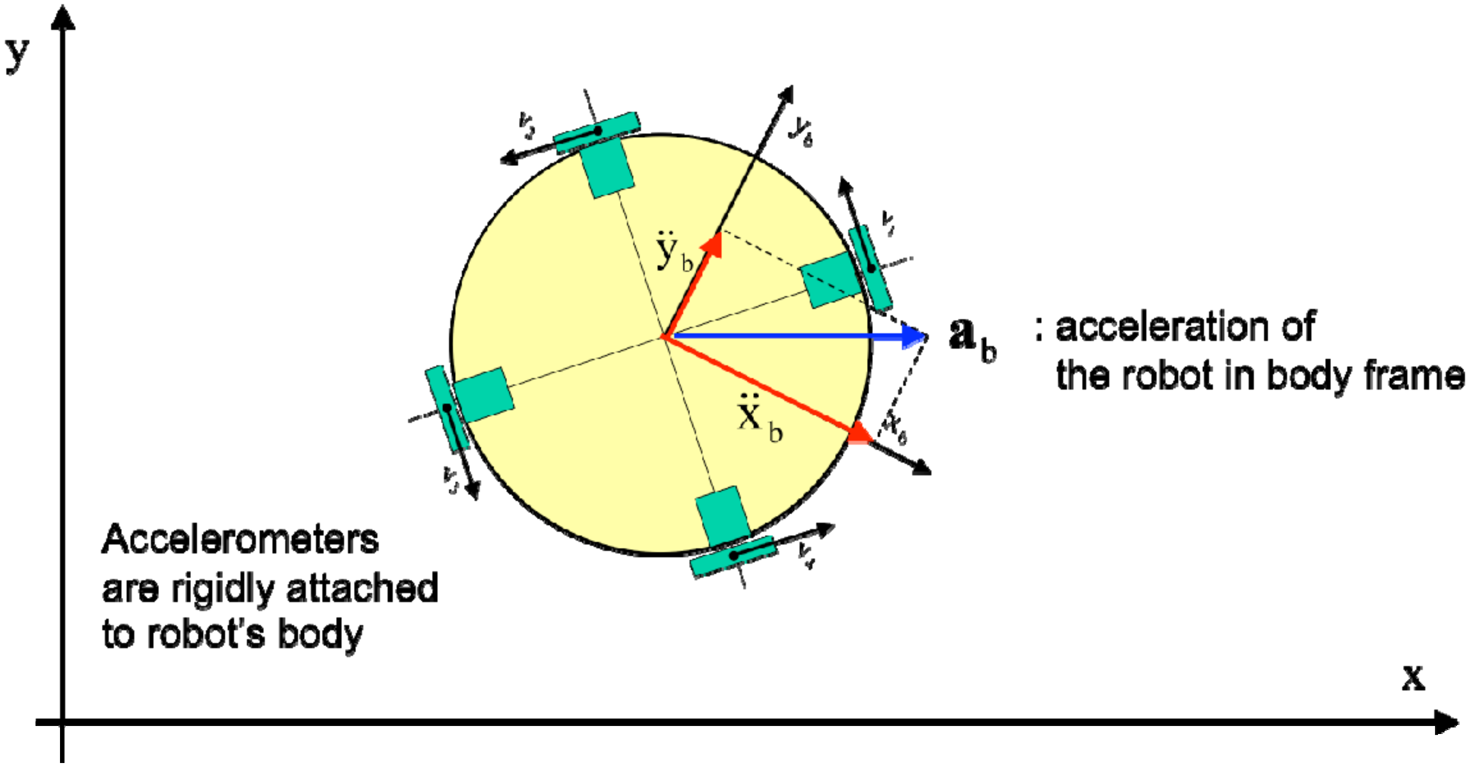


Note: A^{-1} = Transformation matrix from v to w

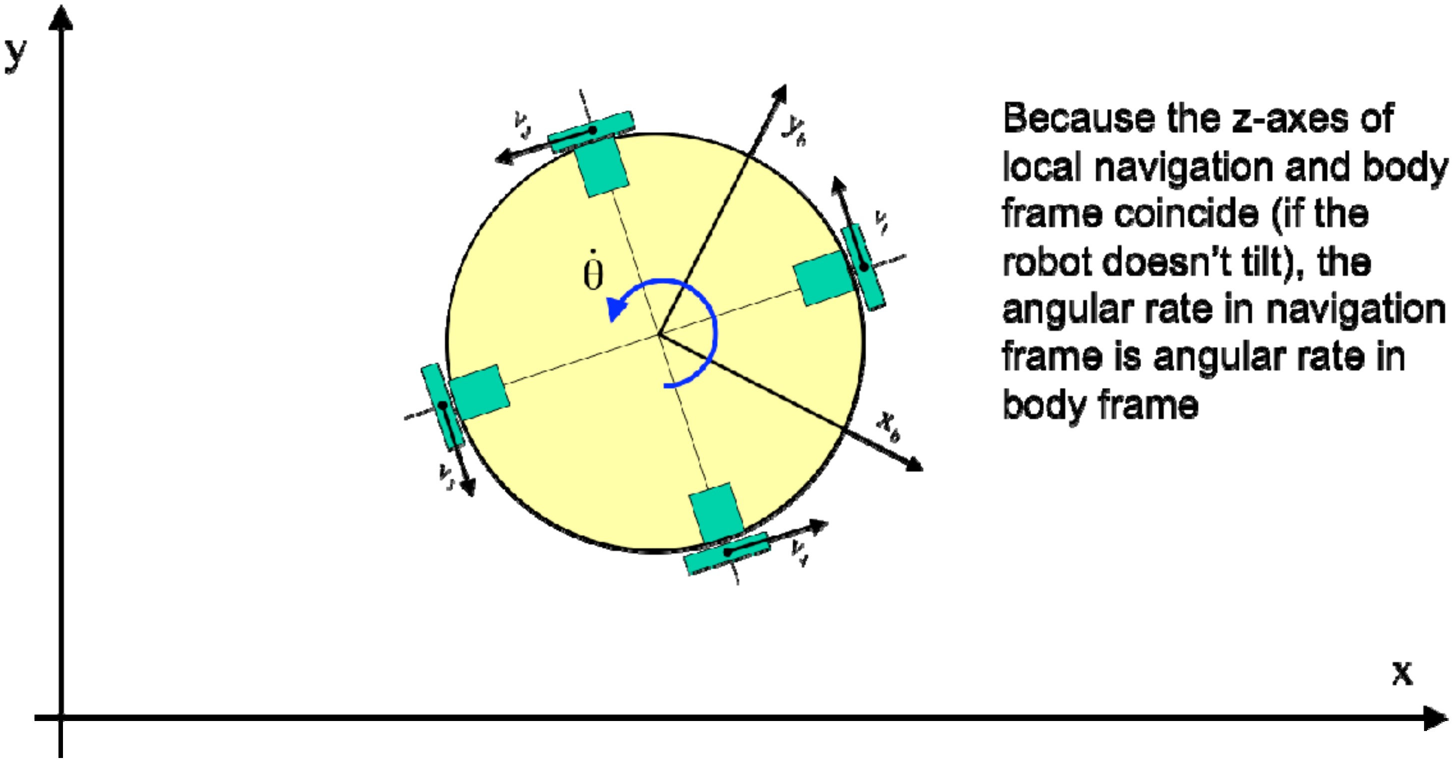
Other Sensors

- Use local sensors to measure **v** directly:
  - Accelerometers:
    - measure body acceleration
    - in other words: accelerations along x_b, y_b
    - units: g (= 9.8 m/s^2)
  - Gyroscopes
    - measure body angular rates
    - in other words: angular rates around z_b
    - units: degrees/second = °/s

Accelerometer



Gyroscope



Because the z-axes of local navigation and body frame coincide (if the robot doesn't tilt), the angular rate in navigation frame is angular rate in body frame

