Experiments for Autonomously Guided Vehicles for Antarctic Traverse

Robotics Institute Technical Report
Carnegie Mellon University

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Contents

Introduction

The U.S. Amundsen-Scott South Pole station is the southernmost continuously inhabited place on Earth since its construction in 1957. Resupply of the station is an annual necessity involving significant cost and risk. During the summer season, October to February, as weather permits multiple daily flights of LC-130 Hercules aircraft arrive from McMurdo Station on the coast delivering everything needed to sustain the South Pole station. All items including construction supplies and scientific equipment must be made air transportable. After 4 years of development the route for a McMurdo-South Pole traverse was established during the 2005/06 field season. The route crosses crevassed terrain on the Ross Ice Shelf, ascends the Leverett Glacier, and crosses the polar plateau. It requires approximately 40 days to complete southbound trek, somewhat less on the return north, still the opportunity to transport large items and overall fuel savings (reduced carbon output) are important benefits.

Motivation

This research is motivated by the potential of the McMurdo-South Pole traverse to reduce fuel consumption, program cost and environmental impact. **Our goals are to increase the average traverse speed and path accuracy and to decrease the fuel consumption, driver stress and expedition risk.** Additionally this may allow multiple traverse convoys per year, further compounding the benefits. We will accomplish this by incorporating state-of-art autonomous navigation technology into the convoy tractors.

Objectives

The ultimate objective of this research is to automate Antarctic traverse and indeed any significant cargo or scientific traverse in polar terrain. This goal will be reached over time and in stages.

The immediate objectives in this first year study are:
(O1)   Configure and integrate a sensing suite for test and evaluation
(O2)   Perform experiments in terrain sensing and modeling in arctic (snow, ice) terrain
(O3)   Perform experiments in position estimation in Antarctic location and environment
(O4)   Evaluate experiment data to inform system engineering
(O5)   Specify requirements and develop preliminary system architecture design for Antarctic
          traverse

This project will test three hypotheses in the course of the technical development and experimentation. That:
(H1)   An integrated suite of terrain sensors will span the range of performance required for
          Antarctic traverse.
(H2)   An integrated suite of inertial, visual, and global sensors will enable localization in the
          Antarctic environment.
(H3)   A distributed architecture for autonomous traverse can be incrementally staged into
   field operation.

Impact

This research is both immediate and long-term benefit to motivated by the potential of the McMurdo-South Pole traverse. We will accomplish this by incorporating state-of-art autonomous navigation technology into the convoy vehicles. This could be applied to any polar cargo or scientific traverse and provide efficiency and safety benefits. We expect that results from this development and analysis will apply to convoying in natural, unprepared terrain.

Technical Approach

This work combines state-of-art algorithms for sensing, terrain modeling, positioning, navigation, and autonomy with off-the-shelf technology, integrated to focus on the unique circumstances of Antarctic traverses including heavy-haul tractors, high reliability and safety, low temperatures, poor visibility, principally straight-line travel, sparse obstacles, deformable snow, and multiple control modes.

In the first year the activity centered around sensing and modeling (terrain and location) for a robotic tractor and configured, developed and demonstrate terrain sensing and vehicle positioning sensors and software for a Case Quadtrac STX530 and AGCO MT865. We identified sensors appropriate to Antarctic requirements and evaluated options in a metric-based trade analysis to configure suites of sensors for terrain and localization. We developed a sensor payload including interface, data logging and necessary power and thermal conditioning. This payload was be deployed in the field with well-practiced methods of calibration and techniques for measuring performance.
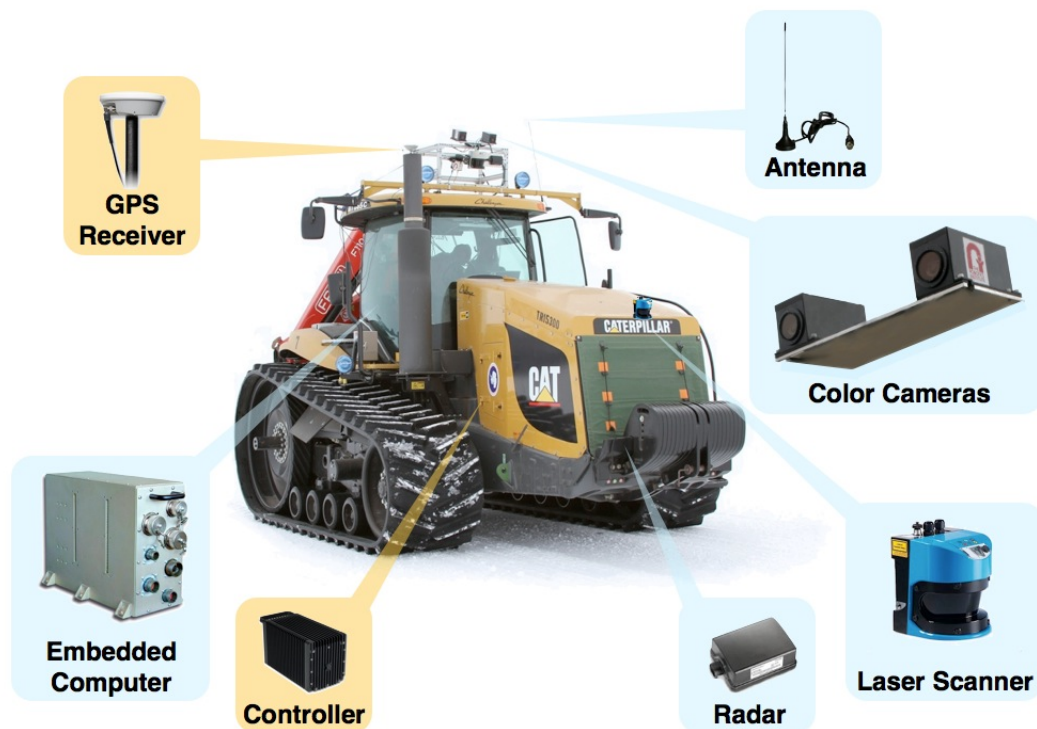
Field experimentation sought to validate the sensors in the Antarctic environment. Specifically we collected data sets with active and passive terrain sensors in a variety of terrain conditions and we simultaneously recorded visual, and global position, orientation, and velocity measures over long distances and durations. Extensive data sets are crucial to thorough evaluation of accuracy, precision and reliability for navigation. These activities will accomplish objectives O1-O4. With better understanding of expected sensor performance we produced an initial system concept design.

We envision an architecture for Antarctic tractors in which each capability is deployable on the multiple embedded processors. This abstraction aids portability and allows behaviors to be pipelined for high performance. One implication is that vehicle commanding becomes event-driven (asynchronous) rather than time-driven. Vehicle velocity tracks the complexity of the situation and anytime algorithms that provide best estimate, terrain model, or driving command at any point can be supported. This architecture can be applied on different vehicle types and is structured for communication and coordinate of multiple vehicles. This also allows incremental deployment as the level of autonomy in traverse increases.

Moving beyond research into methods, demonstration of performance and evaluation of alternatives, we began the process of configuring a best solution to tractor automation. In this first year, the objective (O5) is to identify requirements, evaluate options, and develop a preliminary system design. Hardware (sensors, computing, communication) and software must be examined and systemic trades resolved in order to engineer a best design for automating traverse. The intended outcome was to devise the necessary framework, a system concept design, that will be refined and implemented in order to produce first demonstrations of autonomous navigation.

The primary aim of our technical approach in the first year was to collect information and key measurements that will allow the design and development of a method and system for autonomous traverse in Antarctica.

Prior Research

Autonomous vehicles have been demonstrated in high-performance applications but these vehicles require significant infrastructure: prior maps and road networks, differential GPS corrections for precise localization, and high-performance computing to achieve throughput. With these resources, robots have achieved autonomously-driven speeds well beyond 3 m/s and traveled tens of kilometers on a single command. Yet innovative approaches are needed to improve the efficiency of the sense-plan-act cycle of autonomous navigation and to localize vehicles with minimal absolute references. The Antarctic environment is constrained relative to many terrestrial applications and autonomous tractors are on their own in a variety of aspects. We have conducted research long-distance autonomy under these constraints. We have developed an efficient data representations and algorithms in a distributed architecture that quickly and safely guides rovers through terrain. We describe key enabling concepts below.

Architecting Distributed Autonomy

Multi-vehicle distributed autonomy architecture can be configured for different vehicles and sensing. Functional modes enable/disable modules to create smooth transition from manual operation to teleoperation to full autonomy.

Our software architecture for Antarctic tractors will be informed by a decade of prior work in vehicle autonomy. Each module is a process with one or more threads deployable on the multiple onboard processors. This abstraction aids portability and allows behaviors to be pipelined for high performance. One implication is that vehicle commanding becomes event-driven (asynchronous) rather than time-driven. Vehicle velocity tracks the complexity of the situation and anytime algorithms that provide best estimate, terrain model, or driving command at any point can be supported. This architecture can be applied on different vehicle types and is structured for communication and coordinate of multiple vehicles.

Representing Terrain Efficiently

Recent research has developed terrain representation based on dynamic triangulated meshes. The triangulated mesh represents information at the resolution of sensing and captures relevant detail. Algorithms for adding geometric information provide efficient reduction and merging of meshes. Because rapid mesh merging can be applied, it is possible to maintain individual meshes and merge as needed to create terrain model of only the relevant region. This enables rapid updating in response to changes in the estimated location of sensor observations, so that changes to localization can be readily incorporated. When the belief state of past or current rover location changes, the updated position transforms guide remerging of the relevant meshes to provide a new best terrain model.

Terrain as well as static and dynamic objects, like other tractors and people, can be represented as meshes. Temporal change can come in the form updates to rover position or observation locations, as described in the case of localization corrections. Change can also occur because of dynamic (moving) objects in the environment. Rapid mesh merging techniques allow these changes to be incorporated and the rover's behavior to adapt. Without reasoning about or identifying an person or vehicle, sensing its occurrence nearby results in a obstacle moving through the mesh so that the motion and velocity of the rover responds accordingly. Other

complex sensing and reasoning could be added but responding to temporal changes as primitive level provides essential safety.

Maintaining Safety of People and Equipment
Traverse missions will be precluded from the full benefits of autonomous operation without solid evidence that systems will operate safely. A reliable method is to create simple yet effective bounds on what is considered "safe". When operating near people and equipment, simple behaviors maintain safe distances and speeds. We will evaluate reliable means of detecting the location of people with existing navigation sensors. Reliability could be achieved by incorporating multiple detection methods that have uncorrelated failure modes. For example, using laser scanning and vision and beacons independently classify potential people or vehicles. Each method alone lacks the reliability desired yet the chances of both failing simultaneously could be low.
Another important property is the ability to specify no-go or "slow-go" zones. These zones represent locations of should not be disturbed, including environmentally sensitive areas, locations of known or suspected crevasses, and temporary regions for camp or equipment. Path planning would consider these zones and prevent motion (or fast motion) within them. This capability requires not only reliable constraints on paths planned, but also on reliable rover localization. Tools for quickly and accurately specifying permanent and temporary regions will be developed.

Employing Functional Modes
While it is certain that Antarctic traverse conditions will be uncertain, there will be specific functional modes that will address the range of conditions. Varying conditions will be due to specific tasks, such as start-up, convoy marshalling, traverse, parking, maintenance, and shutdown or due to environmental or terrain conditions like whiteout, sastrugi, and slope climbing.
Our approach is to develop specific functional modes of operation for the tractor automation system. In a method termed sliding autonomy, interaction with the system shifts smoothly from direct manual control identical to unassisted operation of the tractor (steering wheel, fuel, braking, windscreen visibility) to assisted modes of obstacle warning, route tracking, vehicle coordination, with supervisory teleoperation to full autonomy in which operator passively monitors and the vehicle performs terrain and obstacle modeling, path planning, steering and speed control, and inter-vehicle coordination.

