Introduction

Inter-row cultivation is essential to organic producers
- Weed prevention
- Soil aeration
- Increase in cultivation as a practice
Mechanical rod sensors are unreliable at early crop stages (< 15 cm)
RTK GPS integration is expensive
Computer-vision is relatively low-cost and has been shown to be viable by research

Objective

To develop a computer-vision extension for existing cultivator guidance systems which meets the following constraints:
- Robust → various field and light conditions
- Versatile → interfaced with different systems
- Low-cost → non-specialized components

System Design

Intel Atom D525, 1.8 GHz, 64GB SSD
Two cameras
- 640x480, scaled to 320x240 (speed)
- 25 FPS max, throttled to 15 FPS
- 24 IR LEDs for low-light illumination
- 1000 mm height at 15º incline (~1 mm/px)
 PWM microcontroller with logic level converter (LLC)
Developed a Python application using OpenCV which runs on an embedded computer

Testing Equipment

Hiniker 12-row heavy cultivator
Fendt Vario 890
Sukup Auto-Guide hydraulic hitch

Standard Sukup Auto-Guide System
Camera calibration procedure is very simple:

1. Implement is aligned with row*
   1. Distance from row to tools is checked to ensure equidistance
2. Lateral adjustments are made to the camera until row is aligned with center-line of image
3. Vertical adjustments are made to the camera until subject depth from lens to surface is 1000 mm

*Note: any visible line is sufficient

Plant Segmentation - Color Transform

In order to identify the distribution of green plants, the RGB images must be transformed to a de-correlated color-space, in this case via HSV transformation:

\[
R = \frac{425 - 60}{1 - \text{max}R, G, B} \quad Y = \frac{255 - Y}{\text{max}R, G, B} \quad V = \frac{255 - \text{min}R, G, B}{115}
\]

Lastly, morphological opening is used to reduce noise on the BPPD matrix.

Plant Segmentation - Filtering

A dynamic band-pass filter is applied to the HSV image to select for crop colors:

\[\text{BPPD} = \{45 < H < 100, P(50) < S < 255, P(10) < V < P(90)\}\]

Lastly, morphological opening is used to reduce noise on the BPPD matrix.
Low saturation

Yellow bias, exposure, and blur

Hyper-exposed (extremely bright day)

Severe underexposure (night)

**Row Detection**

- Offset estimation is achieved with a robust, statistical approach.
- Detected plant matter is summed in the direction of travel to estimate the row position.

\[ c = \text{sum}(BPPD, \text{axis}=1) \]

\[ i = \text{median}(c > \text{percentile}(c, 95)) \]

Flow chart for row detection
Electro-Hydraulic Control

Actuation of the two 32-in stabilizers on the cultivator was conducted via a Proportional-Integral controller.

An 8-bit PWM device integrated with a logic-level converter mapped the signal to the operational range of 0.1 - 8.0 V.

\[ u = P \times e + I \times \text{mean}(e[-15]) \]

\[ b = \text{limit}(u, 0, 255) \]

\[ v = \text{map}(u, 0.1, 8.0) \]

Data Collection

Tested on corn and soybean crops at Agri-Fusion (St-Polycarpe, QC)

Tractor was manually operated → source of random error

Straight drilled fields using StarFire 3000 RTK

Organic cultivars, i.e. no spraying was conducted

Four (4) travel speeds were tested → 6, 8, 10, and 12 km/h

Four (4) crop stages were tested → <10, <15, <20, and >20 cm

Total of 48 trials*

Results

<table>
<thead>
<tr>
<th>RMSE (cm)</th>
<th>95th Percentile (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr</td>
<td>e</td>
</tr>
<tr>
<td>6</td>
<td>m</td>
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<tr>
<td>8</td>
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<td>8</td>
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Results

<table>
<thead>
<tr>
<th>RMSE</th>
<th>95th Percentile</th>
</tr>
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<tbody>
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<td>8</td>
<td>3</td>
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</tbody>
</table>

Bonneterre (Phase 2)

After the success with Agri-Fusion, our group was approached by Bonneterre, another large-scale organic producer in Quebec.

