Ohio University ∙ M.A.C.S.
Monocular Autonomously Controlled Snowplow

Student Members: Samantha Craig, Matthew Miltner, and Derek Fulk
Faculty Advisors: Dr. Frank van Graas and Dr. Wouter Pelgrum
Team Objectives and Composition

• Team Objectives
  – **Gain:** To gain knowledge in the field of navigation and experience in real-world problems and situations
  – **Aid:** To aid in the advancement of navigation technology
  – **Promote:** Help promote awareness of The ION, Ohio University, and the effects of engineering on everyday life

• Team composition
  – Matthew Miltner, M.A.C.S. team lead, undergraduate EE student
  – Samantha Craig, M.A.C.S. chief engineer, undergraduate EE student
  – Derek Fulk, M.A.C.S. treasurer, undergraduate EE student
  – Wouter Pelgrum, faculty advisor
  – Frank van Graas, faculty advisor
Plowing Strategy

- MACS plowing strategy:
  - Two passes using an angled blade with 22 cm overlap in the center and 11 cm overlap on the sides of the snowfield
  - Overlap for navigation/guidance/control accuracy, and snow fallback behind the blade
  - Acceleration control to minimize wheel slip
  - All turn sequences consist of first backing up followed by a 90-degree turn (twice for 180°)
    - Avoids dragging snow in front of the blade around the turn
  - In the unlikely case where the snowplow doesn't move due to wheel slip or excessive snow build-up, the guidance system will detect this case and command the snowplow to back up and try again until forward motion has been re-established
# Snowplow Vehicle Program Top-Level Rulebook Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>The snowplow shall be autonomous and unmanned and shall not be remotely controlled during the competition.</td>
<td></td>
</tr>
<tr>
<td>The snowplow shall observe a speed limit of 2 m/s.</td>
<td></td>
</tr>
<tr>
<td>The system shall be equipped with both a physical power-off switch and a wireless remote power-off switch. The snowplow shall cease operation within 2 seconds of power-off.</td>
<td></td>
</tr>
<tr>
<td>The snowplow and any of its attachments shall not exceed 2 m in any dimension.</td>
<td></td>
</tr>
<tr>
<td>The snowplow tires shall not be augmented with rivets, spikes, or chains.</td>
<td></td>
</tr>
<tr>
<td>The snowplow shall be self-powered and contain no power source external to the vehicle. Power shall either be combustible fuel, batteries, or both.</td>
<td></td>
</tr>
<tr>
<td>The plowing action shall be accomplished through direct contact with the ground surface.</td>
<td></td>
</tr>
<tr>
<td>The snowplow shall be equipped with an electrical ground.</td>
<td></td>
</tr>
<tr>
<td>Competition specific design requirements: 1) The snowplow will complete each course in under 20 minutes; 2) The snowplow must stay within the buffer zones; 3) The snowplow shall operate in any weather condition (except for severe weather); 4) Navigation aiding sources must be self-powered; 5) The snowplow must operate with snow depths of approx. 5 cm; 6) The snowplow must completely clear all the snow from the snowfield paths.</td>
<td></td>
</tr>
</tbody>
</table>

Source: The first Annual Autonomous Snowplow Competition Rulebook, Revision 2011.2.0
## Snowplow Vehicle Derived Numerical Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position accuracy</td>
<td>0.05 m (rms)</td>
<td>overlap buffer of 0.11 m, control accuracy of 0.05 m, beacon accuracy of 0.02 m, laser accuracy of 0.02 m</td>
</tr>
<tr>
<td>Heading accuracy</td>
<td>10 mrad (rms)</td>
<td>limits position error to 1 cm after 1 m of travel, which is detected/corrected by positioning sensor</td>
</tr>
<tr>
<td>Maximum snowplow speed</td>
<td>2 m/s</td>
<td>competition speed set at 0.5 m/s for accurate control and safety</td>
</tr>
<tr>
<td>Safety stopping distance</td>
<td>&lt; 0.5 m</td>
<td>to remain within outer boundaries</td>
</tr>
<tr>
<td>Safety response time</td>
<td>&lt; 1 s</td>
<td>at 0.5 m/s, vehicle will travel at most 0.5 m</td>
</tr>
<tr>
<td>Blade angle (0.8-m width)</td>
<td>&gt; 20 deg</td>
<td>cover multiple bricks to avoid catching brick edges (brick layout from site visit)</td>
</tr>
<tr>
<td>Vehicle weight</td>
<td>&gt; 500 lbs</td>
<td>derived from extensive testing to ensure traction while plowing 5 cm of snow with &quot;soft&quot; tires</td>
</tr>
<tr>
<td>Vehicle turn radius</td>
<td>&lt; 1 m</td>
<td>to stay within the maneuvering/finish/start zones during maneuvers</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>0° – 30° F</td>
<td>expected temperature range in St. Paul during the competition (average temperature is 16° F)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>&lt; 2 m</td>
<td>in all dimensions with plow attached</td>
</tr>
</tbody>
</table>
MACS: Vehicle Design