Controller: Middle Loop

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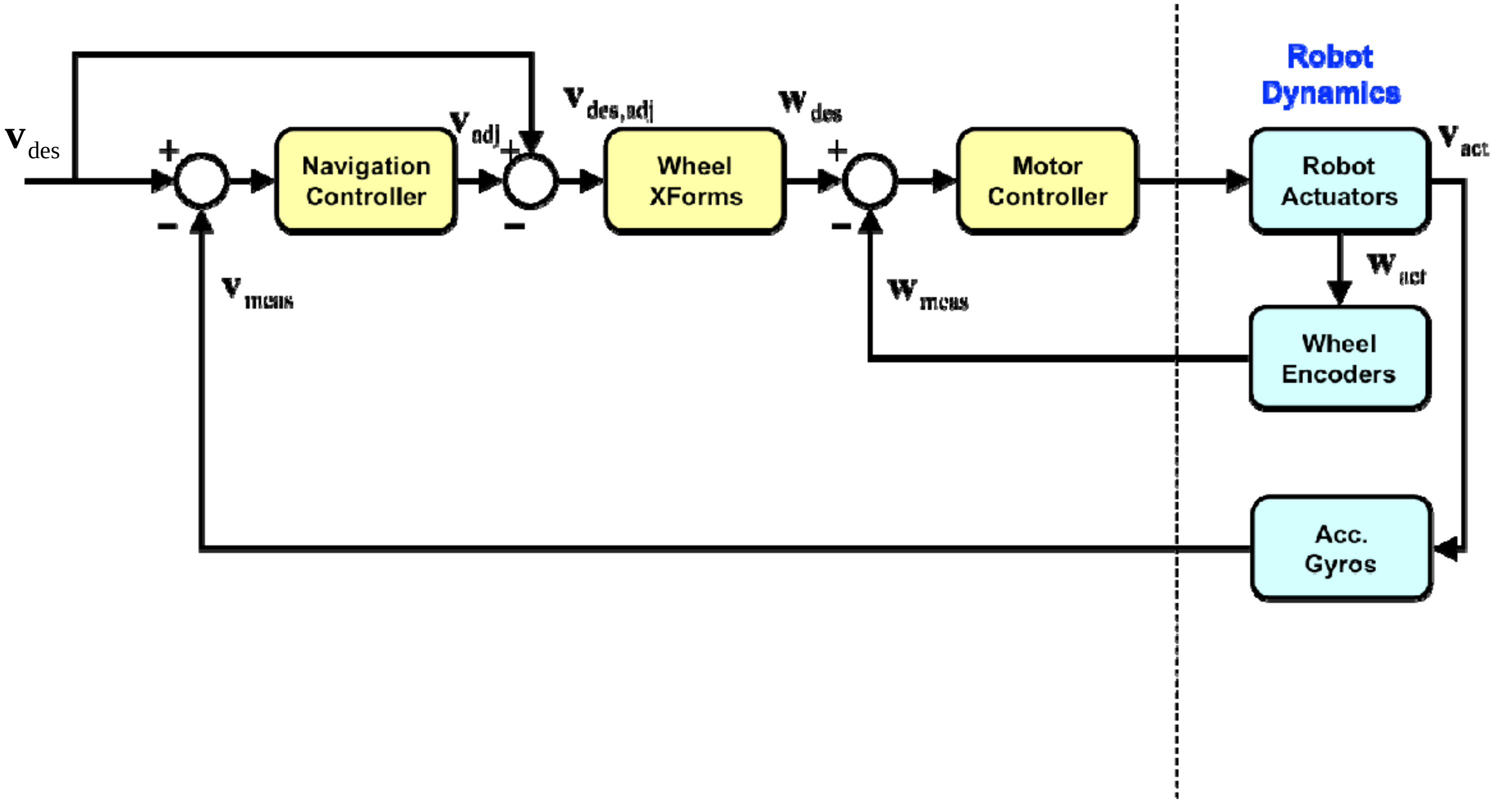

Ohio University System Design

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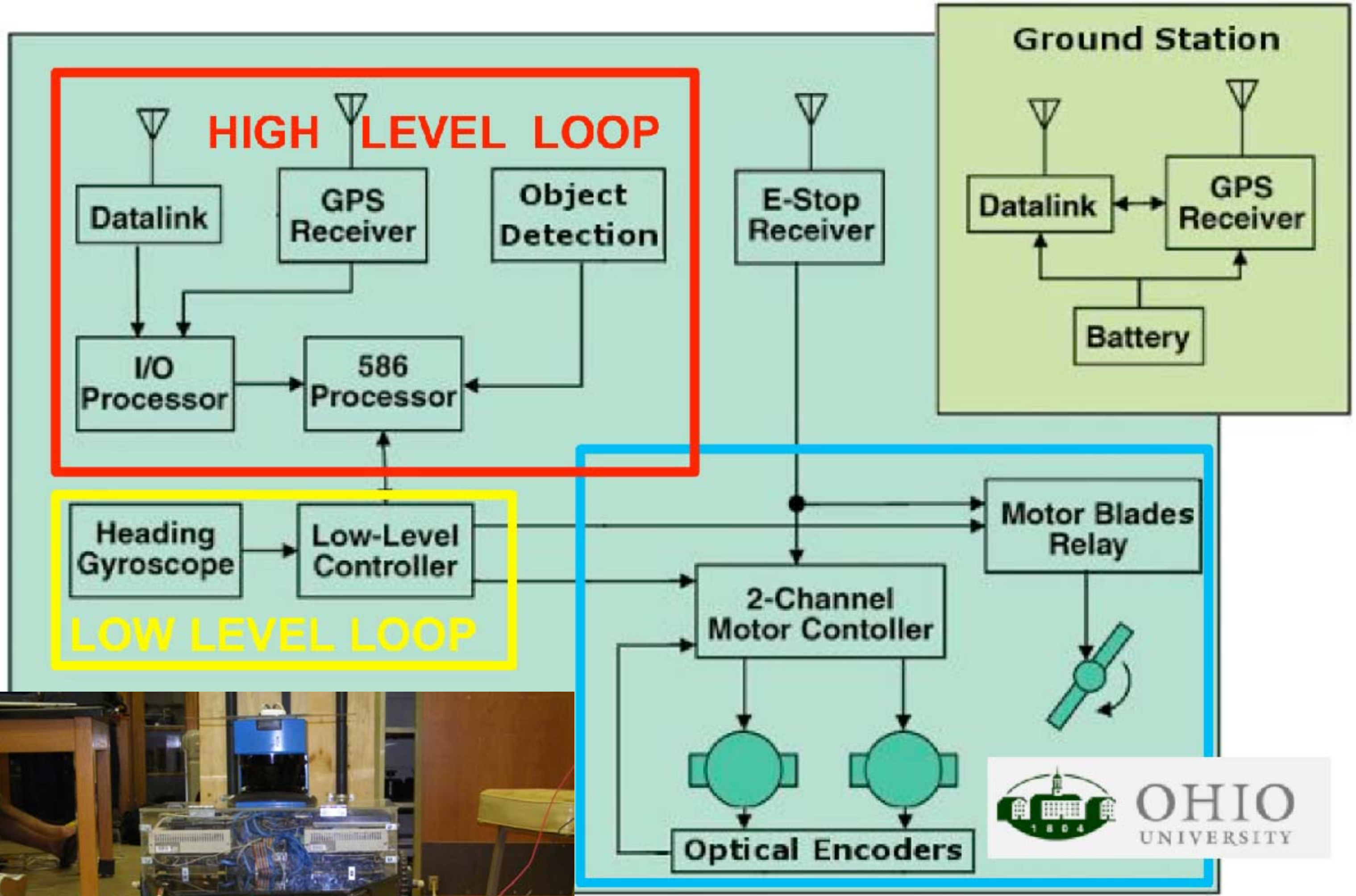

Autonomous Vehicle GNC

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ION Robotic Lawn Mower: Miami RedBlade

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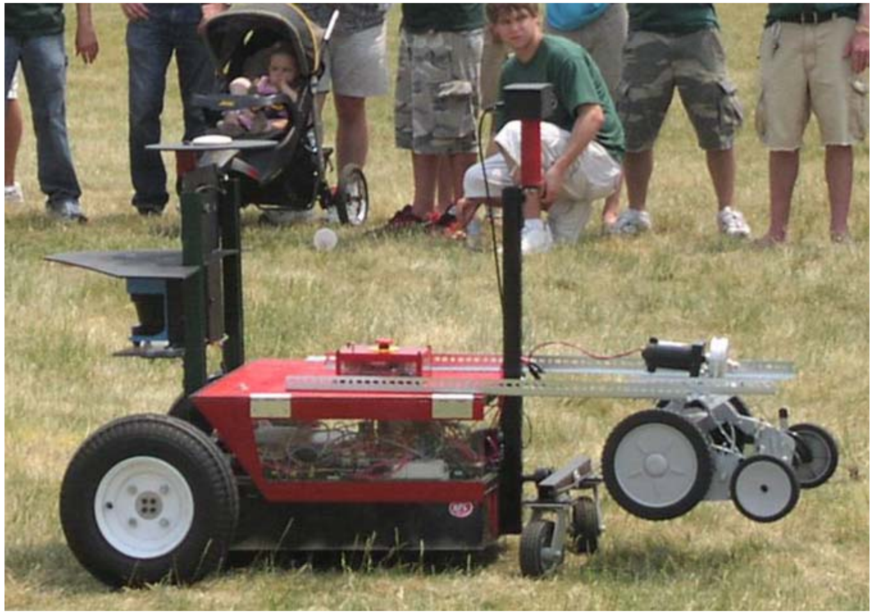