Three (3) more systems were built with several design revisions:

- Non-angled camera
- Fully weather-proof wiring
- ABS enclosure
- Updated code-base and re-tuned control parameters (SunCo AcuraTrak)
Weatherproof Enclosure

- IP65+ connector
- In-cab display
- On/Off button
- Calibration

In-cab Display

- Minimalistic layout
- Basic operator information:
  - Output voltage
  - Estimated offset
  - Direction of adjustment
  - Live video feed
  - VESA standard mounting
  - 12V DC power

Conclusion

System has met the stated objectives:

- Robust
- Versatile
- Low-cost

Computer-vision outperformed mechanical at 10 cm and 15 cm
Mechanical demonstrated equal performance at 20 cm and outperformed computer-vision at >20 cm

This technology has received significant interest from producers
A Mk.III model is under development for Sunco (manufacturer of AcuraTrak)
Estimation of tractor ground-speed with SURF keypoint matching

Trevor Stanhope
M.Sc. Candidate, Bioresource Engineering
McGill University

Introduction
Emerging applications for computer-vision on agricultural implements
- Row-crop cultivation
- Strip tillage
- Post-harvest spraying
Motion feedback is very useful for such applications
Orientation
Responsiveness
Incorporating speed detection into these systems can be problematic
RTK GPS can be expensive

Keypoint Matching
Keypoint matching is the process of extracting feature descriptors from multiple images and determining consistent pairs (e.g., via knn-Matching)
Several mathematical algorithms exist for producing keypoints
- SIFT
- SURF
- ORB
ORB and SURF are >3x faster than SIFT
SURF is very good at handling images with blurring

Objective
Evaluate the effectiveness of a computer-vision system for estimating ground speed of an agricultural vehicle using the SURF algorithm with a single, low resolution camera.

Data Collection
Six (6) surface types
- Pavement
- Gravel
- Soil/Residue
- Turf Grass
- Hay Grass
- Mature Soy
For each surface type, five (5) videos were collected
0 km/h to 18 km/h to 0 km/h in ~45 seconds

Data Collection
John Deere Gator 850D
Trials conducted in high gear
640 by 480 px CMOS camera
1000 mm above surface
25 frames-per-second
Coverage height measured
Two consecutive RGB images, 12.8 km/h

Methodology

Process diagram for Local Vector Estimation (LVE).

Pre-Processing I - Gray-scale Transform
Firstly, the input image must be converted from RGB to gray-scale

\[ Y = 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B \]

Methodology

Pre-Processing II - CLAHE
The contrast of gray-scale images is improved with contrast limited adaptive histogram equalization (CLAHE).
Prevents over-amplification of noise compared to standard histogram equalization
Clips histograms of image subsets (redistributing values equally among bins) before computing the cumulative distribution function (CDF)

Pre-Processing III - Lens Distortion
Lens distortion can be corrected using a matrix transformation
With a checkerboard image we can locate corners (30mm x 30 mm)
Camera calibration parameters found by rectilinearizing the set of points

Pre-Processing III - Lens Distortion
Lens distortion correction with checkerboard pattern.
Pre-Processing IV - Summary

Input image (left) and corrected output image (right)

SURF - Speeded Up Robust Features

SURF is a keypoint detection algorithm which works by iteratively applying Gaussian filters and selecting points which exceed a Hessian threshold.

Wavelet responses in the horizontal and vertical directions produce a 128-dim array of feature descriptors for each keypoint.

For this project, the recommended SURF parameters were used:
- Hessian threshold = 1000
- Gaussian octaves = 4
- Gaussian octave layers = 2

Keypoint Matching

Brute force kNN-Matching (N=2) is used to find keypoint pairs between two consecutive images.

Cross-checking is utilized to produce only high-quality pairs.

Calculating Vectors

Each keypoint pair is converted from x-y to polar:
- $v_x = x_2 - x_1$
- $v_y = y_2 - y_1$
- $r = \sqrt{v_x^2 + v_y^2}$
- $\phi = \arctan2(v_x, v_y)$

A frame-rate of 25.0 Hz is assumed and 1.0 mm/px is converted to kilometers:
- $|v| = 3600 \cdot r / 25.0$

Vector Filtering

Need to reject improper vectors, i.e. those caused by shadows / fixed objects.

Select the largest set of vectors traveling in the same direction.

Compute the 25th percentile of vector speeds within that subset.