• Given the competition requirements, vehicle design was borrowed from Ohio University's Search and Rescue robot (J. Litter, M.S. Thesis, Ohio University)

• Major design modifications
  – V-profile "soft" tires, added weight for traction
  – Electrical re-design with plug-and-play charging and extensive safety circuitry (remote stop, emergency stop buttons)
  – 360-degree laser for positioning
  – Standard blade for plowing
  – Blade attachment to vehicle
  – Weather proofing
  – Matlab® control with C++ for inner control loop

• Design iterations to accommodate rule changes (tires)
From Concept to Final Design

PDR Concept (October 2010)

Implementation (December 2010)
Final Implementation

- 4 motors for a total of 5 Horsepower
- Plow cut to 80 cm at an angle of 26 degrees, allowing for the plow to be the exact width of the wheel base (72cm)
- V-shaped snow tires
- 360 degree laser for navigation
- Achieved 2cm accuracy
MACS Design Details

- Navigation laser
- Status Panel and charging inputs
- Four 1.25-hp motors with gearing and encoders
- Dual Mechanical Shut-Off (top and rear mounted)
- Climate-resistant computer compartment (top inside layer)
- Blade and connection to snowplow

High-Power Wiring
MACS: High-Level Block Diagram

Scanning Laser
SICK LD-OEM1000

TCP/IP
WiFi Comm

TCP/IP
PROCESSOR
AMD 64-bit
2.4 GHz Dual-Core
Total Diss. Power = 45 W
Solid State Drive: 64 GB

USB
Gyroscope
XSENS MTi

USB
Left Motor Controller
RoboteQ

USB
Right Motor Controller
RoboteQ

TCP/IP
Remote STOP

TCP/IP
Safety Circuitry

USB
Charging Circuitry

External Switch
External Power

Motor Power
Four 12-V Batteries

relay switch

Clean Power
12-V Battery
MACS is Weighing-In

Weight: $155 + 136 + 166 + 80 = 537$ lbs
Dimensions: $1.27$ m (length), $0.72$ m (width), $0.97$ m (height)
MACS: Control System Design

• The control system uses three control loops that have been previously implemented and tested on Ohio University's Autonomous Lawnmower

1. Constant velocity control loop using two RoboteQ motor controllers with encoder feedback from the front motors (approx. 1 kHz update rate with a 100 Hz bandwidth PID controller)

2. Heading control loop using an XSENS MTi gyro (0.1°/minute drift after calibration) at a 50 Hz update rate with latencies below 10 ms (approx. 10 Hz bandwidth, limited by RoboteQ command response)

3. Navigation control loop using a SICK LD-OEM1000 with passive beacons at an update rate of 5 Hz to adjust for path deviations. Typical latency of 0.2 s is acceptable:
   1. Vehicle displaces 0.1 m during 0.2 s at the maximum competition speed of 0.5 m/s)
   2. Cross-track velocities are well below 0.1 m/s, resulting in displacement errors of less than 0.02 m due to latency)
MACS: Navigation System Design

- Concept: Develop a navigation solution for dense urban environments that are likely GNSS-challenged (building blockage, severe multipath, interference)
- Accuracy needed: 5 cm (rms) relative to the snow field
- After a trade-off study (GNSS, camera, laser): laser positioning was selected as most effective to satisfy objectives (plowing of sidewalks in urban environments)
  - Update rate and latency requirements are mitigated by using a heading gyroscope that results in less than 1 cm of error between and after position updates
  - For redundancy and fault detection, laser position solution is calculated after every 360-degree scan (5 scans per second)
    - 0.25° increments with a 0.16° beam divergence provides "full coverage"
**SICK LD-OEM1000 Scanning Laser**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type:</td>
<td>Mid Range</td>
</tr>
<tr>
<td>Light Source:</td>
<td>Infrared (905nm)</td>
</tr>
<tr>
<td>Laser Class:</td>
<td>1 (EN/EC 60825-1), eye-safe</td>
</tr>
<tr>
<td>Field of view:</td>
<td>360 °</td>
</tr>
<tr>
<td>Scanning Frequency:</td>
<td>5 Hz ... 15 Hz</td>
</tr>
<tr>
<td>Beam Divergence:</td>
<td>2.8 mrad</td>
</tr>
<tr>
<td>Operating Range:</td>
<td>0.5m ... 250m</td>
</tr>
<tr>
<td>Resolution:</td>
<td>3.9 mm</td>
</tr>
<tr>
<td>Power Consumption:</td>
<td>36 W</td>
</tr>
<tr>
<td>Weight:</td>
<td>2.4 kg</td>
</tr>
</tbody>
</table>
iPad Status Display
Laser Stealth Mounting