Manual	Full manual operation of tractor	Morning check, engine start, connect sleds, disconnect sleds, fueling, shutdown
Supervisory Teleoperation	Hands-off monitoring of selected function Assisted driving Remote or in-cab	Operated assisted condition. Operation near facilities and vehicles, dangerous terrain, mashalling convoy and tracking
Autonomous	Full automation of essential functions Operator parameter adjustment	Nominal traverse condition. Start under load, path following including waypoint tracking, visual flag-line/rut detection, leader following, static and dynamic obstacle avoidance

A property of the sliding autonomy method is that all automated functions operate continuously but they are not engaged until set by the operator. In this way for example, terrain modeling and obstacle detection may provide optional display to the operator in manual operation, but when engaged provide the basis for automatic operation.

Experiments

The experimental plan was in general to explore the widest range of possible driving activities with the widest range of environmental factors. The plan proceeds from first evaluating moving sensors viewing a static world, then dynamic objects from stationary cameras and then most like an actual traverse, moving cameras viewing both static background and dynamic objects.

Plan

Experiment Codes for South Pole Traverse Sensor Evaluation

M1 - Camera/laser scan images moving 2 MPH over level, then tracks, then rough snow
M2 - Camera/laser scan images moving 8 MPH over level, then tracks, then rough snow
Repeat for 3 sun angles (M1-M6)
Repeat for 3 mounting positions: cab, roof, bumper (M7-M12)
Repeat for blowing snow (M13-M14)
Repeat for flat light (M15-M16)
Repeat for blue ice (M17-M18) if possible

S1-S3 - Camera/laser/radar images of tractor (front, side, rear)
Repeat for snow mobile (S4-S6)
Repeat for person standing (S10)
Repeat for person kneeling (S11)
Repeat for person prone (S12)
Repeat for flag (S13)
Repeat for dunnage (S14) and crates (S15)
Repeat each for 3 mounting positions: cab, roof, bumper (S16-S21, S22-S29)

S30-S33 - Camera/laser/radar images of tractor (front, side, rear) from tractor at 8MPH
Repeat for snow mobile (S34-S36)
Repeat for person standing (S37)
Repeat for person kneeling (S38)
Repeat for person prone (S39)
Repeat for flag (S40)

D1 - Camera/laser/radar images of tractor moving away (8MPH)
D2 - Camera/laser/radar images of tractor moving towards (8MPH)
D3 - Camera/laser/radar images of tractor moving across (8MPH)
Repeat for tractor with sled, away and across (D4-D5)
Repeat for snow mobile (D6-D8)
Repeat for person walking (D9-D11)

D12 - Images of tractor moving away (8MPH) while moving (8MPH), relative 0MPH
D13 - Images of tractor moving toward (8MPH) while moving (8MPH), relative 16MPH
D14 - Camera/laser/radar images of tractor moving across (8MPH) while moving (8MPH)
Repeat for snow mobile (D13-D15)
Repeat for person walking (D16-D18)

T1 - Camera/laser/radar images of tractor/sled following (8MPH)
Repeat for 3 following distances: 10m, 50m, 100m (T1-T3)
Repeat offset laterally: 10m (T4-T6) and 20m (T7-T9)
Repeat through 90° turn (T10-T12) for following distances
Repeat as possible in varying weather: flat light, blowing snow
Collect 2 hours of recorded images/positions following tractor/sled in greatest diversity of terrain

L1 - Record Autosteer 1-hour stationary
L2 - Record Autosteer 12-hour stationary
L3 - Record Autosteer 1-hour driving figure 8
L4 - Record Autosteer 1-hour driving 1-mile square

Results

Experiment Completion

Summary of collected data

A majority of the tests outlined in the plan were performed and logged. Notable exceptions include the bad-weather variants and explicit localization runs. Some tests were repeated and several extra experiments and data collection opportunities were also added. In total we performed 188 experiments covering 7 hours and 4 minutes. Additional shorter debugging tests were also saved in 110 logs lasting 2 hours and 39 minutes.

Limitations

Many datasets were collected, however the data was limited in several regards. The weather conditions were often quite good, with some flat lighting. Flat lighting is specifically discussed below and generally can be overcome. Other adverse conditions like precipitation or blown snow were not encountered. Simulation with a snow blower suggests that the laser and stereo vision degrade poorly and will not be robust to poor weather.

Another limitation was the testing locale. Some snow types such as sastrugi were not present, so these results may not apply in certain types of Antarctic terrain. Similarly GPS positioning quality was quite good in our testing area, but could degrade in valleys or more extreme latitudes. The sensors do look promising but should not be relied upon until they have been tested along the entire route.

Experiment Outcomes

Identifying people

Many datasets containing people were collected to characterize the conditions under which they can be detected. Data from the stereo cameras clearly shows standing and walking people at ranges over 30m. They are also visible in laser scans when the laser is oriented horizontally.
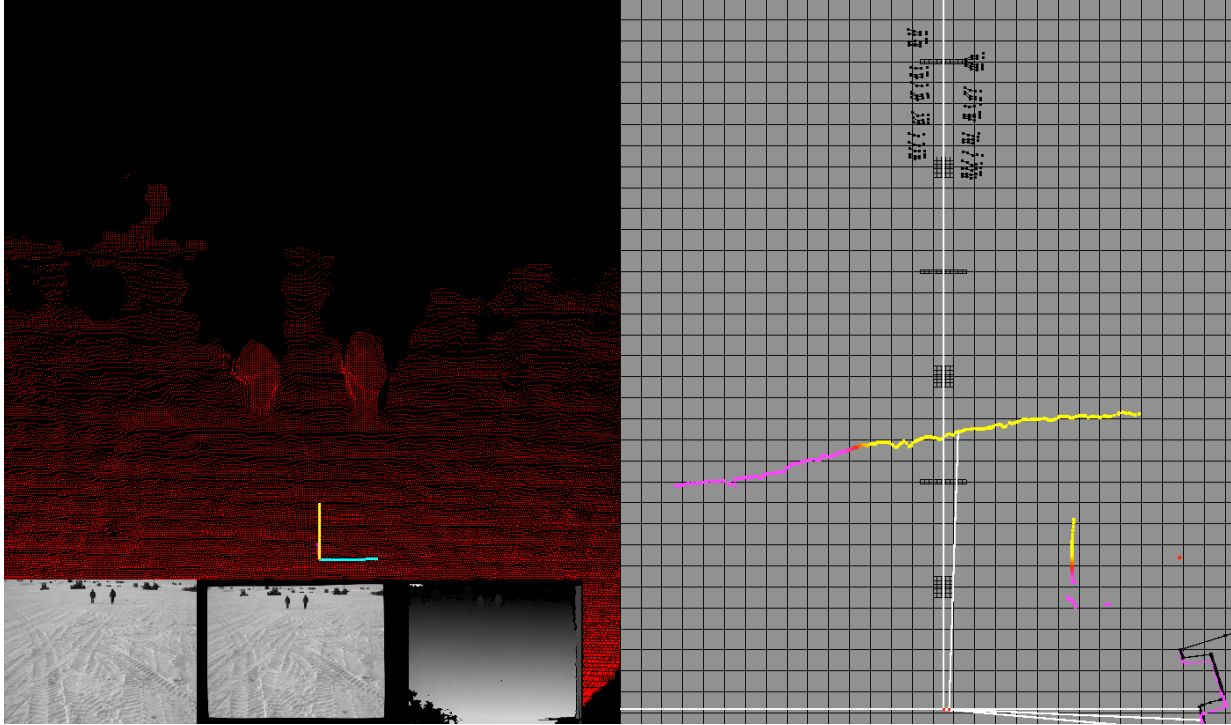
[Stereo and laser data of two people at a range of 25m. The people are walking toward the sensors, appearing as a streak of black dots in the laser data]

However the radar unit was unable to reliably track moving people. In the same scene illustrated above, the radar reported many spurious objects with zero velocity (shown in blue) and none approaching the unit.
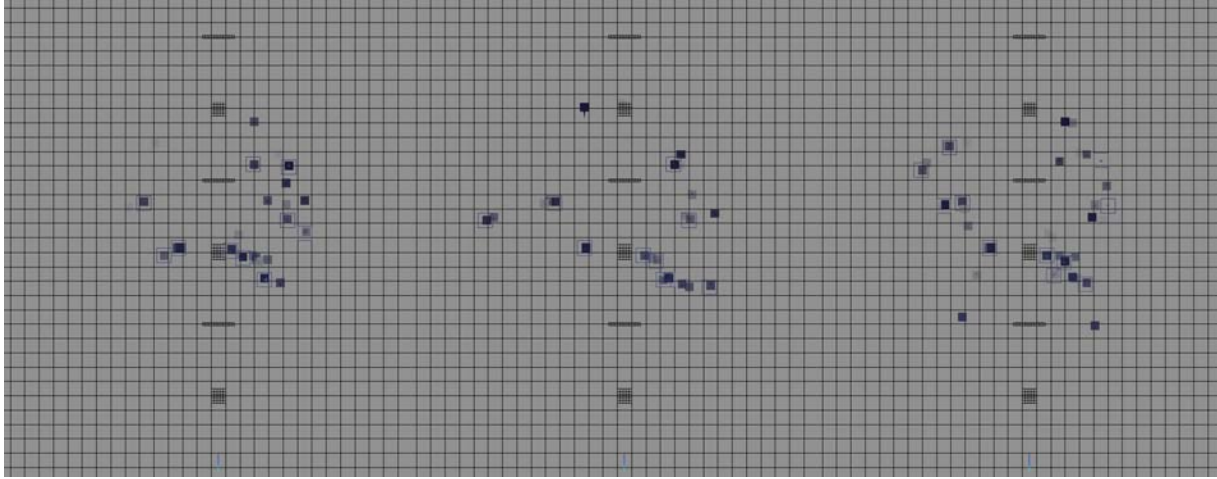
[Radar data from the same experiment. The radar failed to show a signal when the people were 30 (left) 25 (center) and 20 (right) meters from the unit.]

Identifying tractors at close range

The line-scanning laser provided the best identification of tractors up to it's maximum range of 50m. When a leading tractor is directly in front, both the laser and stereo data can be used to identify it.
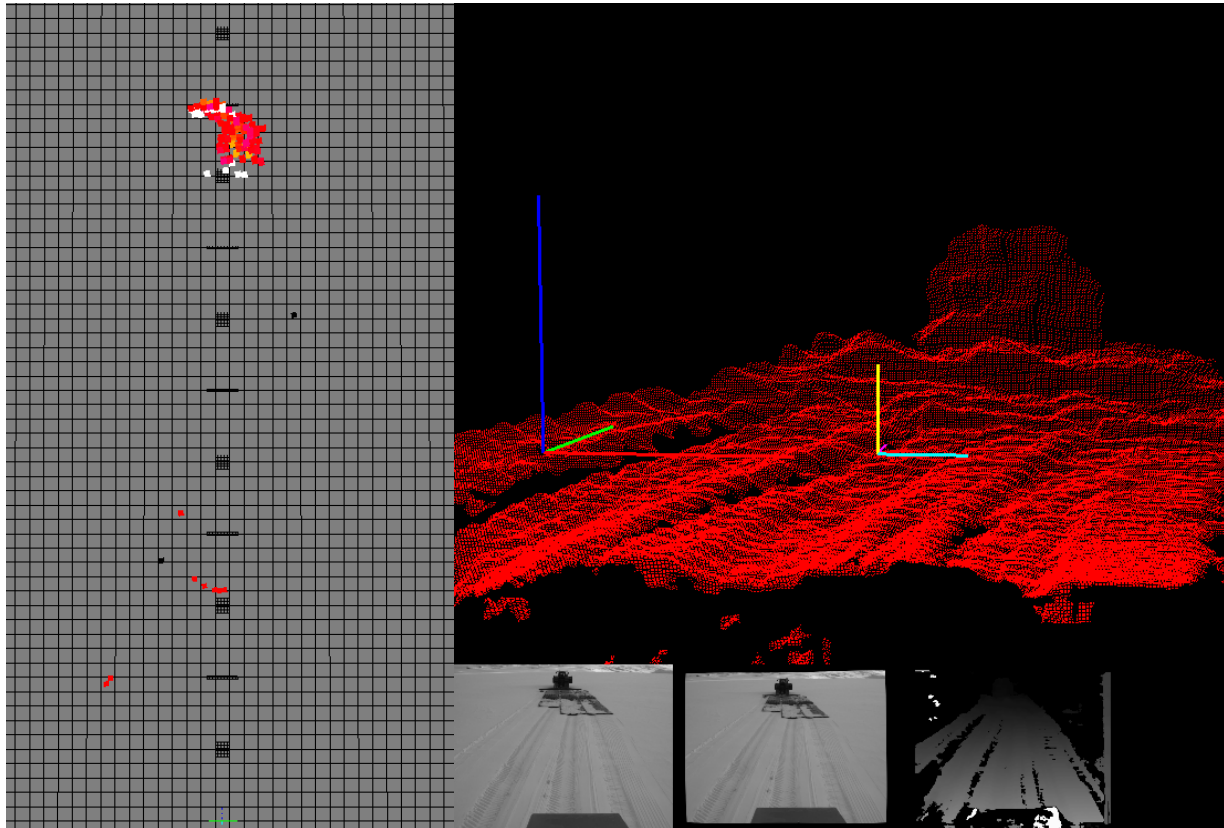

[Views of the tractor ahead. Left: horizontal laser data showing a strong signal 45-50m ahead. Right: stereo data of the same scene. Note that there is good data over the tractor and sled as well as the tracks which are perceptible in the point cloud. The undisturbed snow gives no signal.]

