Plant Growth Measurement Techniques Using Near-Infrared Imagery

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Abstract We examine the usefulness of various imaging techniques, including optical flow, for measuring plant growth for corn seedlings and Caster Oil Bean leaves. A near-infrared camera, which allows one to measure optical flow in the light and in the dark, is used. For corn seedlings we have already used optical flow to obtain 3D image velocity as a measure of growth performance. We propose two new growth metrics for measuring growth, one based on elongation of the stem/leaf and the other based on the area change of the stem/leaf. These metrics are examined by measuring the corn seedling growth under various combinations of root temperatures (warm or cold) and under various lighting conditions (light to dark). For caster oil bean leaves we use Horn and Schunck’s optical flow algorithm to compute the globally consistent flow field for a moving, growing leaf. We use 1st order divergence of the flow to hypothesize where growth might be taking place.

Keywords: Near-Infrared Imagery, Corn Seedling stem/leaf growth, Caster Oil Bean leaf Growth, Optical Flow, Optical Flow Divergence

1 Introduction

We are interested in the measurement of plant growth using optical flow. We use a near-infrared camera with near-infrared light sources, which allows us to measure optical flow in the light and in the dark. Infrared light is just above red light in the visual spectrum and allows us to “see” in the dark with a normal black and white camera with minor modifications. Unlike infrared light, near-infrared light responds only minimally to heat. Using a near-infrared camera will allow us to measure the growth of corn seedling stems/leaves under various temperature and lighting conditions. We also examine the growth of caster oil bean leaves using a divergence of flow calculation.

2 Background

We have presented a non-contact optical method [6] for measuring minute amounts of plant growth using optical flow calculations on an image sequence of a sprouting young corn seedling. This method eliminates the plant contact required by use of displacement transducers [9, 10, 11] and the complexity in the setup required when using interferometry [12, 13]. In that study [6], we demonstrated the feasibility of the method for measuring corn seedling growth in 100 images when the corn seedling’s root temperature was decreased from about 25°C Celsius (room temperature) to about 11°C Celsius and then back again to room temperature. Plant growth and root temperature were well correlated (Pearson’s coefficient of 0.93); the method could measure growth rates as low as 5 microns/second. In further work [7], much longer image sequences (more than 2000 images) was analyzed by optical flow and the growth not only of an original corn seedling but also (separately) that of leaves emerging from the coleoptile could be measured.

A method was presented to measure 3D plant growth using the optical flow computed on an image sequence of a growing corn seedling [8]. Each image in the sequence consists of two views of the same growing corn seedling; one view of the corn seedling is front-on while the second view is an orthogonal view (at 90 degrees) of the seedling made by projecting the plant’s orthogonal image onto a mirror oriented at 45° with respect to the camera. We compute 3D velocity (motion) of the corn seedling’s tip by using a simple extension of the 2D motion constraint equation used in optical flow analysis. We obtain 3D image velocities, (v_x, v_y, v_z), in a single least squares calculation.
3 Apparatus Description

Our imaging apparatus consisted of a Sony XCEI50 black and white camera with a Schneider Xeoplan 1.4/23mm lens (to allow both visible and near-infrared light to enter the camera) and an RM-90 IR filter (Edmund Optics) in front of the camera’s CCD to block out visible light. We used 2 IR LED illumination sources (peak intensity at 880nm ± 25nm) also made by Edmund Optics. We used a LI-COR-1800 spectroradiometer to measure the spectrum of the near-infrared light sources. Figure 1 shows the measured spectrum for one of our light sources. As can be seen, the spectral irradiance is about 0.85 (watts/m²/nm) at 880nm.

![Near-infrared spectrum of the infrared light sources](image)

Figure 1: Near-infrared spectrum of the infrared light sources used in our experiment as measured by LI-COR-1800 spectroradiometer.

Corn seeds were sown singly in modified peat moss growing medium in black polyethylene tubes 10 cm long and of 1 cm inner diameter. The camera, plant/tube and mirror were contained in a wooden box. Figure 2 shows the experimental setup use in our lab.

![Experimental setup](image)

Figure 2: The actual setup

This allowed the elimination of any room air currents and constant maintenance of the scene temperature and lighting. The tube with a corn seedling at the primary leaf stage was inserted into a glass bottle containing water and coils from water baths set at various temperatures. The seedling shoot was exposed to the ambient room air temperature of about 20°C while the roots in the tube were exposed to the water bath temperature. The seedlings were grown initially at temperatures of 12°C or 24°C for periods of either 100 or 300 minutes. Similarly, a fibre optics light source was turned on or off for either 100 or 300 minute intervals. An image was acquired every 2 minutes during this activity (yielding either 50 or 150 images) for each temperature/lighting period.

Each image in the sequence consists of two views of the same growing corn seedling: one view of the corn seedling is front-on while the second view is a orthogonal side view (at 90 degrees) of the seedling made by projecting the plant’s orthogonal image onto a mirror oriented at 45° with respect to the camera. This allows us to measure 3D optical flow by measuring two 2D optical flows [8].