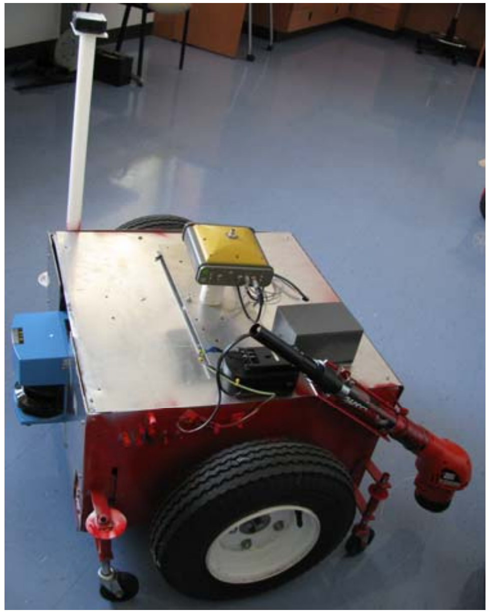

Competition Rule Evolution

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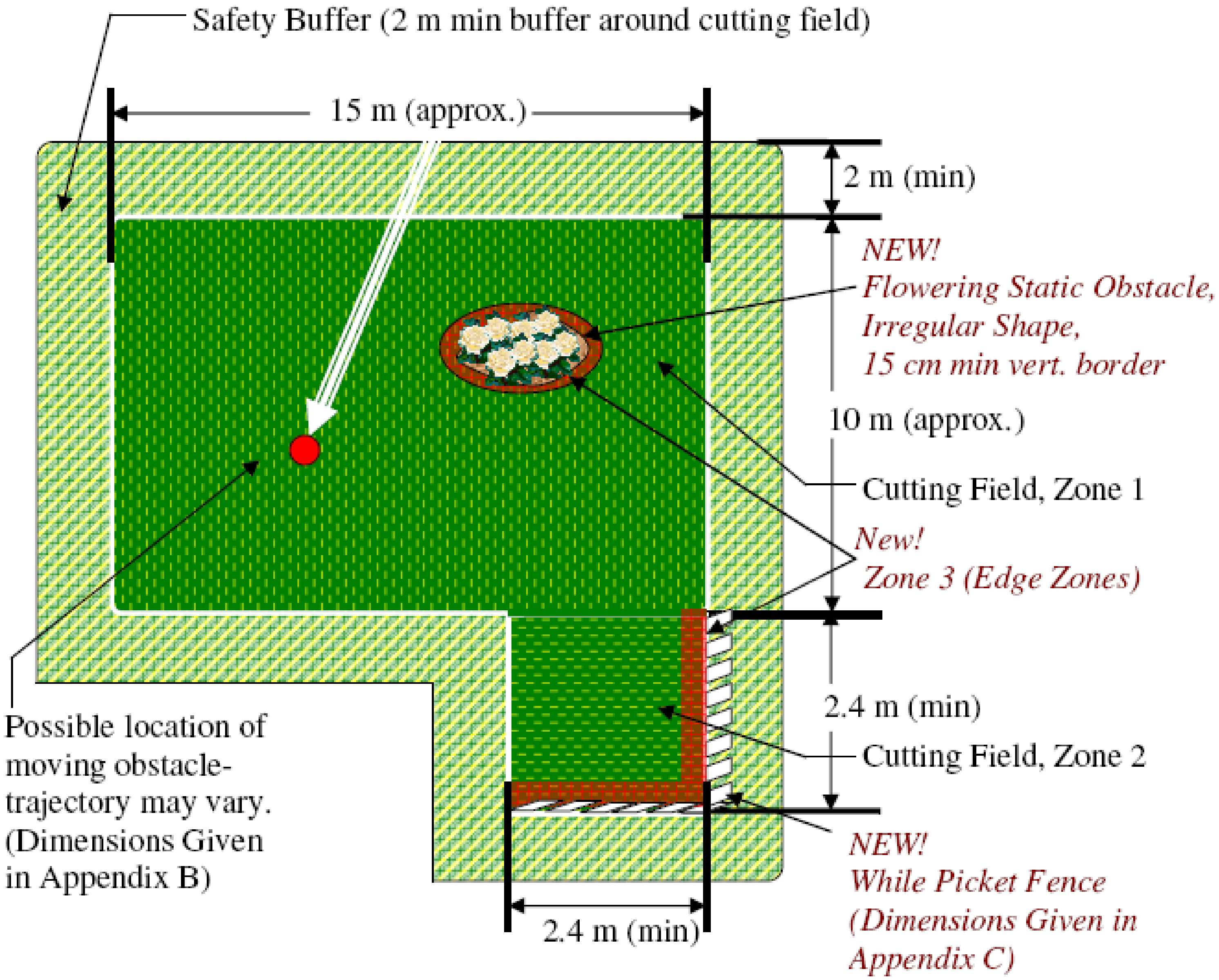
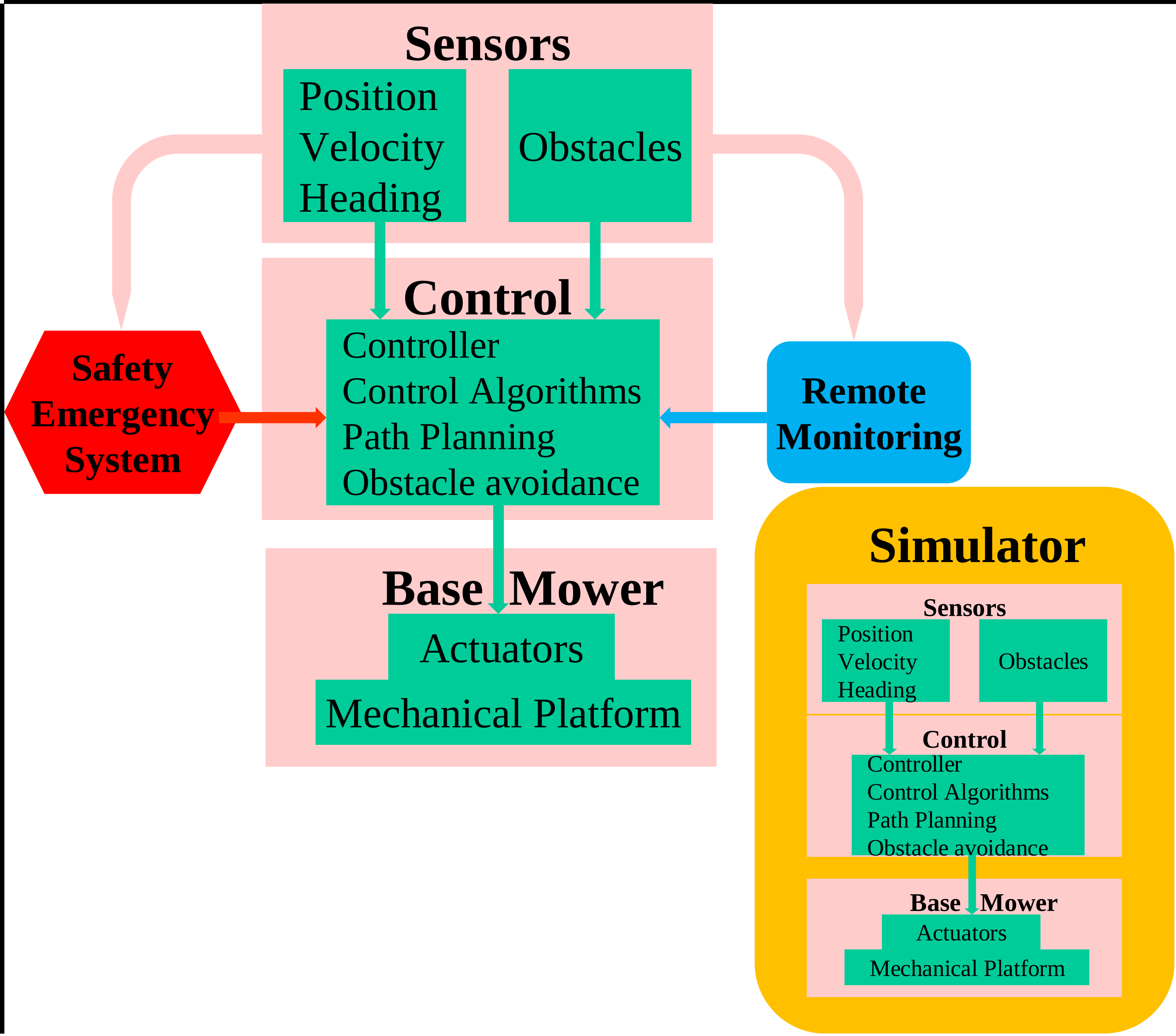


Red Blade Design Components



RedBlade I: Hardware

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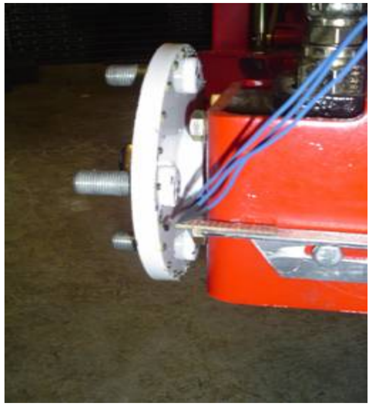
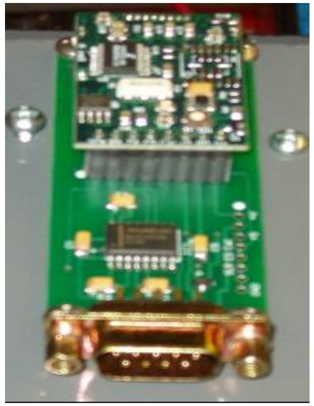
Garmin GPS16
2 * $145

Hall Sensor
$40



HRM3200 Compass
$350 (Donation)



PH Servos
$1200 (Donation)

Freewave Modem
$3000 (Donation)

Snapper Mower
$5000 (Donation)