[Reference image showing the scene slightly earlier]

When a tractor is off to one side it will not be visible to the cameras with their limited field of view. Line scanning lasers have a 180 degree or greater field of view, so they can also be used to track objects to the side.
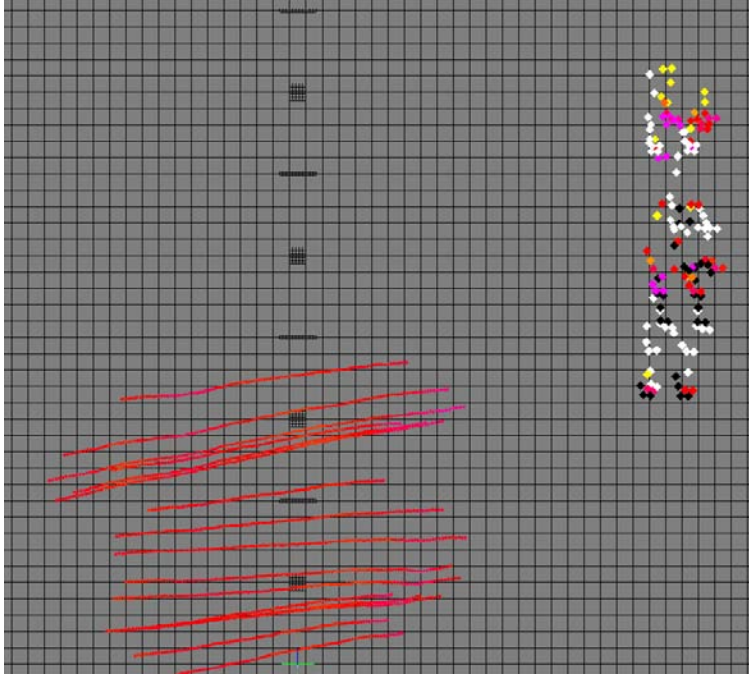
[Laser data while passing a moving tractor about 20m to the right]

Identifying tractors at long range

When convoying, the tractor spacing is beyond the range of our sensors. The leading tractor can still be identified using computer vision techniques to estimate. Color segmentation can be used to identify objects on the snow, much as the drivers currently operate. This gives an estimate of bearing (using the centroid of the segmented object) as well as a coarse estimate of distance (using the size of the object if known or the lowest point if the ground plane is known). Image segmentation techniques work in flat lighting conditions and may be extended to track other objects like flags or lost cargo.
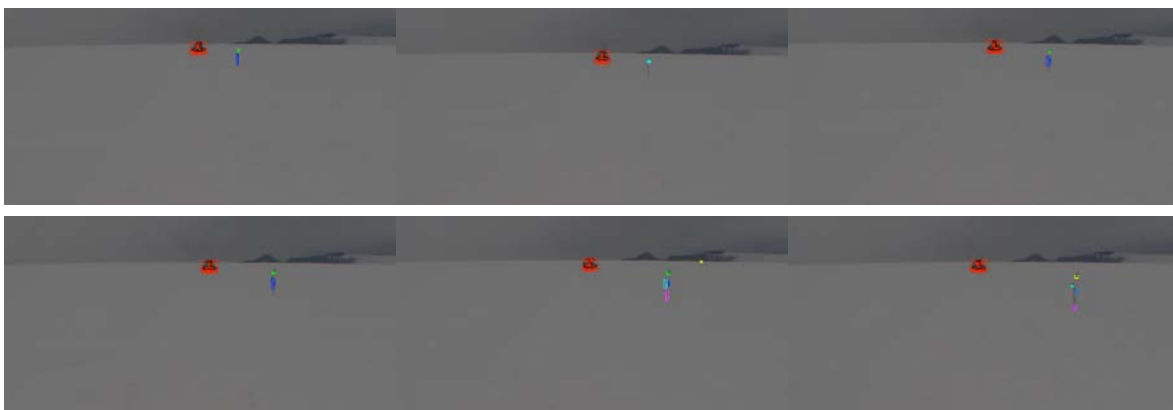

[6 consecutive images showing color-based segmentation identifying a tractor in flat light at a range of about 200m or 1/8th of a mile. Inconsistent detection of the approaching flag as well]

Identifying tracks in fresh snow

Using a downward tilted laser

Vehicle tracks in fresh snow are most easily seen in laser data in any light conditions. The ground can easily be identifying by fitting a line, and tracks are merely deviations from that line. By applying a GPS position to scans and using a false coloring to show distance from line, tracks are readily apparent.
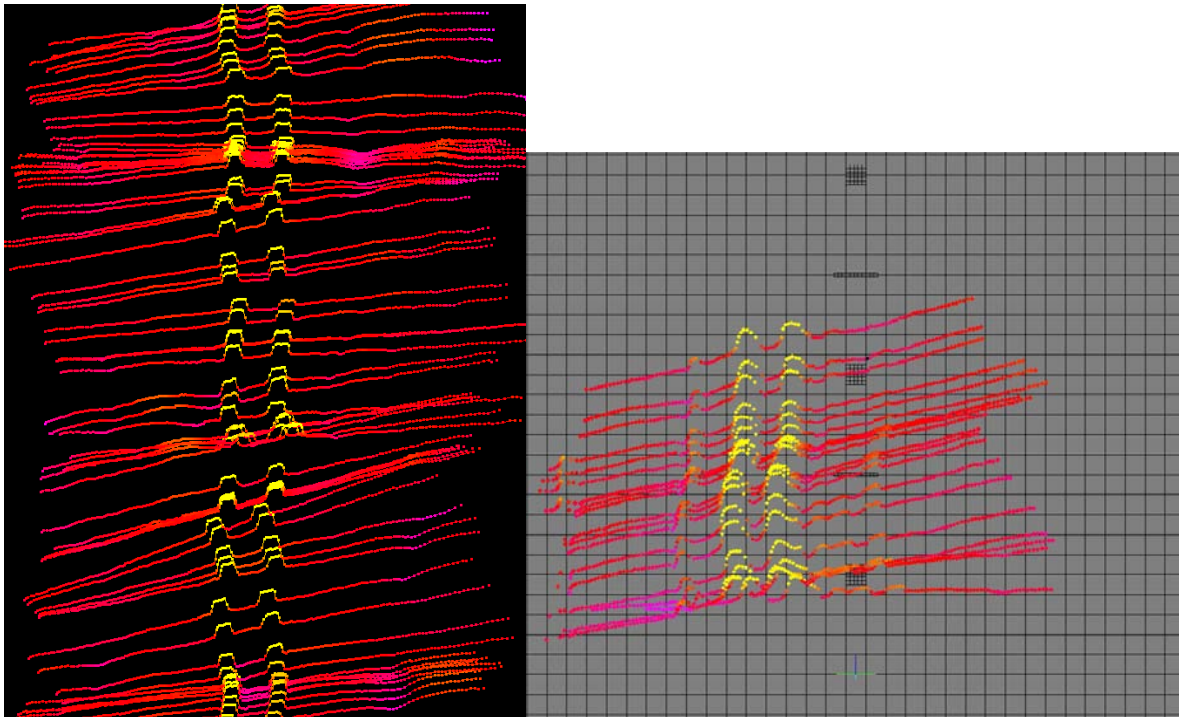
[colored laser data following a tractor. Left: in fresh snow with no sled. Right: on well travelled (but not icy) snow with a sled]

[Reference image showing scene when following a tractor with a sled]

Using stereo vision

Tracks can also be found in the stereo data but not in a reliable manner. The task is feasible in fresh snow when the leading tractor is not towing a sled. But in other conditions it may not even be possible.

Although the tracks can be seen in the point cloud, the terrain geometry is poorly suited to this task because the amount of noise (or error in distance) is large compared to the depth of the tracks. By assuming that the scene contains only fresh snow (which has little or no visual texture) then the tracks can be found as the large linear regions where reconstruction is possible.
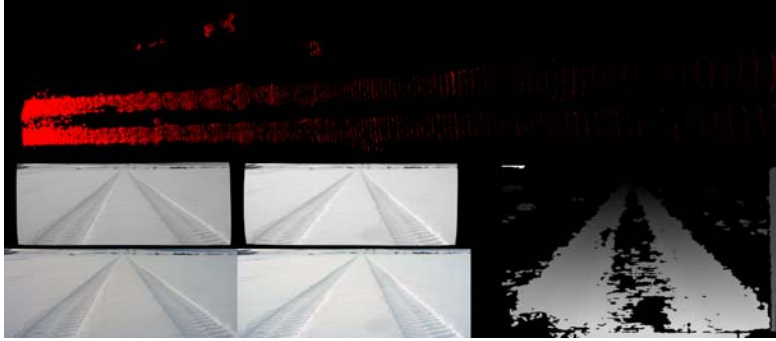
[Tracks in fresh snow, only the tracks have sufficient texture making them stand out.]

Contrast this with the more relevant scene of tracks from a sled in fresh snow. The entire region traversed by the sled is visible. In optimal conditions there may be sufficient geometry to identify the tractor's tracks. But this is unlikely to be a reliable technique.
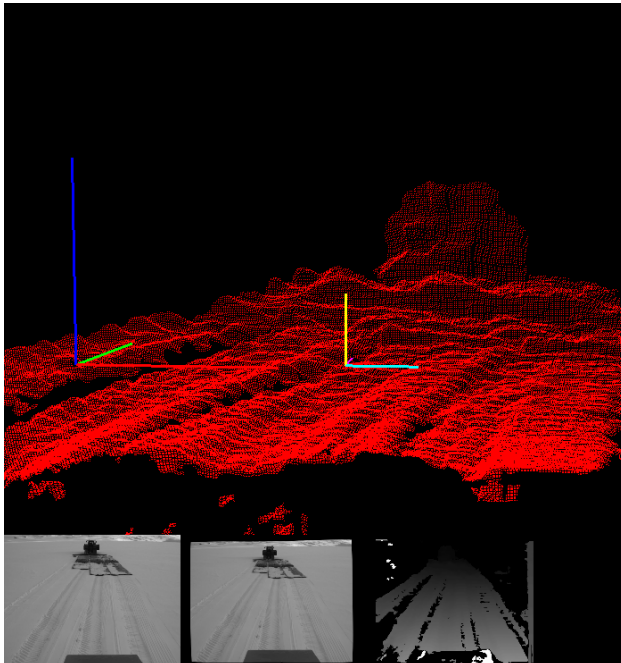
[Stereo data of sled tracks in fresh snow. Although perceptible, this is a more challenging problem.]