Compensates for error caused by subject distance.

Computationally simple and produces consistent results.
Graphical representation of keypoint matching with vector highlighting of good (green) and rejected (red) pairs

Video demonstration of keypoint matching

Table 1. Average RMSE and linear regression values.

<table>
<thead>
<tr>
<th>Surface</th>
<th>RMS (m)</th>
<th>Slope (m/m)</th>
<th>Offset (m/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt (0 cm)</td>
<td>0.221</td>
<td>1.001</td>
<td>0.046</td>
</tr>
<tr>
<td>Gravel (&lt; 2.5 cm)</td>
<td>0.258</td>
<td>0.984</td>
<td>-0.097</td>
</tr>
<tr>
<td>Residue (2.5 – 10 cm)</td>
<td>0.249</td>
<td>1.006</td>
<td>-0.175</td>
</tr>
<tr>
<td>Turf Grass (10 – 15 cm)</td>
<td>0.573</td>
<td>1.067</td>
<td>-1.170</td>
</tr>
<tr>
<td>Hay Grass (15 – 20 cm)</td>
<td>0.858</td>
<td>1.089</td>
<td>-4.054</td>
</tr>
</tbody>
</table>

Figure 1. RMSE of trials by surface type.

Conclusions
Sufficient accuracy in the operational range of most agricultural implements (0 km/h to 12 km/h)
Noticeably different behavior than RTK during acceleration
SURF algorithm was capable of 2 - 6 Hz
Accuracy degrades with surface depth variability, solved by sensor fusion:
- Stereo-vision
- Time-of-Flight / LIDAR
- Ultrasonic
- Laser-point matching
Further Research - Laser-point Matching

Two laser pointers are directed to the surface, parallel to camera
Keypoint matching is used to identify the laser dots
Distance between the dots is used to approximate subject depth

Further Research - ORB vs. SURF

<table>
<thead>
<tr>
<th></th>
<th>SURF</th>
<th>ORB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patent protected</td>
<td>Patent protected</td>
<td>Opensource</td>
</tr>
<tr>
<td>Only capable of</td>
<td>Only capable of 2 - 6 Hz</td>
<td>Theoretically faster</td>
</tr>
<tr>
<td></td>
<td>Great matching with blurring</td>
<td>Poor matching with blur</td>
</tr>
</tbody>
</table>

Research Question (Part II): Which keypoint matching algorithm is best-suited for real-time ground speed estimation, SURF or ORB?

Questions?
A QUICK-INSTALL TRACTOR GUIDANCE SYSTEM RELYING ON COMPUTER VISION

Antoine Pouliot, Trevor Stanhope, Viacheslav Adamchuk
Bioresource Engineering Department of McGill University

PROJECT OBJECTIVE

- To design a camera-based automated guidance system capable of guiding an unladen agricultural tractor within a desired path (crop row) at speeds between 1 m/s and the maximum practical operating speed for the tractor (5 m/s).
- The system also has to meet the following requirements:
  - Not restricted to a specific crop or task
  - Compatibility with all agricultural vehicles equipped with power steering
  - Easy to install within minutes
  - Inexpensive

DESIGN REQUIREMENTS

- Plant Segmentation
  - RGB images must be filtered to distinguish plant matter from soil
  - Capability to handle different crops (e.g. soybeans, corn)

- Row Detection
  - The crop row must be determined after plants have been identified
  - Capability to handle high weed density and inconsistent rows

- Ground Speed Measurement
  - Enough keypoints must be matched to measure progression between frames
  - Capability to handle poor lighting (e.g. shadows)

- Vehicle Control
  - The guidance adjustments must be smooth and not exhibit hunting oscillations
  - Capability to handle rows with 5 cm error

SYSTEM COMPONENTS

- Rugged Camera
- Onboard vehicle computer
- Stepper motor, encoder and mounting hardware
- Joystick and dedicated microcontroller
- HSI band-pass plant detection algorithm
- SURF ground speed estimation
- RTK-level GNSS receiver (for performance evaluation)

SYSTEM DIAGRAM

CAMERA IMPLEMENTATION

One meter above garden hose on tarmac (a), and above soybeans with the GPS antenna (b)
PLANT SEGMENTATION