RedBlade I: Custom DGPS

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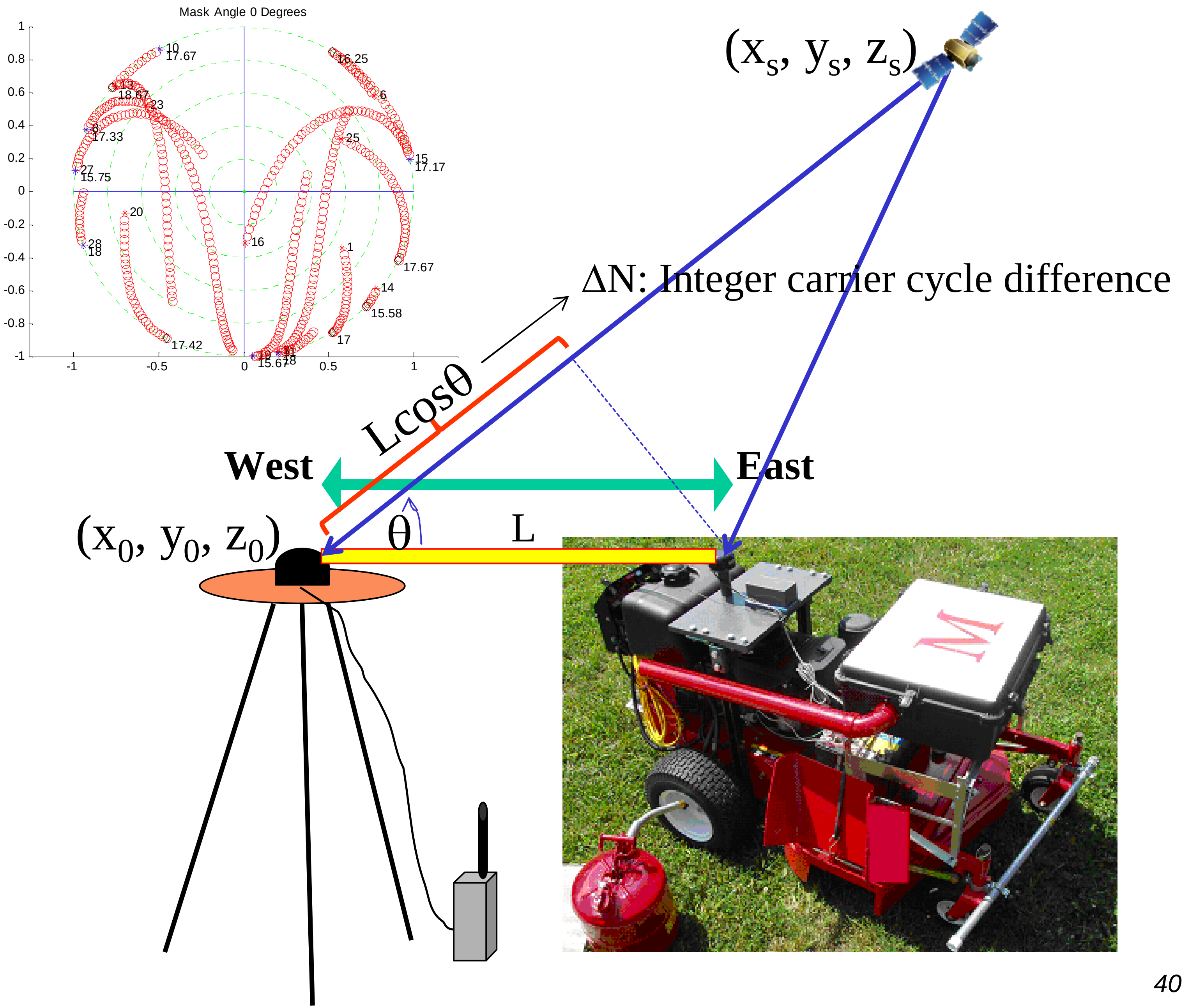


RedBlade I: Custom DGPS

Carrier phase measurement: $\phi = r - I + T + c\left(\delta t_u - \delta t^s\right) + N\lambda + \varepsilon$

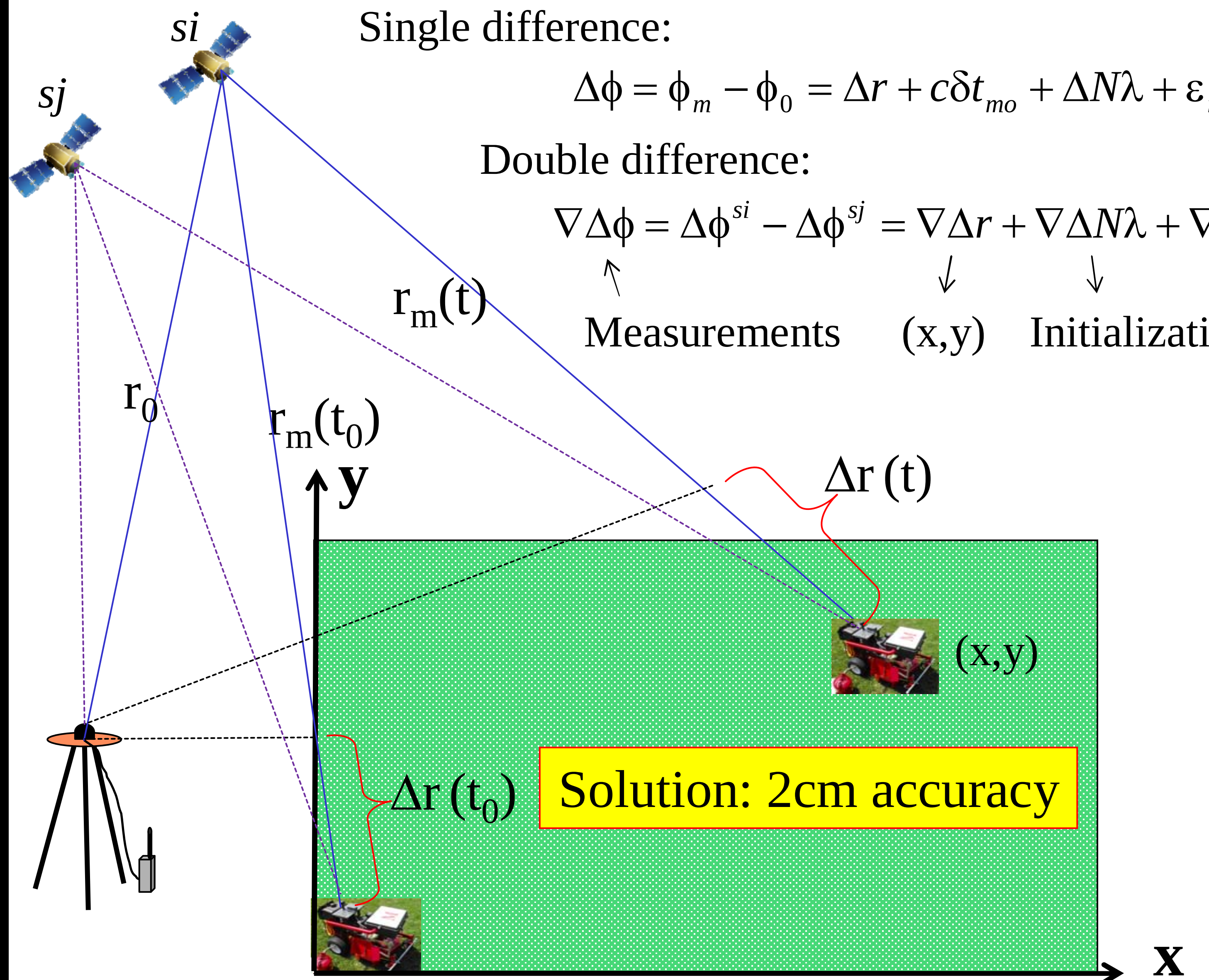
Single difference:

$$\Delta\phi = \phi_m - \phi_0 = \Delta r + c\delta t_{mo} + \Delta N\lambda + \varepsilon_{m0}$$

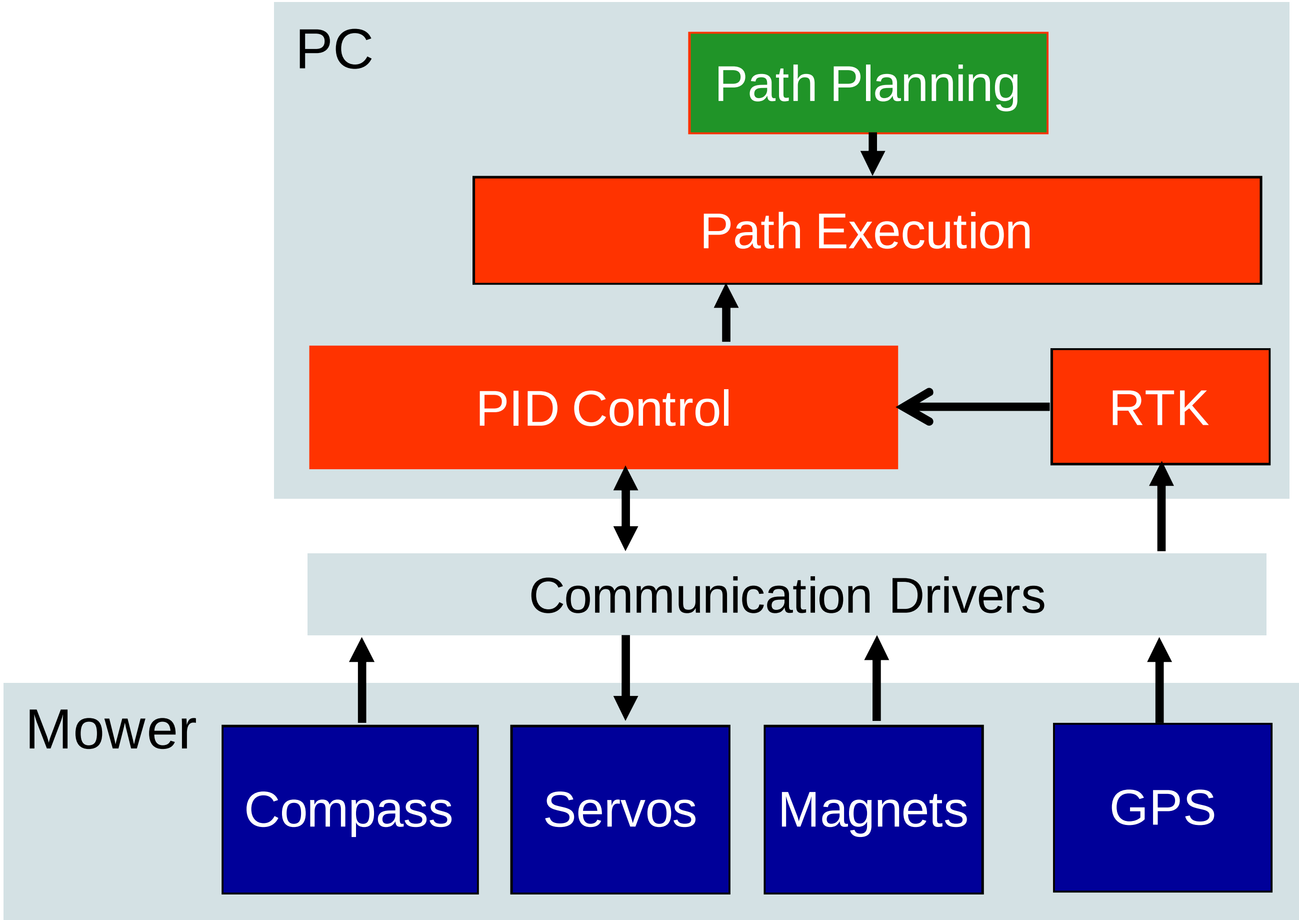
Double difference:

$$\nabla\Delta\phi = \Delta\phi^{si} - \Delta\phi^{sj} = \nabla\Delta r + \nabla\Delta N\lambda + \nabla\varepsilon_{m0}$$

↑ Measurements ↓ (x,y) ↓ Initialization



Control Architecture



Control Algorithm

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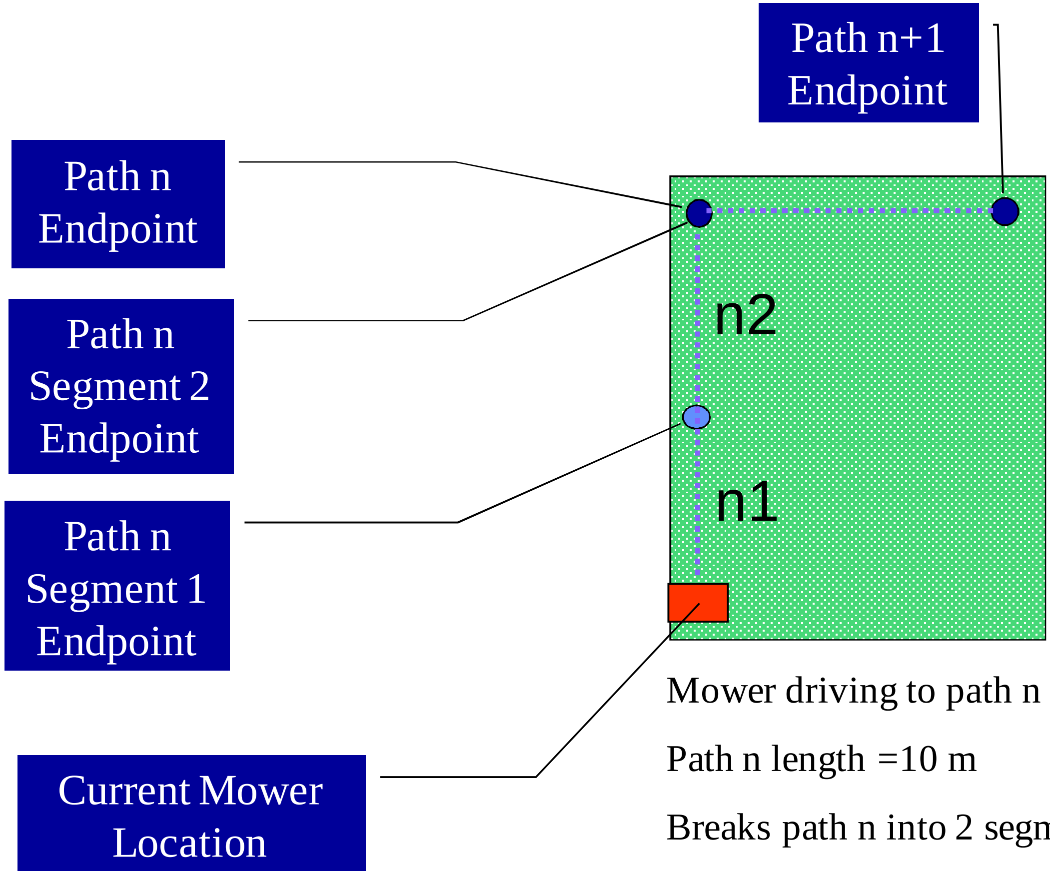

Mower driving to path n endpoint.

Path n length =10 m

Breaks path n into 2 segments: n1, n2

Given current GPS location, drive 5 meter North, stop,
Take new GPS reading and continues to n2 goal goal.

PID Control

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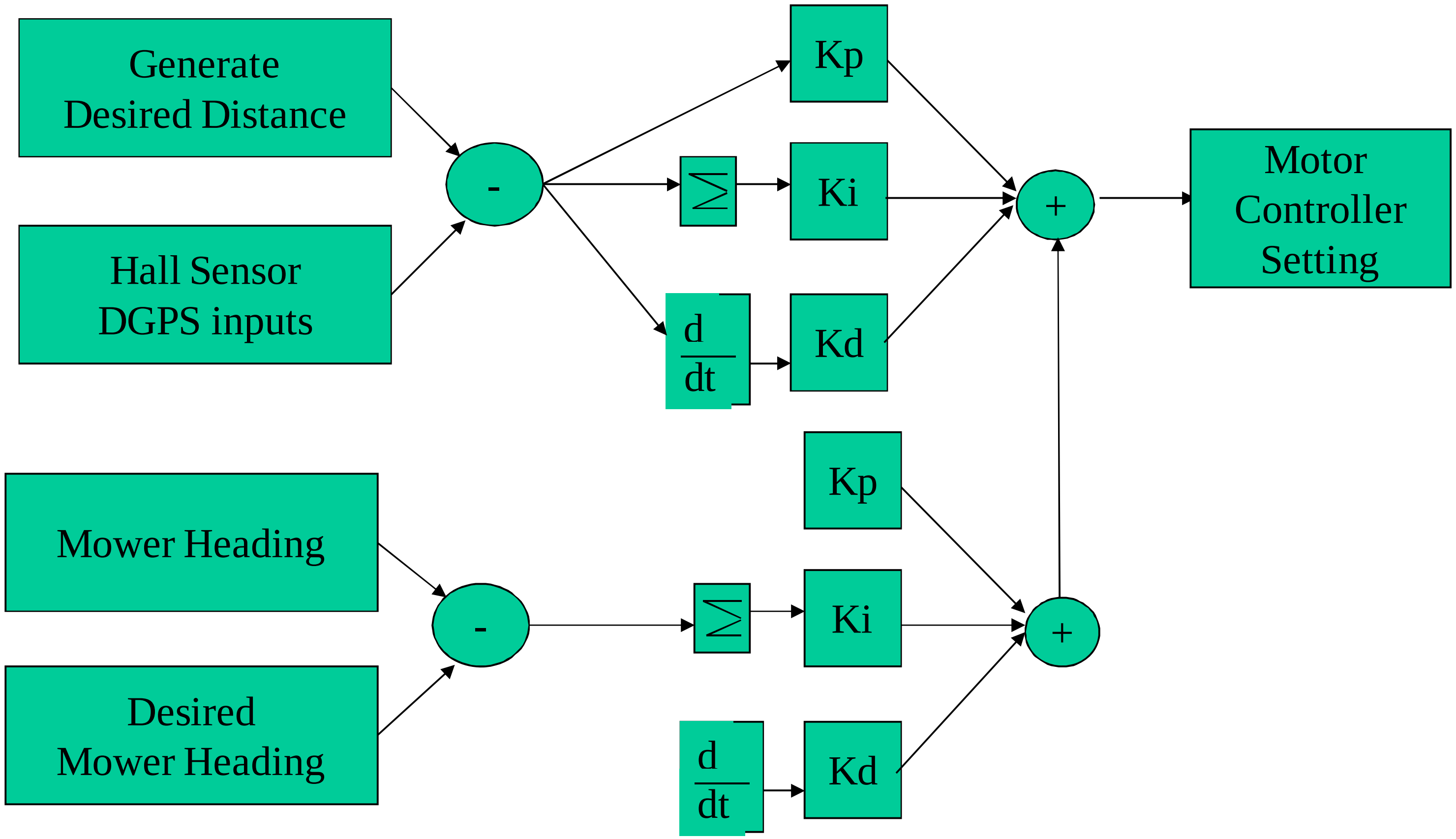