Laser cover is required to shield against direct sunlight into the laser

Design credit: F-117 engineers

Stealth design for supports:
- Non-reflecting black paint
- Sharp corners toward the laser to minimize reflections
Scanning Laser Position Solution

- Two beacons are sufficient to solve for 2-D position and 4-quadrant laser heading based on one 360° scan.

\[
\begin{pmatrix}
Y_1 \\
X_1 \\
Y_2 \\
X_2
\end{pmatrix}
= \begin{pmatrix}
0 & 1 & R_1 \cos(\theta_1) & R_1 \sin(\theta_1) \\
1 & 0 & -R_1 \sin(\theta_1) & R_1 \cos(\theta_1) \\
0 & 1 & R_2 \cos(\theta_2) & R_2 \sin(\theta_2) \\
1 & 0 & -R_2 \sin(\theta_2) & R_2 \cos(\theta_2)
\end{pmatrix}
\begin{pmatrix}
X \\
Y \\
\sin(\psi) \\
\cos(\psi)
\end{pmatrix}
\]

- Compensate laser scan with gyro measurements.
- Use redundant beacons: at least 4 visible at all times.

Where:
- \(X_1\) and \(Y_1\) = beacon coordinates
- \(R\) = Range to the beacon (measured)
- \(\theta\) = Angle to the beacon (measured)
- \(\psi\) = Laser heading

Parameters to solve for:
- Laser position \((X, Y)\)
- Laser heading angle \(\Psi\).
MACS: Beacon Design and Placement

The laser beacons are designed out of PVC pipes supported vertically on PVC drains and pavers for stability.

Beacons 1 & 2 are placed to define the relative location of the snow field using a ruler. Other 4 beacons are placed approximately in their indicated positions and are surveyed with the scanning laser during initialization.

Beacons 1 through 4 are placed to define the relative location of the snow field using a ruler. Other 6 beacons are placed approximately in their indicated positions and are surveyed with the scanning laser during initialization.
MACS: Guidance System Design

- MACS uses several commands that are used in a script generated to clear the snow of the field.
  - Snow field coordinates are used to generate command set actions that are executed successively as a function of position

- MACS command set:
  - Initialize
  - Idle
  - Stop immediately
  - Track heading at a set speed (positive or negative) and a set control gain
  - Turn using a commanded final heading at a set speed
    - For zero speed, robot will have a zero turn radius (skid steering)
  - Slow stop at a set deceleration and a set control gain

Straight Line Illustration
MACS: Processor and Software Design

- Single processor (AMD 64-bit, 2.4 GHz Dual-Core)
  - High-level software written in Matlab® for rapid prototyping and advanced development environment
    - Laser processing, path execution
  - Low-level software written in C++ for speed (latency)
    - Drivers for laser, gyro and motor controllers
    - Heading controller software

![Timelines]

- Laser updates: 200 milliseconds
- Gyro updates: 10 milliseconds
- Motor updates (RoboteQ): 1 millisecond
Safety System: Fail-Safe Design

- Emergency shut-off implemented using high-power relays that switch power to the motors (without power, relays are off)
- Motor power is enabled if and only if all of the following are true:
  - Remote stop control is active and within range
  - Two emergency stop buttons are enabled (pulled-out)
  - Motor controllers receive commands at least once per second (watchdog timer #1): fail-safe for processor failure
  - High-level software passes data to low-level software at least once per second (watchdog timer #2): fail-safe for software bugs
  - Guidance calculations determine that snowplow is within the boundaries: fail-safe for guidance and control errors
  - At least three beacons are visible to the laser to provide an over determined solution that passes an integrity residual check: fail-safe for laser measurement errors
Safety System (Continued)