Live experiment

The clear signal visible in the laser data prompted an experiment to follow tracks based on that data alone. Two tractor drivers steered by looking at a screen showing the laser data. For safety, the tractors were driven at low speeds and a second person in the cab monitored the area. Both drivers learned to follow straight tracks after only a few minutes of practice.
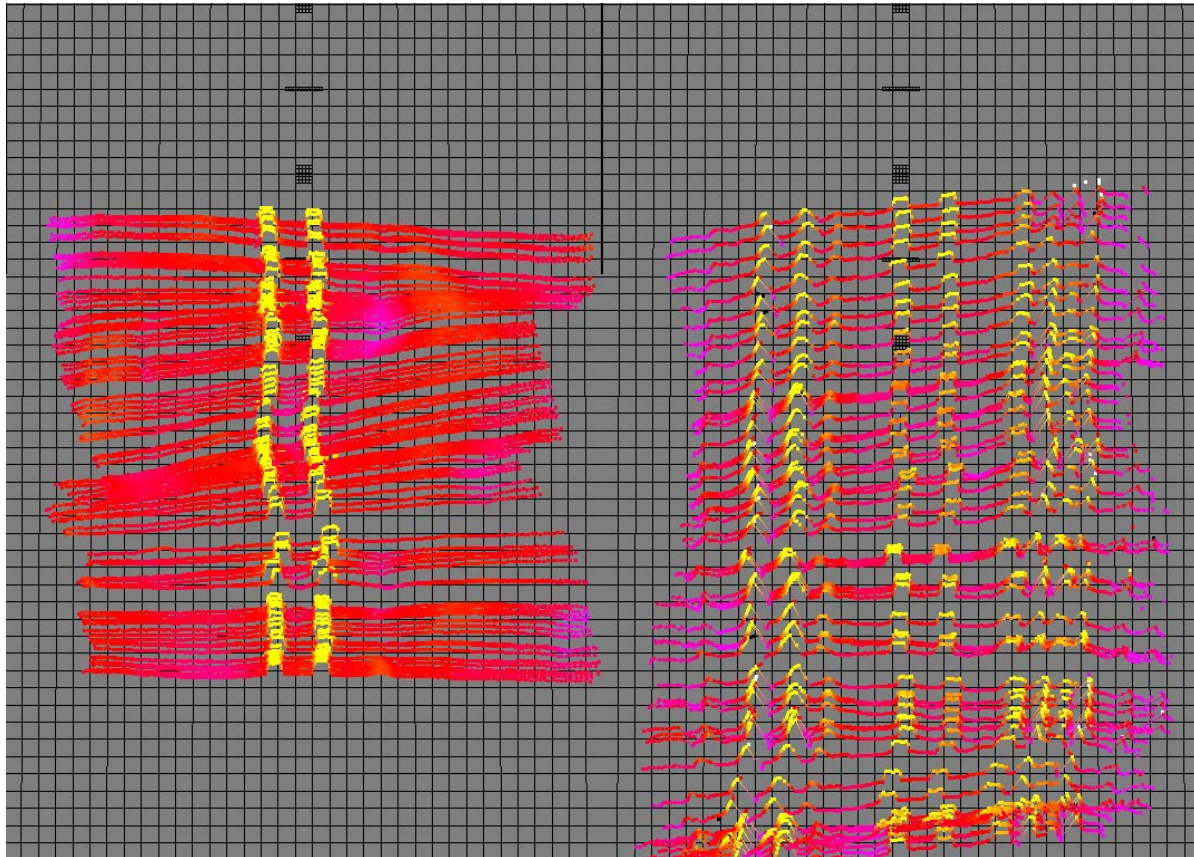
[Laser data with drivers following based solely on laser data. Left: low speed in terrain with single set of tracks. Right: faster speed with multiple tracks present.]

Identifying tracks in other snow conditions

Tracks are more difficult to identify in other snow conditions. In one part of our test area we drove over heavily compacted snow. The snow was so packed that there was no depth to the tracks, making any geometric analysis useless.

[Scene showing densely packed snow, note the lack of sinkage in the ruts.]
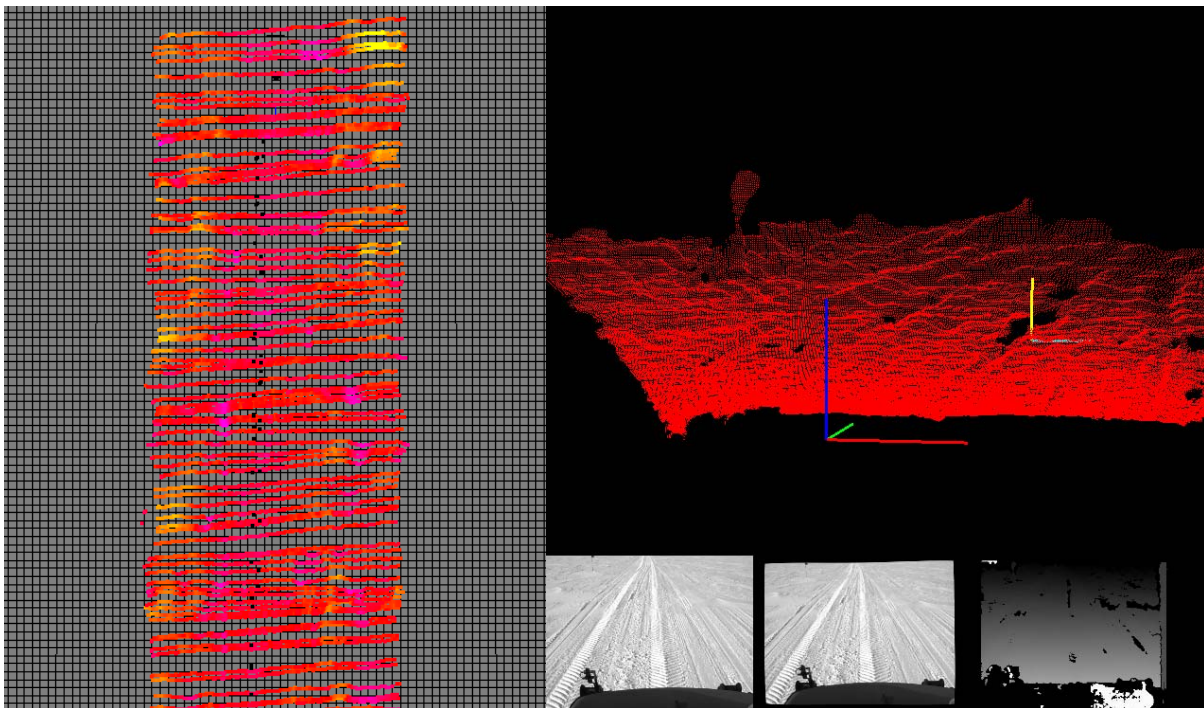
[Laser and stereo data of densely packed snow. No clear signal of the tracks.]

Note that there may be little utility in identifying tracks in this type of snow.

Identifying Flags

Flags are easily seen in the laser data, but the data must be used carefully to avoid filtering them out. Since the poles are very skinny, often only a single beam hits. In a single scan this may appear as noise, so multiple scans must be used together to disambiguate.
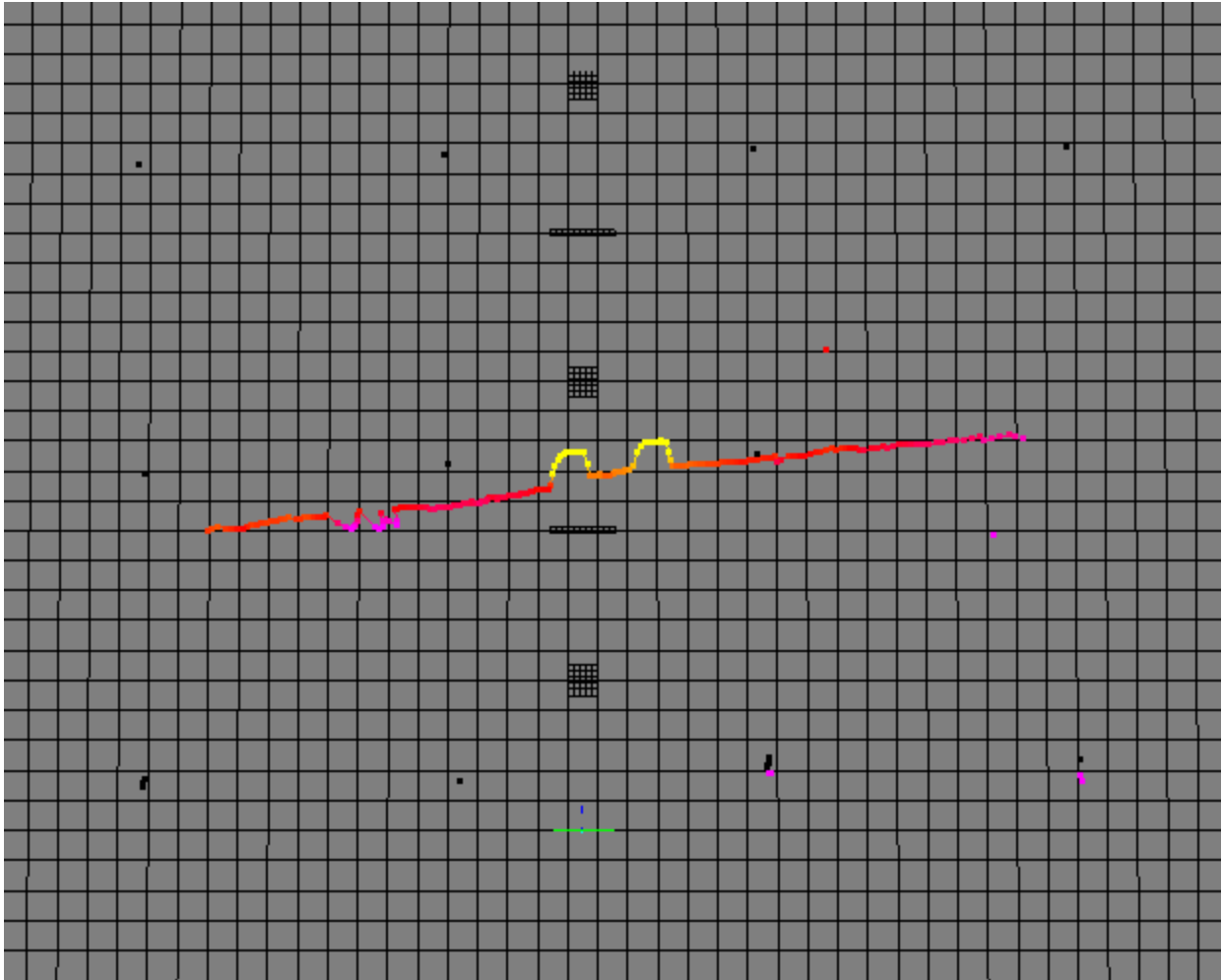
[Laser data inside the fabricated grid. A 10m grid of flags can be seen with 3 rows and 4 columns. One of the 12 flags is obscured. The furthest flag is 28m away; 23m forward and 17m to the right.]

It is useful to spot flags at long distances and around the side of the vehicle. For longer range viewing, monocular vision technique should provide the best opportunity to track flags (and other markers). Although they can be be seen in stereo data, their shape is ambiguous at longer ranges, making it impossible to distinguish between a flag pole and a person.

Effects of blown snow

During our field test, we encountered little inclement weather. We did have a significant amount of flat light, but no precipitation or blown snow. To simulate those effects we used a small snow blower to loft snow. A snowmobile was driven through the cloud to provide a target. The following data is shown at 5m intervals (about a second apart).

[Reference images showing the snowmobile at 30,25,20,15,10 and 5 meters away.]