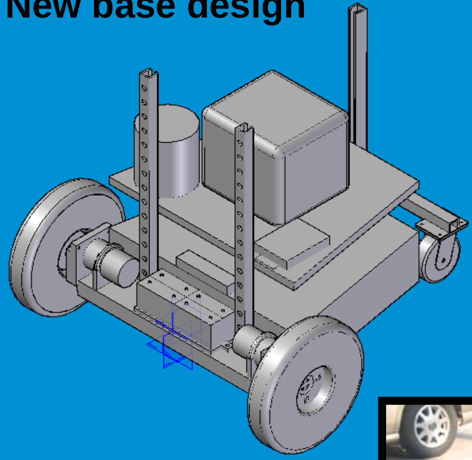
Competition Day

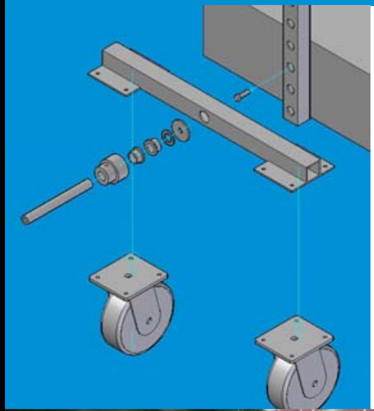
- Introductions
- Overview
- **Autonomous GNC**
  - Basic Control
  - **ION Robotic Mower**
  - MUC
  - Mindstorm Robots
- Lego® Mindstorms Intro
- Lego® Mindstorms Challenge

RedBlade II: Platform Re-design

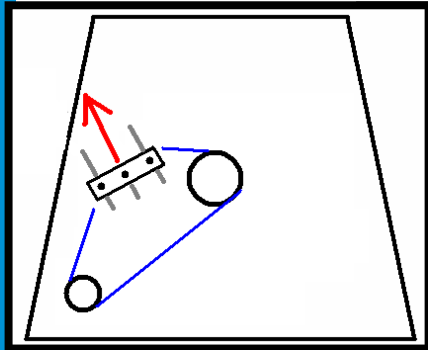
- Introductions
- Overview
- **Autonomous GNC**
  - Basic Control
  - **ION Robotic Mower**
  - MUC
  - Mindstorm Robots
- Lego® Mindstorms Intro
- Lego® Mindstorms Challenge

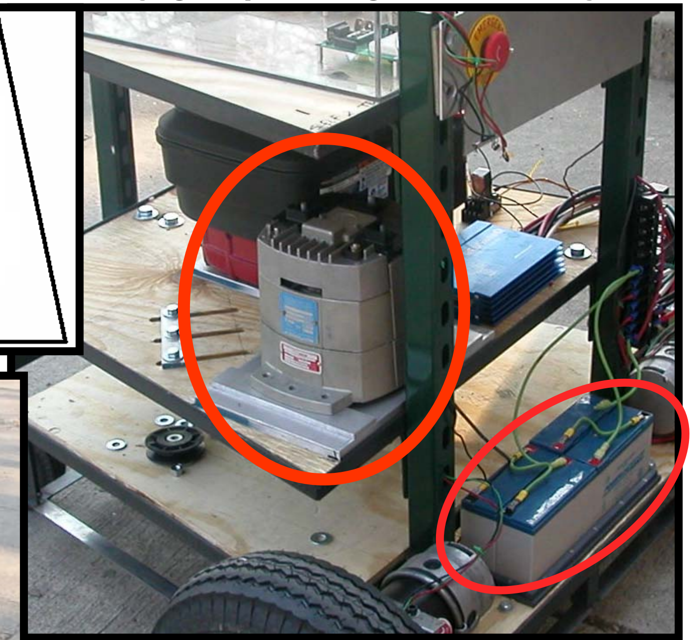
New base design

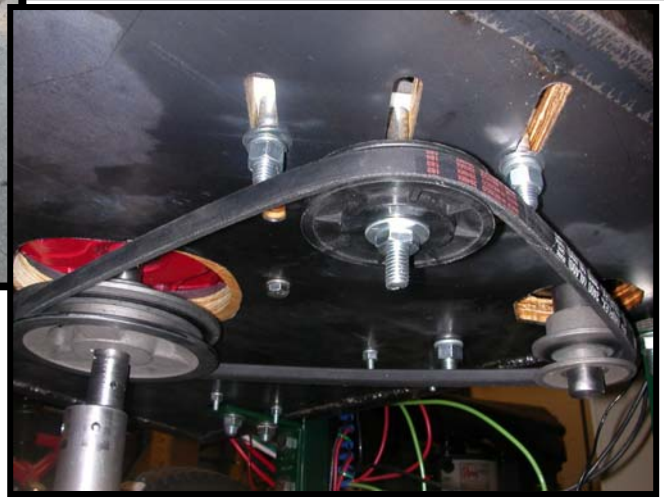




Hybrid battery/gas power generation system







Multi-layered shelves
Electric motors

RedBlade II: New Electronics

- Introductions
- Overview
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- 2 on-board NovAtel Superstar II RX: mower heading
- Optical encoder
- Roboteq motor controller
- Systronix Saje Processor
- Programmed in Java
  - Multi-threaded execution, dynamic class loader

RedBlade III: Obstacle Avoidance

- Introductions
- Overview
- **Autonomous GNC**
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Sonar
(Parallax)

Range < 3m

Scanning Laser
(Sick)

Stereo Vision
(Unibrain)

Over a range of 12m,
the ranging error <5%.

RedBlade III: Dynamic Path Planning

- Introductions
- Overview
- **Autonomous GNC**
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  - MUC
  - MUC
  - Mindstorm Robots
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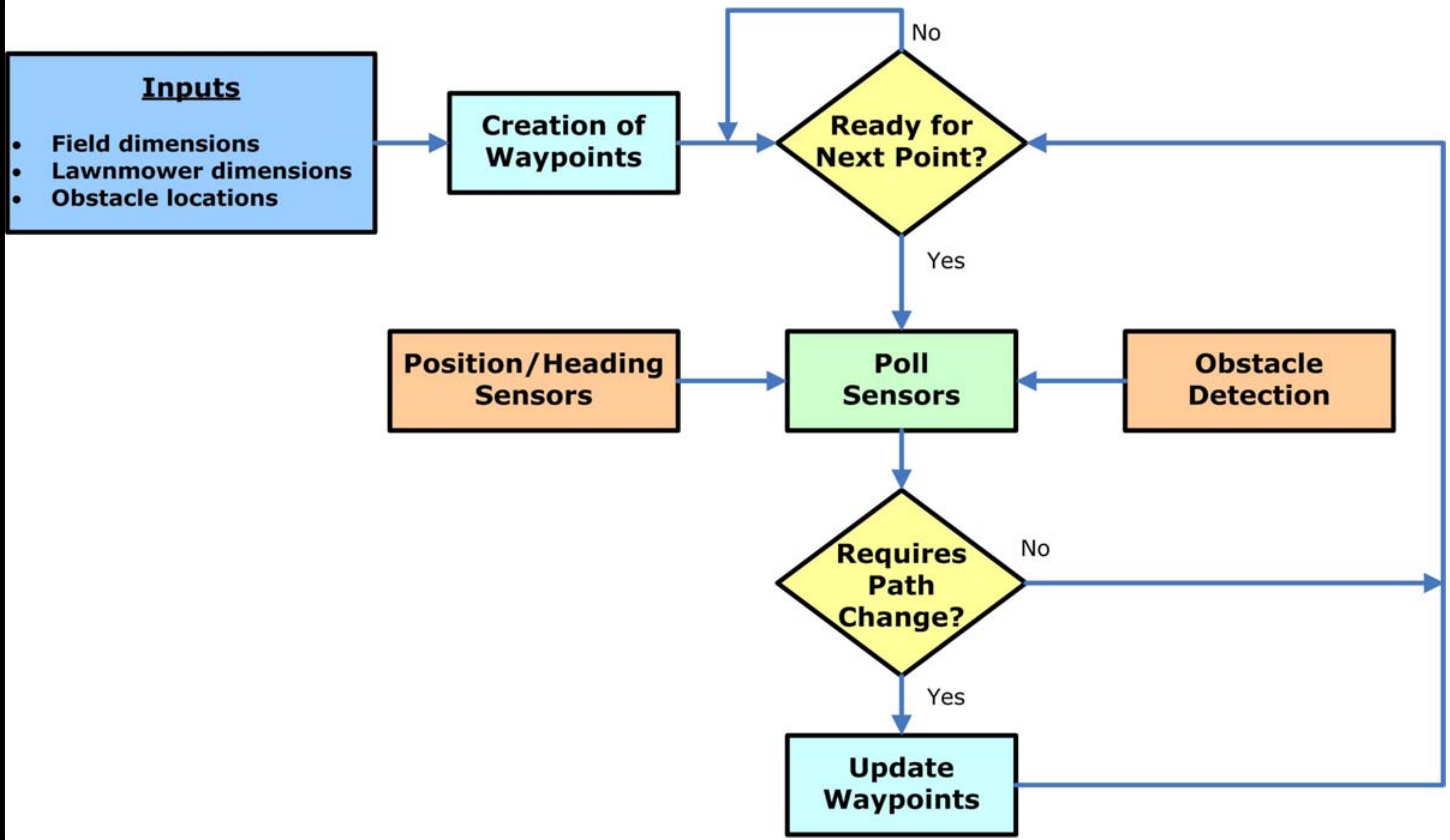
- Lego® Mindstorms Challenge