• Safety system designed to keep snowplow within the snow field safety boundaries.
  – Maximum velocity used during the competition: 0.5 m/s
  – Buffer zone area not used by the snowplow for maneuvering is at least 0.5 m
  – Stopping distance from competition speed is less than 0.5 m
    (tested on snow-covered roads including on packed snow conditions to be expected during the competition)

• Extensive tests were performed to verify proper safety system functioning:
  – Range of remote shut-off was limited to 15 m to enforce a clear view of the snowplow during maneuvers
  – Power relays are directly controlled by other relays and switches to mitigate software malfunctions in the remote and emergency stop safety system
# Failure Modes and Recovery Actions

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Recovery Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer system malfunctions</td>
<td>Verify wiring and restart the computer</td>
</tr>
<tr>
<td>No snowplow displacement due to insufficient traction</td>
<td>Reverse direction of travel and try again</td>
</tr>
<tr>
<td>Motor controller malfunction</td>
<td>Reset motor controller when commanded velocities are not achieved (takes 0.5 seconds during which the robot stops)</td>
</tr>
<tr>
<td>Positioning system malfunction</td>
<td>Stop the snowplow until scanning laser is able to identify at least 3 beacons in five successive 360° scans</td>
</tr>
<tr>
<td>Computer or electrical circuitry failure</td>
<td>Diagnose problem and repair ASAP. If due to temperature below 0 F, install spare heating element. If due to temperature above 40 F, install additional computer cooling</td>
</tr>
<tr>
<td>Snowplow moves one of the beacons</td>
<td>Discard beacon from the navigation solution when its residual is larger than a set threshold (5 cm)</td>
</tr>
</tbody>
</table>
Test Program Summary

- Plow testing took place in November 2010 with artificial snow → decided to use a standard tractor snowplow blade
- Initial snowplow testing took place at an indoor ice-rink in December 2010 (original plan for competition venue)
  - Added weight, tire chains, and V-shaped tires to increase traction
- Outdoor testing in January 2010
  - Reduced blade width to 0.8 m and switched to dual tires, removed chains
  - Experienced St. Paul, MN weather conditions → no changes needed
  - Collected data under various conditions for playback (used to test software updates)
  - Verified blade angle and performance over irregular surfaces
## Overall Risk Assessment Summary

<table>
<thead>
<tr>
<th>Sub-System</th>
<th>Risk Description / Known Issues</th>
<th>PDR Risk Assessment</th>
<th>FINAL Risk Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot</td>
<td>Robot is not suitable for the competition</td>
<td>Low, robot has 5 hp motors and has been used previously</td>
<td>Mitigated through testing</td>
</tr>
<tr>
<td>Traction</td>
<td>Insufficient traction</td>
<td>Medium, will be tested in October 2010</td>
<td>Mitigated through added weight, tires</td>
</tr>
<tr>
<td>Plow</td>
<td>Train plow design is not adequate for the competition</td>
<td>Medium, will be tested in October 2010</td>
<td>Mitigated through use of standard tractor blade</td>
</tr>
<tr>
<td>Navigation system</td>
<td>Laser beacon system is not accurate enough</td>
<td>Low, previously tested for the lawnmower</td>
<td>Mitigated through testing</td>
</tr>
<tr>
<td>Computer and electrical circuitry</td>
<td>Components fail during the competition due to bad contacts or environmental conditions</td>
<td>Low, use professional technician for construction and perform outdoor tests</td>
<td>Prepared for field repairs</td>
</tr>
<tr>
<td>Guidance and control system</td>
<td>Guidance and control not sufficiently accurate and/or stable for the competition</td>
<td>Low, re-use lawnmower design</td>
<td>Mitigated through testing</td>
</tr>
</tbody>
</table>
Sponsor Acknowledgments

- Components, parts and student support
- School of EECS for student travel support, Avionics Engineering Center for parts, travel and student support
- SICK LD-OEM1000 purchase
- Last-minute rescue with a XSENS MTi Inertial Measurement Unit (the orange heart of M.A.C.S.)
- ION North Star Section for competition operation, management, and constructive feedback on the snowplow design, ION/ION Satellite Division for competition sponsorship and travel grant
2nd Annual Autonomous Snowplow Competition

Where: St. Paul, MN
When: Jan. 26th-29th, 2012

New Challenges:
- A simulated post will be placed in the snowfield. Competitors will be able to move, remove, or avoid this obstacle with no penalty, unless the movement causes a boundary infraction.

More Information:
http://www.autosnowplow.com/welcome.html
Any Questions?