The laser performed poorly, it was completely obscured by the snow. The laser does provide multiple returns which should provide additional ranges when part of the beam's energy is detected early. This typically works well when the scene is lightly obscured, for example with dust in the air. However the lofted snow was too dense in this case.
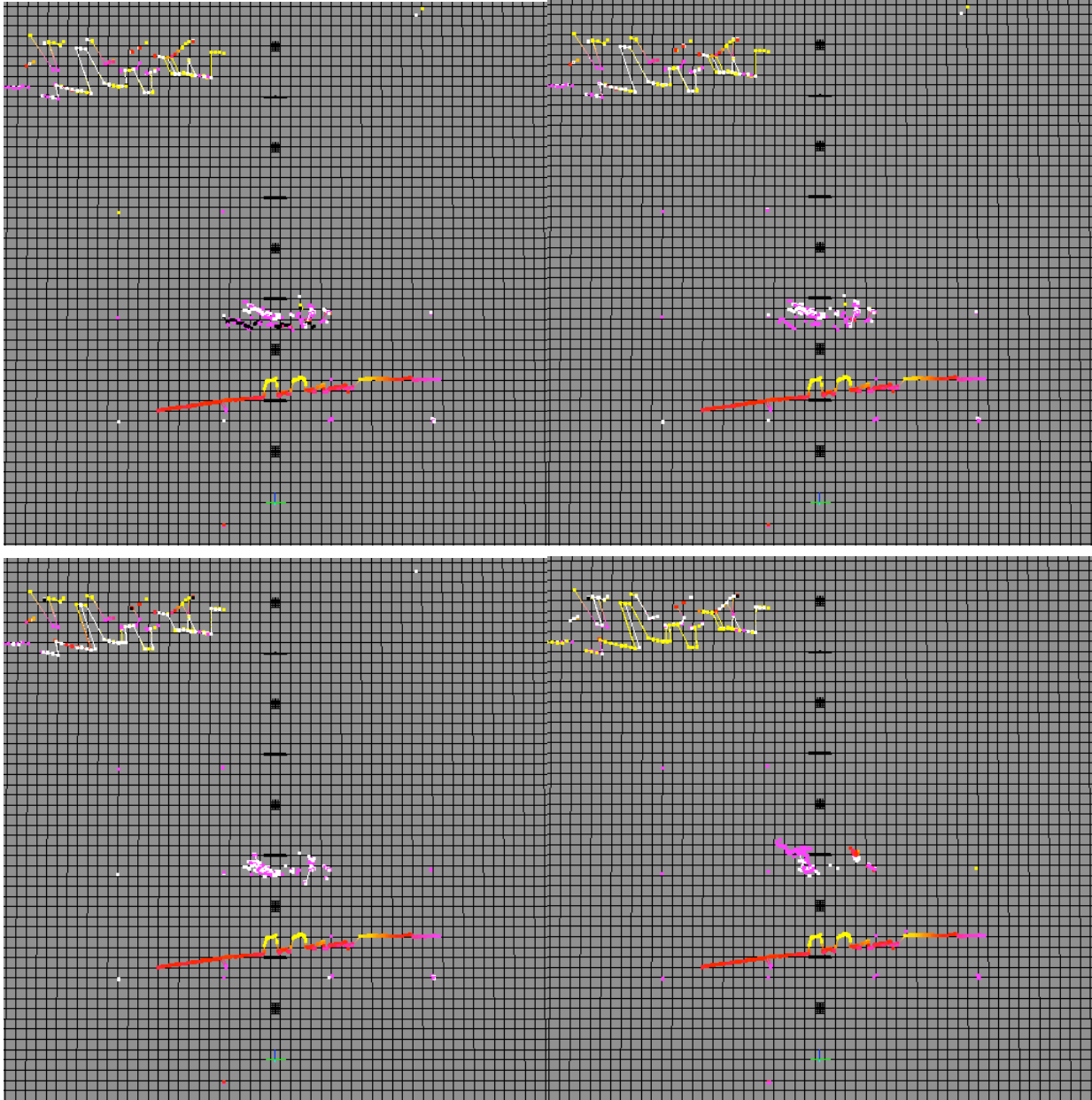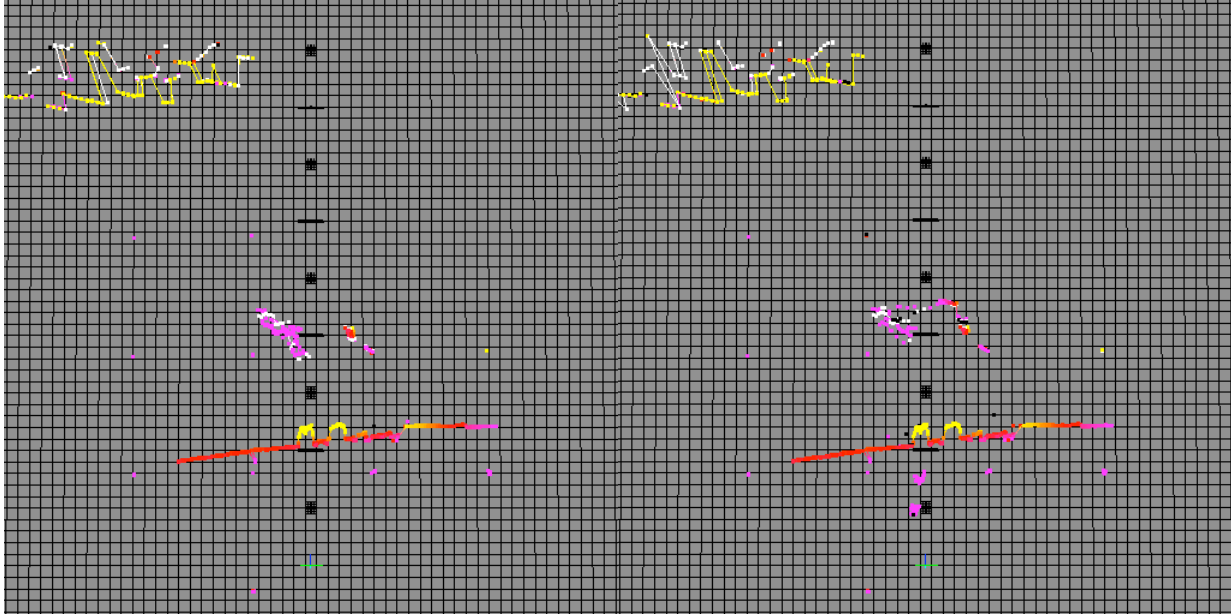
[Laser data with the snowmobile at 30,25,20,15,10 and 5 meters away. The horizontal laser is entirely obscured by the lofted snow, and the driver is below the laser's beam when he emerges from the plume. The downward laser detects the snowmobile after it crosses the 10m mark.]

The stereo performed slightly better than the laser, but is almost entirely obscured by the snow. The snowmobile becomes partially visible inside the plume, but again the snow is too dense for this sensor to see through it.
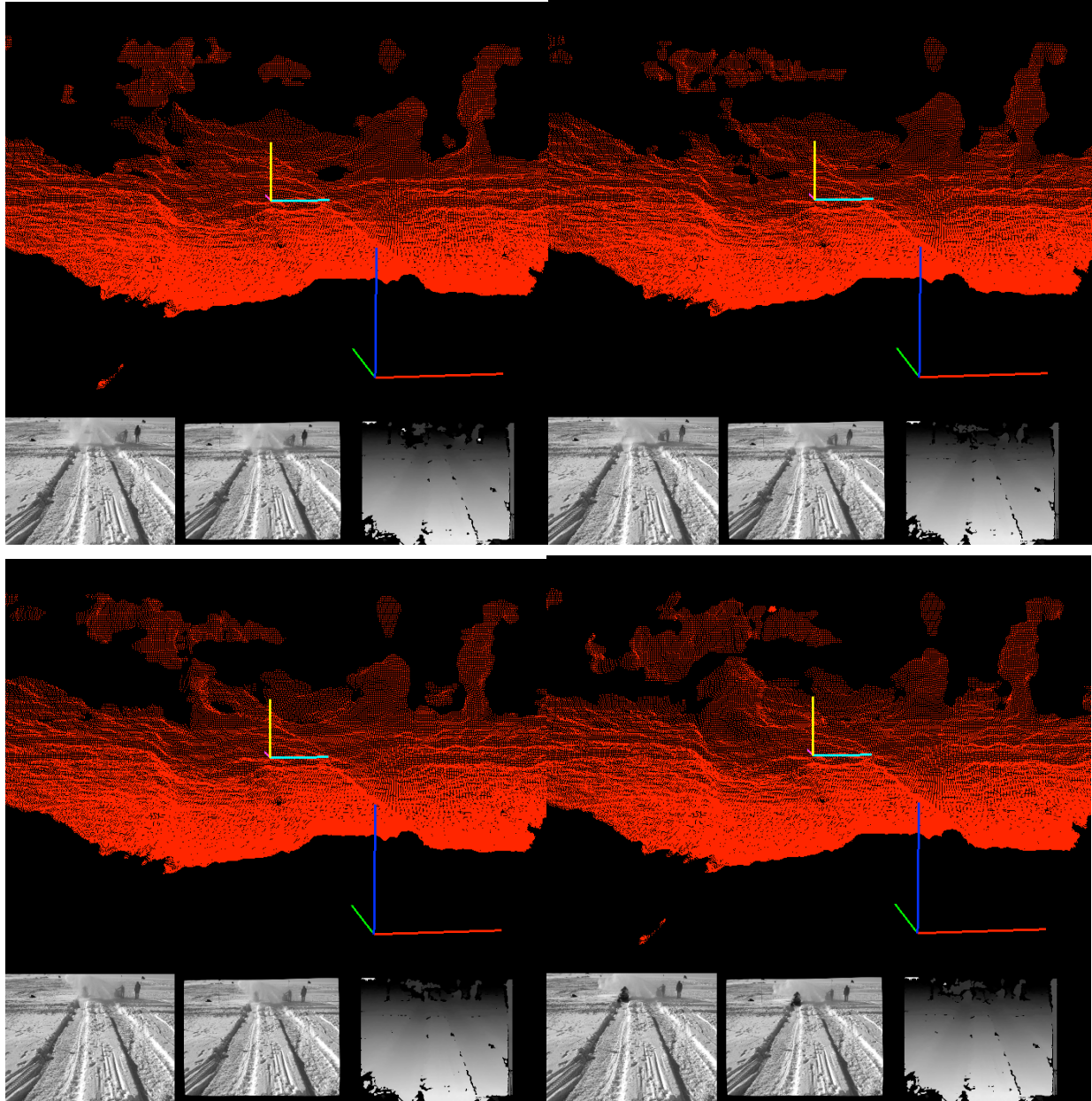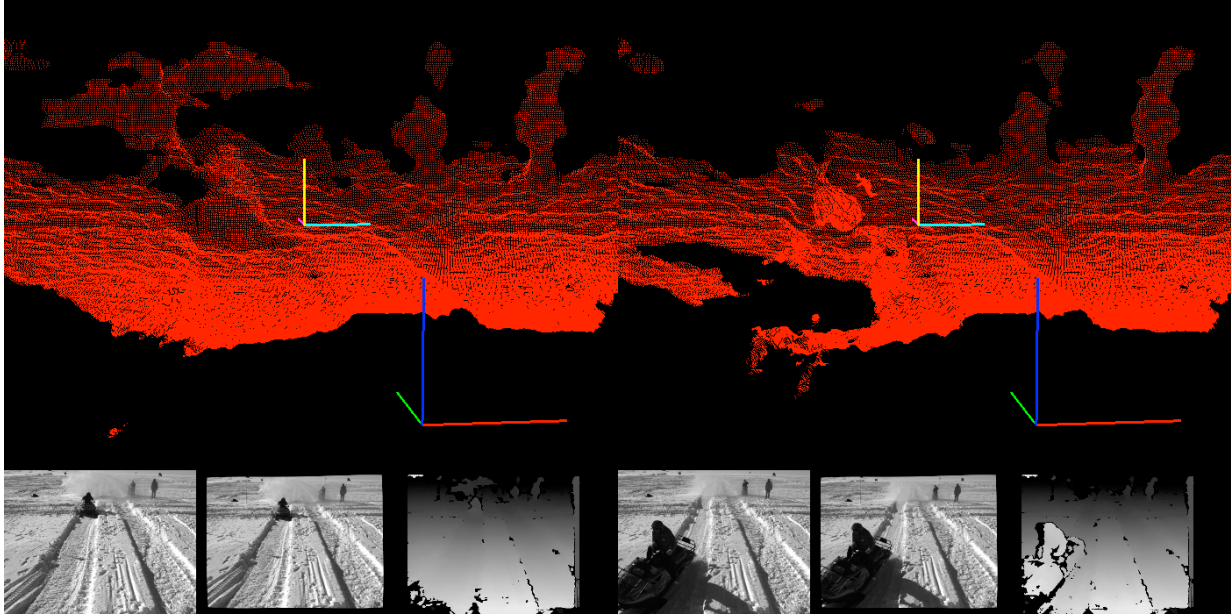
[Stereo data with the snowmobile at 30,25,20,15,10 and 5 meters away. The snowmobile is partially visible at 20m while inside the plume.]