RedBlade III: An Example Path Layout

- Introductions
- Overview
- **Autonomous GNC**
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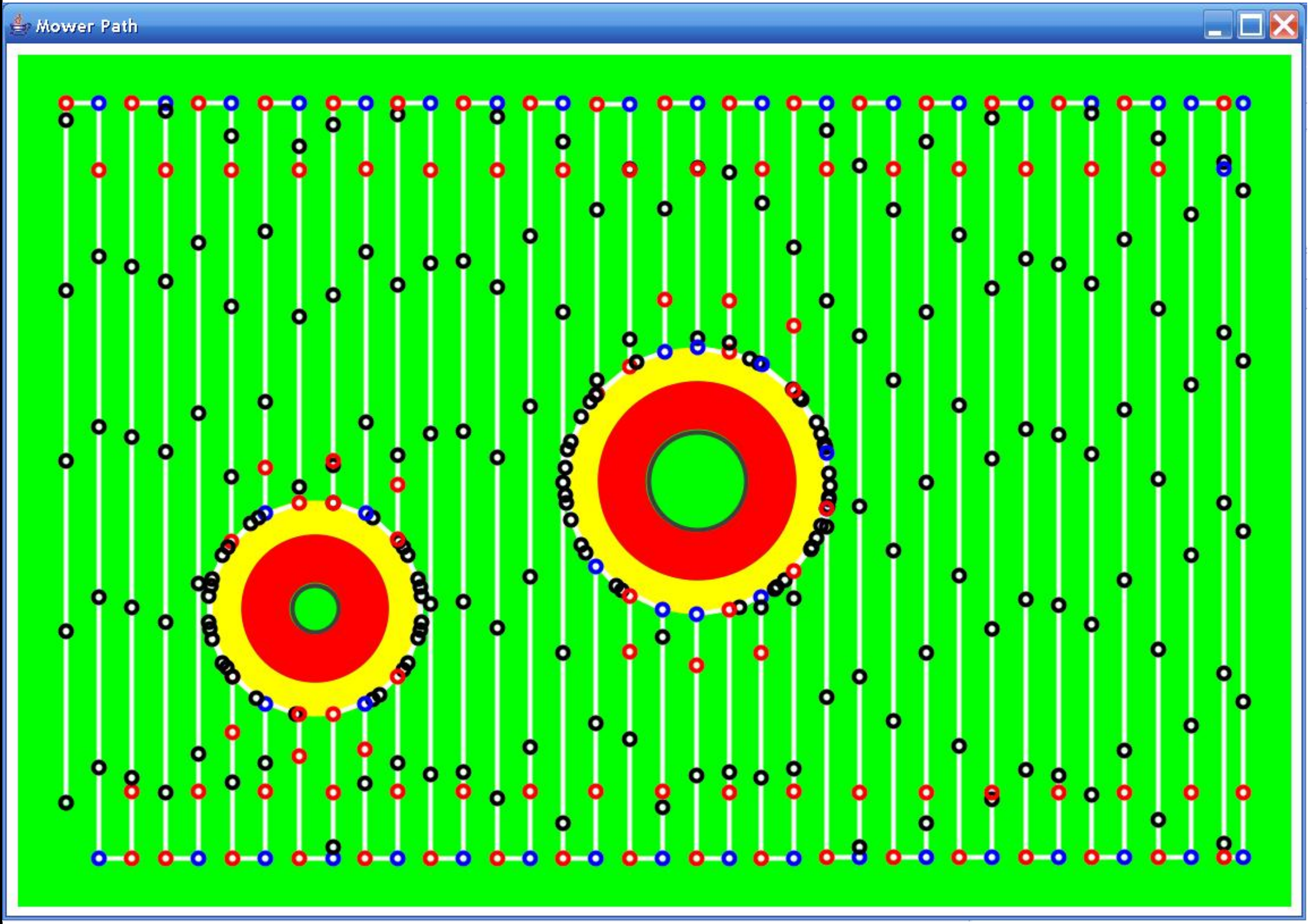

Final Two Days

- Introductions
- Overview
- **Autonomous GNC**
  - Basic Control
  - **ION Robotic Mower**
  - MUC
  - Mindstorm Robots
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- Lego® Mindstorms Challenge

We left campus in this shape

....

Mechanical support problem

Laser problem

IMU problem

....

Two days later....

RedBlade IV: Everything All Over Again…

- Introductions
- Overview
- **Autonomous GNC**
  - Basic Control
  - **ION Robotic Mower**
  - MUC
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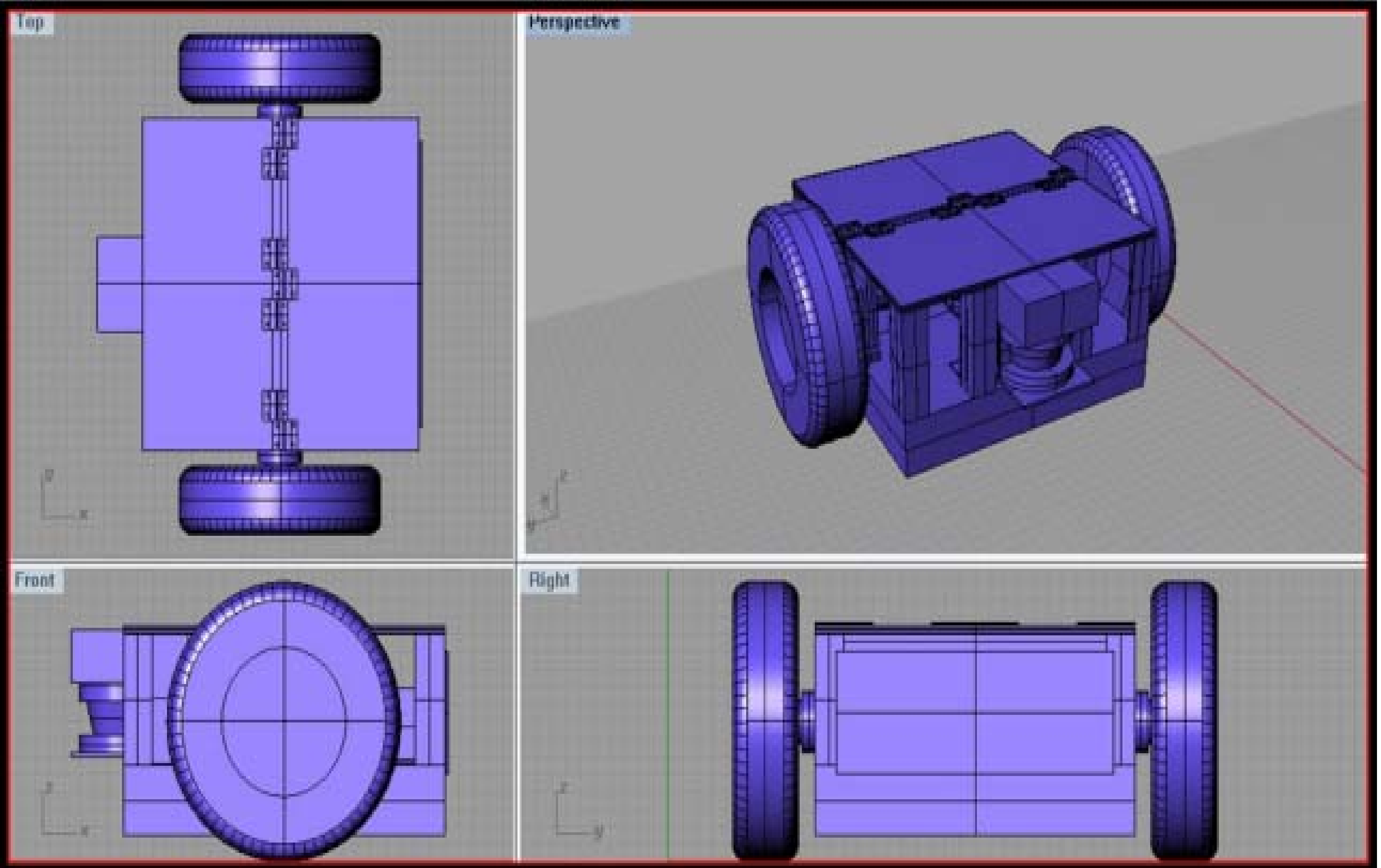
New Platform



RedBlade IV: New Gadgets

- Introductions
- Overview
- **Autonomous GNC**
  - Basic Control
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  - MUC
  - Mindstorm Robots
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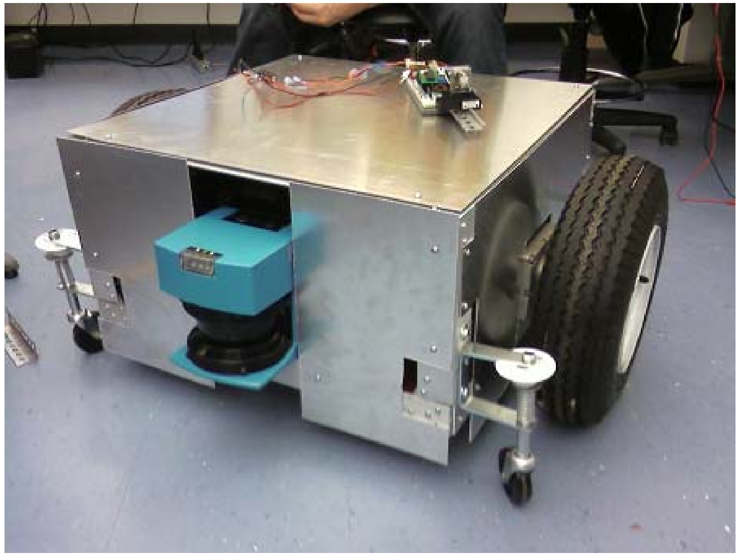
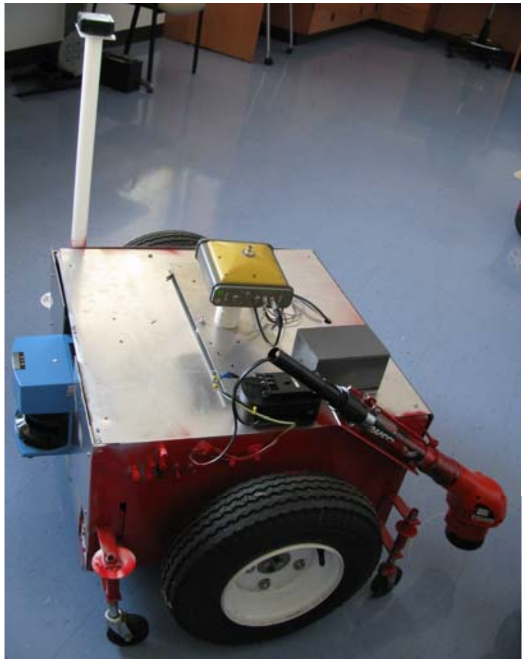