- A HSI Band-Pass Plant Detection algorithm (BPPD) was developed to address false-negative and false-positive plant identification in non-diffuse lighting.

\[ BPPD_i = \begin{cases} 1 & \text{if } H_i > H_{\text{min}} \land H_i < H_{\text{max}} \land |S_i| > \text{mean}(S) \land I_i > \text{mean}(I) \\ 0 & \text{otherwise} \end{cases} \]

HSI SEGMENTATION ALGORITHM

Original (a) compared to improved HSI filter (b)

CROP ROW DETECTION

- A statistical band-pass filter for estimating lateral crop offset was developed based on work by Slaughter et al. (1996) and Brivot et al. (1997)

\[ CS = \frac{1}{N} \sum_{i=0}^{N} BPPD_i \]

\[ CI_i = \begin{cases} i/A & \text{if } CS_i \geq \text{mean}(CS) + 2 \cdot \text{std}(CS) \\ \frac{i}{N} & \text{if } CS_i < \text{mean}(CS) + 2 \cdot \text{std}(CS) \end{cases} \]

\[ Offset = \begin{cases} \text{median}(CI) - \frac{n}{2} & \text{if } \text{count}(CI) > 0 \\ \frac{n}{2} & \text{if } \text{count}(CI) = 0 \end{cases} \]

ROW DETECTION DEMONSTRATION

Stanhope et al. 2014

GROUND SPEED MEASUREMENT

- Using two consecutive frames of the video stream to identify keypoints using SURF algorithm (Bay et al. 2006)
- K-means nearest neighbor matching finds matching keypoints
- Average velocity calculated by determining positional change multiplied by average frame rate of camera (Stanhope, 2015)

GROUND SPEED MEASUREMENT

Simplified ground speed estimation flowchart and illustration.
**VEHICLE CONTROL**
- T5050 New Holland tractor steered by stepper motor and steering wheel hub adapter attached to front window using suction cups
- PD feedback controller design

**VEHICLE CONTROL ALGORITHM**
Simplified control algorithm flowchart.

**TRIALS ON TARMAC**
Arrangement of the two test layouts for the garden hose, on tarmac.

**TRIALS ON TARMAC AT 2.5 M/S**

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Direction of Travel</th>
<th>Trial</th>
<th>Number of Records</th>
<th>Mean Absolute Error (mm)</th>
<th>RMSE (mm)</th>
<th>95th Percentile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
<td>East-West</td>
<td>1</td>
<td>110</td>
<td>4.6</td>
<td>6.1</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>110</td>
<td>5.9</td>
<td>7.1</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>109</td>
<td>7.8</td>
<td>9.6</td>
<td>17.4</td>
</tr>
<tr>
<td>West-East</td>
<td>1</td>
<td>111</td>
<td>10.9</td>
<td>12.5</td>
<td>25.9</td>
<td></td>
</tr>
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<td></td>
<td>2</td>
<td>112</td>
<td>2.3</td>
<td>2.5</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td></td>
<td>552</td>
<td>8.9</td>
<td>9.8</td>
<td>16.7</td>
</tr>
<tr>
<td>Curved</td>
<td>East-West</td>
<td>1</td>
<td>98</td>
<td>15.2</td>
<td>16.4</td>
<td>27.5</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>127</td>
<td>4.1</td>
<td>5.5</td>
<td>8.9</td>
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<tr>
<td></td>
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<td>3</td>
<td>129</td>
<td>4.6</td>
<td>5.7</td>
<td>10.6</td>
</tr>
<tr>
<td>West-East</td>
<td>1</td>
<td>128</td>
<td>9.1</td>
<td>11.3</td>
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<td>Overall</td>
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<td></td>
<td>396</td>
<td>9.2</td>
<td>11.3</td>
<td>23.6</td>
</tr>
</tbody>
</table>

**RTK TRACKING**
Tracking of the test tractor as recorded by GPS, in relation to arbitrarily chosen reference point.

**RTK TRACKING CONT’D**
Tracking of the test tractor as recorded by GPS, in relation to arbitrarily chosen reference point.
WORK IN PROGRESS

- Higher operating speeds (5 m/s)
- Kalman Filter
- Operator Assisted Reinforcement Learning

→ Q-Learning

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