Of the three sensors, the radar was the only one unaffected by the snow. It detected the snowmobile at a range of 30m.
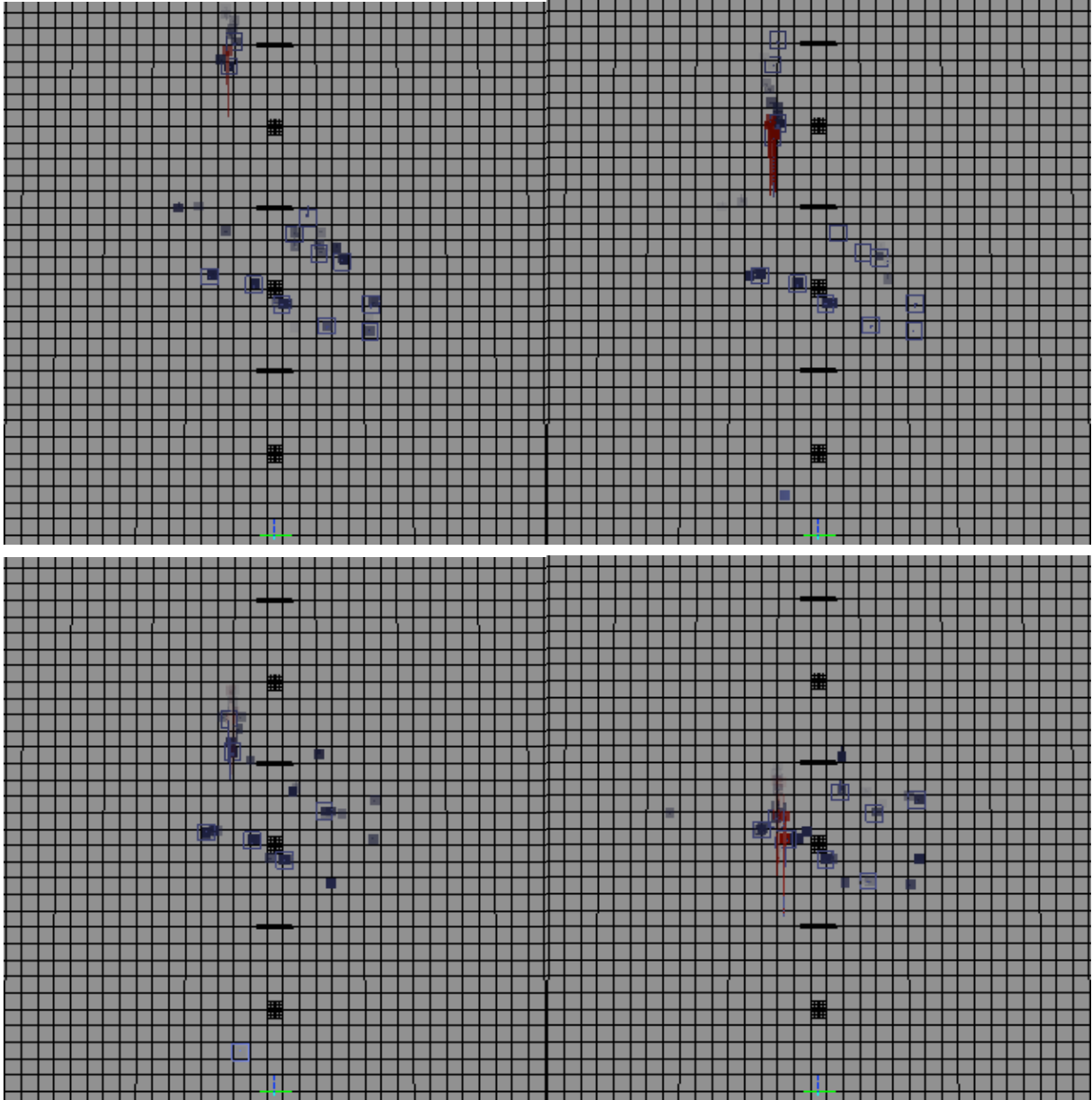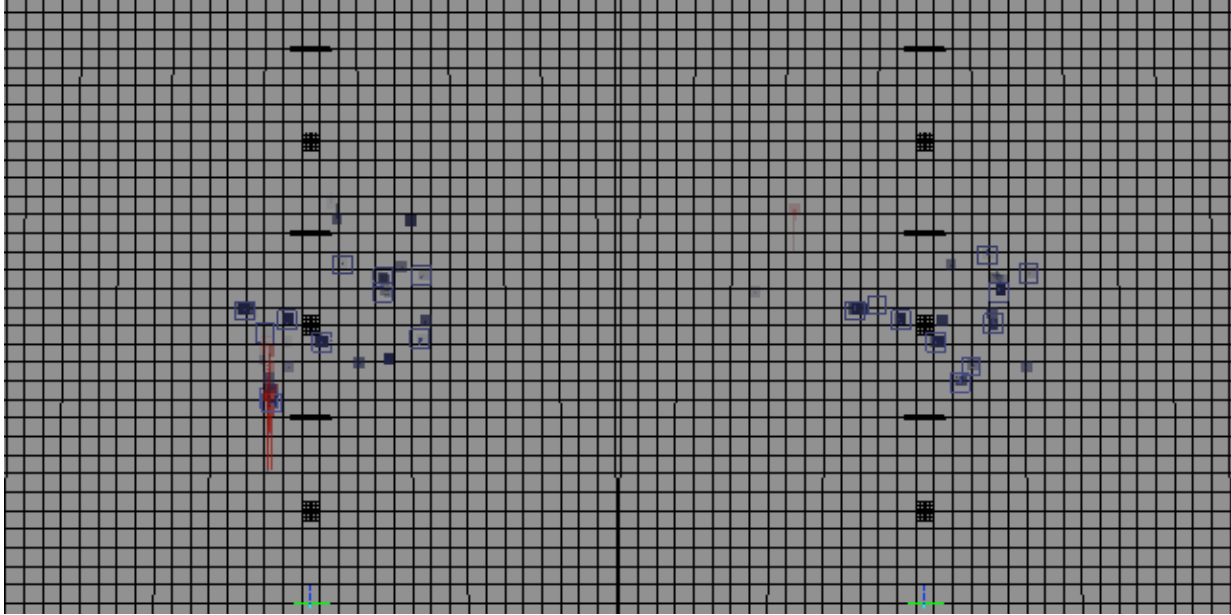
[Radar data with the snowmobile at 30,25,20,15,10 and 5 meters away. The signal is particularly strong at 25m. At 5m the snowmobile is out of the field of view.]

Recommendations

1. Maintain multiple estimates of the tractor position

One estimate can be GPS relayed over the communication system, which should not be affected by weather. The other estimate should be directly sensed and may be limited by environmental conditions. In convoy situations we recommend using monocular vision to verify this data. In tandem operations with close spacing (< 50m) a horizontal laser should provide the highest accuracy estimate.

2. Multi-modal sensing, such as vision plus radar, should be pursued.

As noted in the experiments vision performed well under many conditions but it's failure mode in flat-light and white-out is well established. Other sensing modes are needed. Laser is likely limited in the same conditions as vision, at least in white-out.

Use of radar appears promising but evaluation is inconclusive. The radar unit is poorly suited to tracking people and the other sensors out-perform it for tracking tractors. In tandem operations where two tractors are close together and highly accurate positions are needed, the horizontal laser performed best. When convoying with longer spacing, monocular vision performs well and degrades gracefully with range. In both situations the radar provides a poor alternative due to unreliable tracking, poor accuracy and limited range.

However, the radar is the sensor that should be least affected by poor weather. While the laser and monocular vision are unaffected by flat light, our experiments suggest they will degrade poorly with precipitation and blown snow. In these cases the tractors can still communicate their GPS information over a network, but that system would be less reliable with have a single point of failure. Radar technology should be investigated further as a tertiary source that could enable operations in more adverse conditions.

3. Communication of vehicle state is fundamental to coordination

It is observed that with reliable position information, even in the absence of environmental sensing, tractors can avoid each other and can optimize their speed and direction by moving in coordinated fashon (which is currently achieved by drivers coordination their control over radio). Establishing continuous distribution of tractor position, perhaps also including display of all convoy tractor positions, alone will likely improve efficiency and manual operation.

4. Design as obstacle avoidance rather than terrain modeling

The most profound insight of the field experimentation is that construction of detailed terrain models may be unnecessary. Rather than model the surface and then distinguishing the salient features, it seems that the world can be assumed to be a flat plane for all be a few rough terrain areas.

A different formulation would be track every object, stationary and moving, that is not level, snow-covered terrain and generate driving control that proceeds toward the goal while avoiding any tracked object.

Suggested Approach and Concept Design

Our suggest approach follows a progression from first building infrastructure for state monitoring (including sensing the world) and for vehicle control. These are fundamental to enabling autonomous guidance of a tractor--it must be able to sense and monitor relevent details and it must be able to effect control over its actions. With an autonomously guided tractor we can either enable it to lead, safely finding it's own way to each goal, or follow another tractor and properly match behavior. With coordination (and communication) among vehicles then leading and following can be combined to produce convoy behavior.
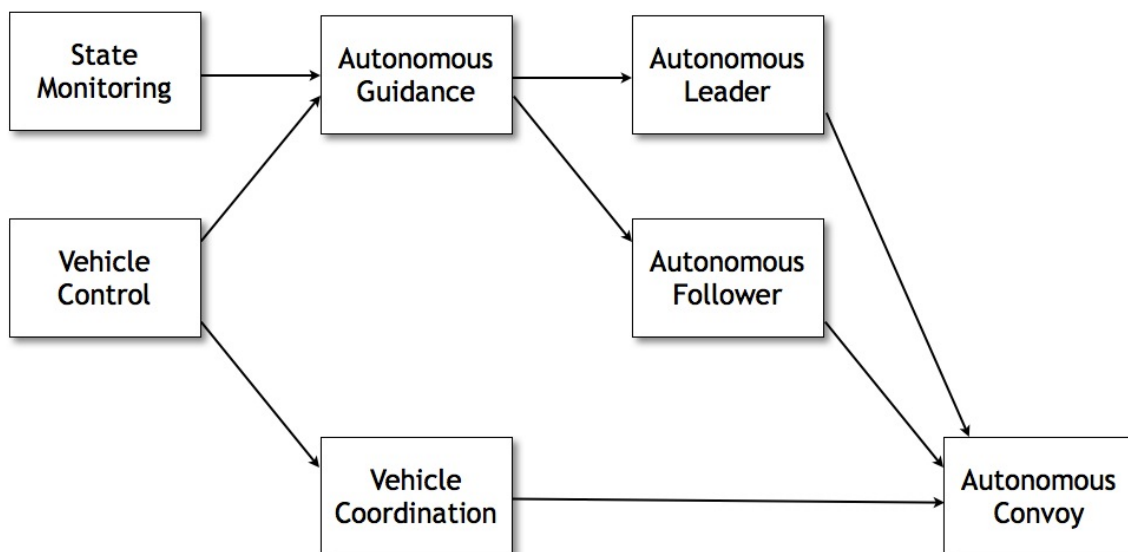
Improve State Awareness/Coordination