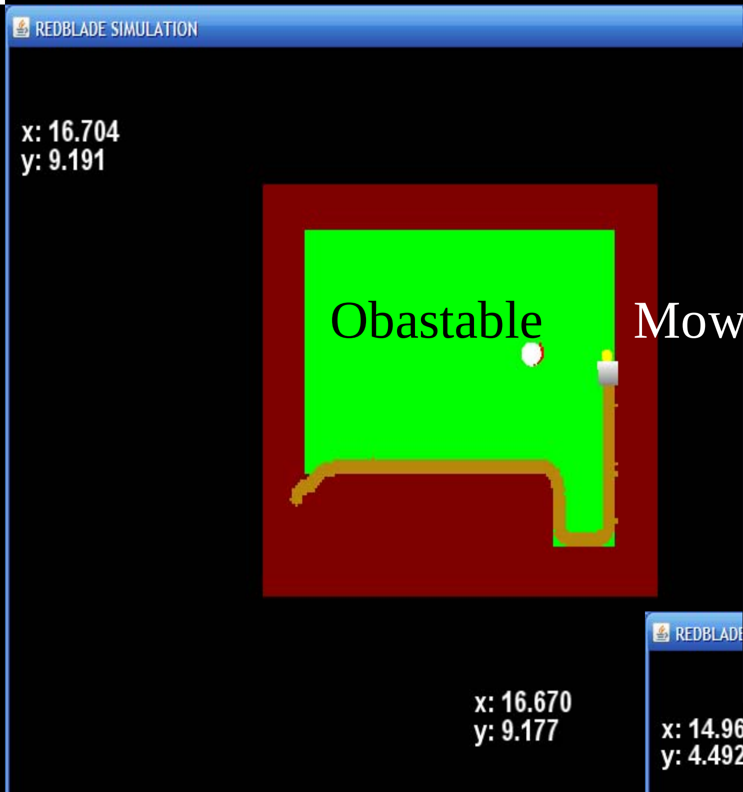
Topcon Hiper Lite+

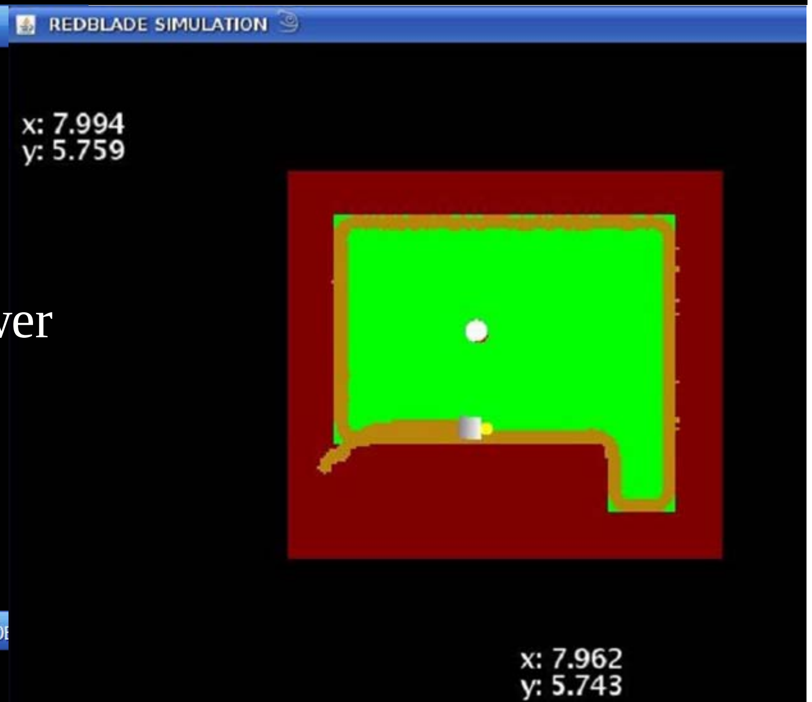
IMU

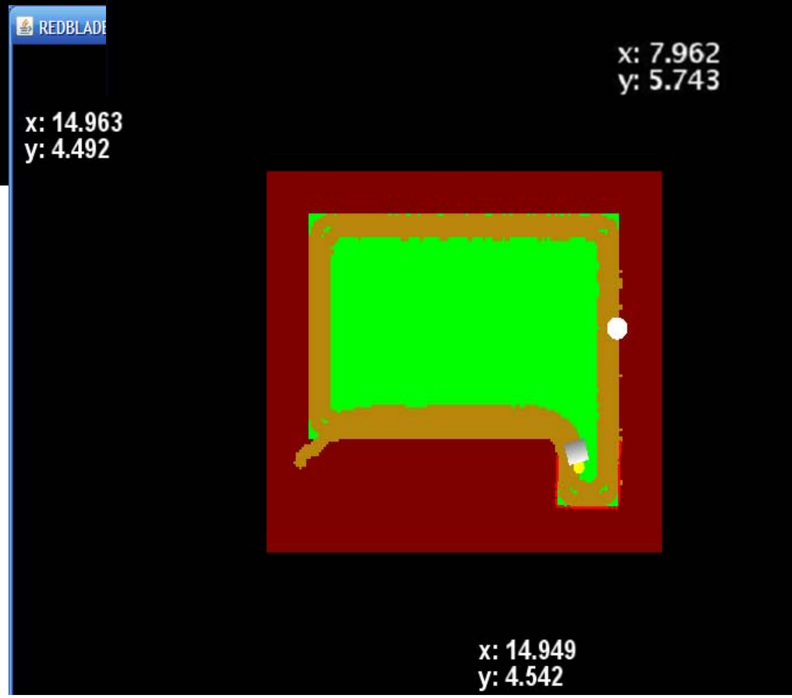


Edge Trimmer

RedBlade IV: Control Simulator







Variables:
- Field layout
- Obstacle control
- Sensor error model
- Sensor update rates
- Mower response time

It is raining, lightening, and thundering, but we are not ready yet….

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Highlights of RedBlades Features

- Introductions
- Overview
- Autonomous GNC
  - Basic Control
  - ION Robotic Mower
  - MUC
  - Mindstorm Robots
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- Lego® Mindstorms Challenge

- RedBlade I: Custom DGPS
- RedBlade II: Mechanical platform
- RedBlade III: Obstacle avoidance
- RedBlade IV: Control simulator
- RedBlade V: ?

Students/Faculty/Staff Involved

- Introductions
- Overview
- **Autonomous GNC**
  - Basic Control
  - **ION Robotic Mower**
  - MUC
  - Mindstorm Robots
- Lego® Mindstorms Intro
- Lego® Mindstorms Challenge

Students
Brett McNally
Micah Stutzman
Collin Koranda
Chris Mantz
Jeff Macasek
Scott Miller
Marcus French
John Russler
Jason Smith
Lauren Smith
Tom Walters
Kyle Green
Dan Anderson
Mike Lane
James Reynolds
Greg Newstadt

Faculty/Staff
Jade Morton
Scott Campbell
James Leonard
Mike McCollum
Jeff Peterson

Sponsors:
Snapper
NovAtel
Topcon
Outback Guidance and Control
Freewave Technologies
Parker Hannifin Corp.
Auto Zone
Honeywell
Miami University

Sample Designs from Competition

- Introductions
- Overview
- **Autonomous GNC**
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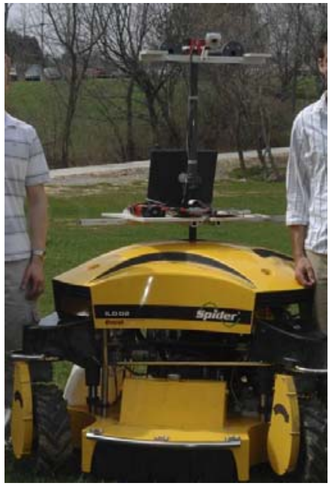
CWRU



Cedarville

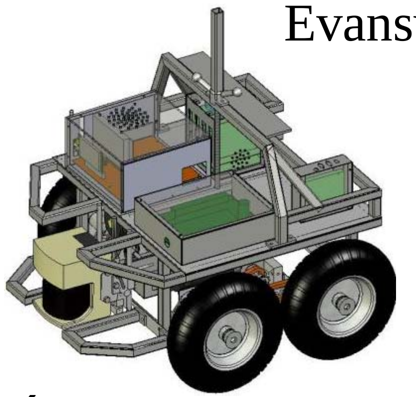
Ohio University

Florida State

University Evansville

University of Waterloo

Wright State University



École de technologie supérieure