Goal: Communicate and display tractor state
Tasks:
- Implement dynamic communication network (protocol for reconfigurable, moving nodes)
- Install high-precision GPS
- Access to tractor performance data
- Incorporate satellite imagery and DEM (and register)
- Detect flags

- Display state information
- Communicate state between vehicles

Enable Autonomous Operation

Goal: Enable electronic control of tractor direction and velocity and integrate vehicle and terrain sensing
Tasks:
- Access tractor, develop hardware interface
- Determine protocols (coordinate with manufacturer)
- Calibrate steer and speed/power/gear commands
- Develop and calibrate path tracking
- Designate and maintain heading (follow path)
- Configure, mount, and integrate terrain sensors
- Configure and integrate position sensing (including GPS)
- Validate obstacle detection

Drive Lead Tractor

Goal: Automate obstacle detection, path tracking and drive control for lead vehicle in traverse
Tasks:
- Develop and validate terrain model including calibration
- Detect and identify tractors, tracks and flags
- Verify reliable obstacle avoidance
- Verify reliable route following (extended path) including recovery
- Develop robust localization
- Develop operator interface
- Integrate external commanding
- Drive (many) routes

Drive Follower Tractor

Goal: Automate obstacle detection, path tracking and control for following vehicles in traverse
Tasks:
- Observe leading tractor
- Detect and model vehicle tracks
- Develop leader model for behavior prediction
- Develop following behaviors (speed, path)
- Develop stopping behaviors

Drive Tandem Tractors

Goal: Coordinate the load sharing between tractors pulling sleds in tandem
Tasks:
- Instrument load
- Model and coordinate power
- Measure slip (non-odometric methods)
- Control slip, individually and by load sharing

Schedule and Deliverables

The one year project was divided into four phases to research and configure; then field test; then evaluate sensors for terrain modeling and position es
timation. Finally we assimilated this knowledge and formulated recommendations for a system design in this report.

Year 1	Phase 1	Phase 2	Phase 3	Phase 4
Schedule	Oct 1 – Dec 31 2010 (3 months)	Jan 1 – Feb 28 2011 (2 months)	Mar 1 – June 30, 2011 (4 months)	July 1, 2010 – Sept 30, 2011 (3 months)
Activities	Evaluate sensor options/ conduct trade analysis Design sensing and data collection system Procure sensors, computing and communication Perform component tests Integrate sensor and computing payload Define experiment metrics and plan Package and ship	Deploy to Antarctica Calibrate tractor autosteer (optionally install) Prepare and conduct navigation experiments Retrograde sensor payload	Analyze terrain data Evaluate sensor performance Recommend tractor terrain sensing configuraiton Analyze navigation data Evaluate positioning accuracy and errors Recommend tractor navigation method	Define conops Specify travese requirements Identify system engineering trades Evaluate sensors and technologies Define navigation and autonomy method Formulate autonomous traverse system design
Deliverables	Sensor Trade Study Payload Design Experiment Plan	Field Report Data Archive	Sensor Evaluation	System Concept Design

Appendix: Field Reports

Antarctic Field Report

January 21-25, 2011

Pittsburgh, Pennsylvania to Christchurch, New Zealand

Overview, Motivation and Objectives

The U.S. Amundsen-Scott South Pole Station is the southernmost continuously inhabited place on Earth since its construction in 1957. Resupply of the station is an annual necessity involving significant cost and risk. During the October-to-February summer season flights of LC-130 Hercules aircraft arrive at the pole from McMurdo Station, which is 1000 miles distant on Ross Island. These airplanes deliver everything, including fuel, that is needed to sustain the South Pole station. All supplies including construction supplies and scientific equipment must fit in an airplane.

In 2005/05 an overland route for tractors established the South Pole Traverse (SPoT). Tractors towing cargo and fuel, and a home for the drivers and technicians, completed a first cargo run to the pole. This traverse crosses the vast Ross ice shelf and polar plateau as well as crevassed glacial terrain in between. It requires about 40 days to complete, each way.

Since 2007/08 over 2 million pounds of cargo and fuel have been delivered to the pole while saving $2M in operating costs and 300,000 lbs of fuel. While there are important reasons to fly to the pole, for example to deliver people and fresh food, thus far the fuel cost of SPoT cargo is less than half that of air cargo. For the Antarctic continent these reduced emissions are an important benefit.

This research is motivated by the future potential of the McMurdo-South Pole traverse. Our goals are to increase the average traverse speed and path accuracy and to decrease the fuel consumption, driver stress and expedition risk. We will accomplish this by incorporating state-of-art autonomous navigation technology into the convoy tractors.

Participants

There are over 1000 people in McMurdo Station in the summer. The South Pole Traverse involves a large number of people, including drivers and technicians, who are helping us. The group responsible for evaluating sensors and performing experiments in Antarctica is:

James Lever, Cold Regions Research and Engineering Lab

David Wettergreen, Robotics Institute

Dominic Jonak, Robotics Institute

James Teza, Robotics Institute

This field Report serves as an informal record the activities of the project in Antarctica. We will describe what we plan on doing and what is actually happening. We will include interesting images and events, interesting to us anyway. We care about the weather and you may too. Enjoy.

Agenda

• Depart Pittsburgh with all of our equipment

• Arrive McMurdo with all of our equipment

Status and Progress

• Departed Pittsburgh. Try checking in with a few 69.8 lb cases full of electronics and sensors and you won't make friends. Mentioning that you are headed to Antarctica helps but you still have to drag everything to excess baggage. Interesting that it was colder in Pittsburgh than in McMurdo Station where we were headed.

• Transited Los Angles and Auckland. In retrospect all very routine for commercial air travel these days. We were coming on three different flights and some made the boarding call to Auckland by only 10 minutes. In Auckland, two of our equipment cases did not arrive (until the next day) and some reservations to Christchurch were missing. That necessitated some real-time rebooking on other airlines but by the evening of January 24 we had all reached Christchurch sans two cases.

• Received crate in Christchurch. In addition to checked bags we express shipped a wooden crate containing calibration targets. We were worried they would be roughed damaged so we built an oversized wood crate to protect them.

• Waited to fly to the McMurdo. Our initial flight to McMurdo was postponed due to weather. We suffered through a gorgeous sunny day in Christchurch. Early Tuesday we arrived at the

U.S. Antarctic Program Clothing Distribution Center to get our red parkas, bunny boots and all manner of glove, sock, underwear and hat. We got fully suited for an Antarctic blizzard and boarded a C-17 to fly. To make a long story, very short: we flew to McMurdo, circled overhead looking down at clouds, and then flew all the way back to Christchurch. 11 hours. We try again tomorrow.

Upcoming

• Arrive McMurdo (we hope)

• Receive equipment, Set up lab (Wednesday), Assemble components

• Install equipment on tractors, Calibrate sensors, Perform static obstacle detection experiments

Weather

Pittsburgh: Overcast, -5°C, Snowy

Christchurch: Clear, 24°C

McMurdo: Cloudy, Windy, -2°C

Antarctic Field Report

January 26-27, 2011

McMurdo Station, Antarctica

Agenda

• Arrive, check-in and set up

• Build and install sensor frame and power system

• Calibrate cameras and align sensors

• Interface tractor controller and GPS

Status and Progress

• Arrive McMurdo. We made it in our second attempt to reach McMurdo and landed smoothly on the Pegasus sea ice runway. We emerged to low visibility and blowing snow for the drive to McMurdo. After an in-briefing with NSF we picked up gear and equipment and distributed to our rooms and the South Pole Traverse offices.

• Assemble equipment. We unpacked equipment and upon inspection everything seemed in good condition. We connected sensors and computers powered each up and then began assembling the sensor frame. The frame was designed to be reconfigurable and after three iterations we had a form that would mount to the tractor roof and hold the cameras, lasers and radar with appropriate view directions. We installed the power and signal distribution box inside the tractor cab and set up so that riding two in the cab, one driving and one operating sensors, we could begin experiments.

• Calibrated cameras. We had designed a large (flat) checkerboard, which provides squares of known size and distribution, in order to calibrate the camera optics and the relationship between the two cameras in the stereo pair. Calibration involved imaging the target at dozens of locations and then performing an optimization that converged to the best fit camera parameters.

• Interfaced GPS. Not knowing whether we could connect to the tractor GPS system we brought along a high precision system, thanks to our colleagues working on agricultural automation. It took some quick code development, and a little reverse engineering, to work out how to record position estimates, but now when our sensor system records images and scans, the exact location is also logged. This will help us to identify the data, but also is necessary to merge observations together to build larger maps.

Upcoming - Approximate Field Schedule

• (1/27 Thursday) Install equipment, Calibrate sensors, Perform S1-S15 (Static Obstacle Detection)

• (1/28 Friday) Begin Snowcraft training, Test Autosteer, Perform L1-L3 (Localization)

• (1/29 Saturday) Conclude Snowcraft training, Conclude L3, Perform L4

• (1/30 Sunday) Perform M1-M12 (Terrain Modeling Experiments), Present Sunday Lecture

• (1/31 Monday) Perform S16-S29 (Statics, relocate sensors) and S30-S42 (Statics, moving tractor)

• (2/1 Tuesday) Perform D1-D12 (Dynamic Obstacles), Present Morning Talk

• (2/2 Wednesday) Perform traverse T1-T12 (Traverse)

- (2/3 Thursday) Perform D12-D18
- (2/4 Friday) Perform repeats from M1-M12, S1-S15, S30-42 and D1-D18
- (2/5 Saturday) Repeat traverse T1-T12 with simulated blowing snow
- (2/6 Sunday) Perform repeats from S30-42 and D1-D18
- (2/7 Monday) Perform repeats from M1-M12, S1-S15, and T1-12
- (2/8 Tuesday) Remove sensors and equipment, Secure data, Bag drag

Weather

McMurdo: Cloudy, light wind, -5°C (low -12°C)

Antarctic Field Report

January 28-29, 2011

McMurdo Ice Shelf, Antarctica

Agenda

• Complete Snowcraft I training

• Test autosteer system

Status and Progress

• Survived Antarctic overnight. In order to work out on the McMurdo Ice Shelf we were required to complete the basic snow survival course, Snowcraft I, known widely as "Happy Camper". The course involved learning use of VHF and HF radios, helicopter safety, survival gear including stoves and Scott tents, building shelters, as well as information on risk evaluation, health issues and team dynamics. We also completed several survival scenarios including searching for someone lost in a white-out (with buckets on our heads). We all survived.

• Operated autosteer. Two of the tractors, have been set up with an autosteering system. This additional controller receives GPS signals for position and then can steer the tractor to a particular location. It is configured for agricultural work and provides methods to cover, meaning plow, an area automatically. We experimented with the basic performance and will eventually evaluate how accurately it can reach a specific location (with no sensing of the environment other than its position.)

Upcoming

• Test sensors on snow

• Present Sunday science lecture.

Weather

Light clouds then clear, sunny, -10°C rising to 0°C, beautiful

Antarctic Field Report

January 30, 2011

McMurdo and Ross Ice Shelf, Antarctica

Agenda

• Operate tractor on snow

• Present science lecture

Status and Progress

• Drove instrumented tractor to the ice. With all sensors and GPS functioning we drove the tractor 7km from McMurdo out onto the Ross Ice Shelf. We followed the snow road to the airfield and stopped to collecntion observations of fresh snow and of tracks and road surface. Initial examination reveals that the cameras to not measure texture in the snow and uniformly see nothing. (This is more informative than a noisy result.) However looking at tracks or the compacted road, the cameras detected enough features to be able to reconstruct the surface very accurately, meaning it looked like a flat road. The lasers produced strong returns from snow under all conditions. We also tried putting people in the scene and they were strongly detected by all sensors.

• Presented Sunday science lecture. We don't have much result yet this field season but we presented a lecture on related robotics technologies and on our objectives adding robotic capabilities to the South Pole Traverse. Constructive discussions with people experienced with tractor traverse in Antarctica, to South Pole and elsewhere, has helped us focus on several important issues like the detection of flags and the need to coordinate tractors that are pulling sleds together.

Upcoming

• Back to the ice shelf

Weather

Cloudy, light breeze, flat light, -12°C (wind chill -17°C)

Antarctic Field Report

January 31, 2011

Ross Ice Shelf, Antarctica

Agenda

• Perform experiments observing static objects

Status and Progress

• Thawed cameras. Today at startup our cameras did not immediately come alive. This was their first night left outside so they reached ambient of -12°C. Their minimum storage temperature is -30°C but the aren't supposed to operate below -10°C. The exterior cameras have heaters that are supposed to hold them at ambient, and we had tested them in a freezer back in Pittsburgh. It took about an hour but the cameras did come online. Surprisingly the ones in the cab too a bit longer than the external, heated enclosures. The laser scanners operated fine, both the thermally regulated unit and the "indoor" unit.

• Improved camera calibration. Calibrating cameras often requires iteration. In examining our first data from yesterday it seemed that the terrain models were warped somewhat to one side. We took time to collect more images of our checkerboard target to more completely cover the field of view. With now over 100 calibration images, the optimization that solves for the camera parameters has converged to a solution that corrects the warping that we saw. It is still not perfect but looking better.

• Ran static obstacle experiments. We took the tractor out to the South Pole Traverse staging area on the Ross Ice Shelf (next door to where Long Duration Balloon project launches its high altitude balloons). Since this was our first real shakedown of the system we started by getting a quick grab of lots of observations by driving around in the staging area and "looking" at tractors, sleds, snowmobiles, and people. We spent some time driving over fresh and tracked snow.

Upcoming

• Experiments with moving tractors

Weather

Light clouds then clearing, -6°C to -12°C then back to -6°C

Antarctic Field Report

February 1, 2011

Ross Ice Shelf, Antarctica

Agenda

• Perform experiments with static objects and moving tractor

Status and Progress

• Assembled target field. We arranged a uniform grid of flags and added various other objects, including snow machines, sleds, crates, and for which we must develop reliable methods of detection. By creating grid of flags we will also estimate modeling accuracy.

• Observed static objects. Using the tractor mounted sensors, all of the objects, including the flags, were observed from various directions. We spent some time adjusting viewing angles of the sensors to determine coverage and in the case of the lasers to gain the maximum look ahead. It turns out that ruts from tractor tracks are more obvious in range images, particularly the lasers, at lower incident angle because the distance from the snow surface to the bottom of the rut is greatest--this is balanced against getting a good signal return from the snow surface.

• Observed static objects from moving tractor. We drove the tractor through the obstacle grid in four directions at speeds of 2 MPH and 8 MPH. Stereo imaging, at 4 Hz, performed as expected with good return on all but the fresh (textureless) snow. The lasers produced particularly good surface returns as they pushed through the scene.

• Observed dynamic obstacle. In the static obstacle tests the radar produced mostly noisy results. So we ran the snowmobile through the grid while observing from the tractor, capturing motion towards, away and across the sensor field of view. The radar tracked objects within an approximately 20° field of view but was able to accurately measure the velocity of the snowmobile.

Upcoming

• Experiments with two moving tractors

Weather

Overcast but bright, light breeze, 10-15KPH, -10°C

Antarctic Field Report

February 2, 2011

Ross Ice Shelf, Antarctica

Agenda

• Perform experiments with static objects and moving tractor

Status and Progress

• Perform experiments with two tractors. We spent an entire day configuring experiments to try to capture all the conditions in which our sensor payload would observe another tractor in operation. We began with the instrumented tractor stationary as the quad-track machine, dragging a sled of fuel bladders, drove toward, away and at several angles across the field of view, at 2 MPH and 8 MPH (top towing speed). We then began experiments with both tractors moving, toward and across each other but primarily with the sensor tractor following the quad-track with sled. Experiments included following at various distances, 10, 50, and 100 meters, following behind, in track-packing configuration with overlaping tracks and offset by 10 and 20 meters. We ran at 2 MPH and 8 MPH for each and then chased circles around and around. Finally we recorded speed differences with the sensor tractor closing on the lead, fading back and passing. The goal was to obtain diverse data sets that capture just about all the conditions under which one tractor would observer another while on the South Pole Traverse.

• Molting. For the past couple days, one lone Emperor penguin has been standing beside the road to our field site. We learned that it is molting season so he'll be there a few weeks waiting for new feathers before waddling back to the sea, about 10 km.

Upcoming

• Repositioning sensors

Weather

Sunny with southern clouds, windy, -10°C, snow flurries

Antarctic Field Report

February 3, 2011

Ross Ice Shelf, Antarctica

Agenda

• Reposition sensors (move to front end)

• Enable color imaging

• Repeat observations of static objects from moving tractor

Status and Progress

• Moved sensors. The location of sensors on the tractor is another issue that must be evaluated so, having explored roof mounting many sensors, we moved the main sensor frame to the front of the vehicle hood and moved the radar even lower pointed level ahead. Of course we picked the coldest windiest day thus far to spend 3 hours outside loosening screws, adjusting sensors, and running cables. Amazingly everything was working when we finished.

• Enabled color imaging. For stereo reconstruction the imaging system currently samples only one channel to obtain a grey-scale image. We are finding that everything is so distinct on white snow that a monocular color image may be a reliable detector alone. We modified the image capture software to record full-color (RGB) images.

• Ran on clear snow and static object tests. We began evaluating the hood sensor position by running out on fresh snow and following previously impressed tracks on the snow. We reran our static obstacle test in the flag grid. The lower sensor position seems to be reasonable, providing slightly better distinction of track depths and good flag detection.

• Ran dynamic object tests with truck and snow mobile. We continue to explore the use of radar having found that its response to snow is correct--it is stationary--but the sensitivity to moving objects is noisy. We ran tests with a 4x4 truck and a snowmobile running towards, away and across the radar field of view. When it finds the target the velocity estimate is good.

Our tractor is circle in red in this image from the McMurdo live webcam.

Upcoming

• Interface tractor engine datastream

• Repeat traverse experiments

Weather

Windy, 30KPH, -22°C with wind chill, some sun in the afternoon.

Antarctic Field Report

February 4, 2011

McMurdo Ice Shelf, Antarctica

Agenda

• Interface tractor engine datastream
• Repeat traverse experiments

Status and Progress

• Examined traverse lead vehicle. The South Pole Traverse is lead by a modified snow grooming machine that deploys a ground penetrating radar on a cantilevered boom. This radar searches for voids under the snow surface and is especially important in crevassed areas between the McMurdo and Ross ice shelves, called the shear zone" and while climbing up glaciers onto the polar plateau. We spent some time inside this machine looking at how its steering and drive controls might be automated and how sensors might be mounted in order to enable it to navigate autonomously.

• Interface tractor data. We were able to synchronize software that records tractor performance data (wheel and ground speed, engine rpm, power levels, etc.) with position and perception sensing. This helps to provide more complete data on the experiments for use when we reconstruct events later.

• Following experiments. We ran a series of experiments, collecting simultaneous position, perception, and tractor data while towing a fuel sled. This is our closest simulation to actual traverse conditions. The sled tractor ran a preprogrammed path while the sensor tractor followed at various distances and cross-track offsets. The tractor speeds were varied and both straight and curving paths were performed.

Upcoming

• Blowing snow

Weather

Partly cloudy, calm, -5°C, beautifully sunny after dinner

Antarctic Field Report

February 5, 2011

McMurdo Ice Shelf, Antarctica

Agenda

• Enable color
• Repeat traverse
• Blow snow

Status and Progress

• Enable color. Our previous work in autonomous navigation has used greyscale images in the stereo correlation algorithm. This is sufficient for modeling terrain and has now shown to be sufficient even to model snow, as long as the snow has some visible texture. In Antartica, just about everything that is not white is an obstacle or at least of interest. So visual as well as geometric detection of features seems reasonable. We modified our camera data logging to record images in color so that we can later experiment with tracking colors in the scene.

• Repeated traverse simulation. We repeated the previous experiment simulating traverse conditions today with bright sunlight, instead of overcast skies (flatter light) and with a new sled. This time tool and equipment/storage sleds were used. An interesting, though unsurprising, result is that the radar could more reliably track these large boxes.

• Created blowing snow. Thus far we have had remarkably good weather conditions which is good in almost all respects for almost everyone, except us when we are trying to test sensor performance in poor weather, like blowing snow and white out. We created a somewhat deteriorated blowing snow condition with a snowblower. Returning to our flag grid and standard collection of obstacles we re-observed the scene while blowing snow past the sensors. We also ran the tractor toward the scene while blowing snow and approached the tractor blowing snow along the way. Lastly we focused on the radar's potential for seeing through snow by having people and snowmobiles move from the distance, through the cloud of snow, and emerge.

Upcoming

• Prepare for long traverse

Weather

Clear, calm, very sunny, -4°C

Antarctic Field Report

February 6, 2011

McMurdo Station, Antarctica

Agenda

• Prepare for long traverse

Status and Progress

• Prepared for long traverse. Our final experiment this field season will be to ride along on a 50 kilometer traverse to the shear zone between the McMurdo and Ross Ice Shelves. This is a heavily crevassed area where the ice shelves run past each other that must be crossed to reach the south pole. We moved our sensor and computing payload to a quad-track vehicle that is equipped with autosteer and tractor performance monitoring. We will simultaneously log this data along with position and perception sensors. The sensor logging functions were also modified to log less frequently in order to get a long continuous data set of many kilometers of traverse.

Upcoming

• Traverse to McMurdo/Ross Ice Shelf shear zone

Weather

Partly cloudy, winds 15MPH, -10°C, cold

Antarctic Field Report

February 7, 2011
McMurdo and Ross Ice Shelves, Antarctica

Agenda

• Traverse to shear zone

Status and Progress

• Completed round-trip to Shear Zone. Our last experiment and data collection opportunity was to follow the first 50 km of the South Pole traverse. Having equipped a tractor with our sensing rig and computers we rode along for a 7 hour, out and back trip to the shear zone. It was sunny on the way out, then flat light on the way back, giving experience how lighting affects sensor performance. The flag spacing was 1/4 mile but the visibility was so good that it seemed shorter and spotting tractors sevearl miles distant was possible. As such the convoy spacing was quite large. The ride in the tractor was rough as expected - much rougher than in shorter distance tests near McMurdo.
• Engaged Autosteer. On the way to the shear zone we tried autosteer several times, but the flag route was not straight enough for that to be useful. This revealed an interesting difficulty, while it is possible to enter a specific absolute coordinate and drive a straight line to that goal, the rules of traverse are to follow the known safe path of the flag line. This is particularly important in regions such as the shear zone where there are many crevasses and where the flowing ice means the that the flags and the safe ice beneath them are always moving in absolute position.

At the shear zone we adjusted the cameras upwards (about 5°) to see above the horizon, leaving only a tiny sliver of the hood visible. The laser scanner (LMS511) was vibrating significantly (well over 1°of pitch) and the mount will need to be redesigned.. The LMS111 remained rigid but on this harder snow the tractors made shallows tracks that may not be so readily detectable. The radar was also rigidly mounted, but potential targets were well out of range for most of the trip. Despite vibration the LMS511 laser scanner may have been able to detect flags on the way back. Later impage processing on a single image sequence may also allow detection and tracking of tractors. .

• Concluded first field season experiments. The shear zone traverse was the experiment and capped a remarkably successful field season in which we completed 112 of 121 planned experiments (93%). In total we collected 300GB (7 hrs) of integrated logs plus 100GB of extra data for specific instruments. The continuous traverse to shear zone (over 2 hrs) will provide a valuable resource for developing and testing algorithms in preparation for future experiments and support of the South Pole Traverse.

Upcoming

• Return to Pittsburgh

Weather

Clear, sunny, no wind, -7°C