4 Optical Flow

We use two optical flow algorithms in the work described here. We use Lucas and Kanade’s algorithm [3] extended to give a single 3D image velocity, \((v_x, v_y, v_z)\), from front and side views of the same corn seedling. We also use Horn and Schunk’s algorithm [4] to measure smooth flow fields on a Castor Oil Bean leaf.

4.1 Lucas and Kanade Optical Flow

The basis of all differential optical flow methods is the motion constraint equation,

\[
I_x v_x + I_y v_y = -I_t, \tag{1}
\]

where \(I_x\), \(I_y\) and \(I_t\) and the spatio-temporal image intensity derivatives and \((v_x, v_y)\) are the \(x\) and \(y\) components of the 2D image motion (image velocity). If the camera is reasonably close to the plant these 2D motions are very good approximations to the actual 3D motions in those dimensions as then perspective projection is roughly orthographic projection. Equation (1) is one equation in two unknowns. Any velocity that satisfies this equation is potentially the correct velocity. If we assume the motion is constant in some neighbourhood than two (or more) sets of derivatives can yield a non-singular linear (least squares) system of equations that yield values for \((v_x, v_y)\).
The velocity with the smallest magnitude on the motion constraint equation is called the normal velocity as it is one of the endpoints on the shortest line from that point to the origin (this line is perpendicular to the motion constraint line) and is given by $v_n = \frac{-I}{||\nabla I||}$ and $\hat{n} = \frac{(I_x, I_y)}{||\nabla I||}$ (2) are the normal velocity magnitude and the normal velocity direction and $\nabla I$ is the spatial intensity gradient. We do not compute or use normal velocities in this study.

Differentiation was done using Simoncelli’s [5] matched balanced filters for low pass filtering (blurring) $(p_5)$ and high pass filtering (differentiation) $(d_5)$ [see Table 1]. Matched filters allow comparisons between the signal and its derivatives as the high pass filter is simply the derivative of the low pass filter and should yield more accurate derivative values. Using these two masks $I_x$ is computed by applying $p_5$ in the $t$ dimension, then $p_5$ to those results in the $y$ dimension and finally $d_5$ to those results in the $x$ dimension. $I_y$ and $I_t$ are computed in a similar manner. Before performing this filtering we use a simple averaging filter $[\frac{1}{4}, \frac{1}{4}, \frac{1}{4}]$ to slightly blur the images. Simoncelli claims that because both of his filters were derived from the same principles more accurate derivatives result and he demonstrated this on the Yosemite Fly-Through sequence [5, 2]. We use in the least squares sense (we must have at least one derivative set from each of the views or a $(v_x, v_y, v_z)$ calculation is not possible).

4.2 Horn and Schunck Optical Flow

Horn and Schunck [4] combined the gradient constraint (1) with a global smoothness term to constrain the estimated velocity field $\vec{v} = (v_x, v_y)$, minimizing

$$\int_D (\nabla \cdot \vec{v} + I_t)^2 + \lambda^2(||\nabla v_x||^2_2 + ||\nabla v_y||^2_2) dxdy$$ (4)

defined over a domain $D$ (the image), where the magnitude of $\lambda$ reflects the influence of the smoothness term. We used $\lambda = 1.0$ and $\lambda = 10.0$ in this study. Iterative equations are used to minimize (4) and yield the optical flow field as:

$$v_x^{k+1} = v_x^k - \frac{I_x [I_x v_x^k + I_y v_y^k + I_t]}{\alpha^2 + I_x^2 + I_y^2}$$

$$v_y^{k+1} = v_y^k - \frac{I_y [I_x v_x^k + I_y v_y^k + I_t]}{\alpha^2 + I_x^2 + I_y^2},$$ (5)

where $k$ denotes the iteration number, $v_x^0$ and $v_y^0$ denote initial velocity estimates which are set to zero, and $v_x^k$ and $v_y^k$ denote neighbourhood averages of $v_x^k$ and $v_y^k$. We use at most 100 iterations in all testing below. Differentiation for computing $I_x$, $I_y$ and $I_t$ was done using Simoncelli’s filters [5] as outlined above.

4.3 Experimental Nomenclature

Our experiments consist of measuring corn seedling growth/motion in a variety of conditions. For example STEM-LDL-CWC indicates a sequence for a stem, with the light/dark condition will change as Light/Dark/Light sequence and the change will occur every 150 frame. While for the temperature condition, CWC means Cold/Warm/Cold sequence and the change occurs every 50 frame. At the end of every 150 frame, the CWC sequence will repeat itself again in a different light condition in this case. 50 image subsequences is equal to 100 minutes while 150 images is equal to 300 minutes because we take a frame every 2 minutes.

The name LEAF-LDL-WCW indicates a sequence for a leaf always in light/dark/light changes on 150 frame basis, while the temperature condition changes every 50 frames from Warm to Cold, and the same sequence gets repeated again after 150 frames.

4.4 Experimental Definitions

For estimating the seedling growth value, in Barron and Liptay’s work [6, 7, 8], the image velocities were

<table>
<thead>
<tr>
<th>n</th>
<th>$p_5$</th>
<th>$d_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.036</td>
<td>-0.108</td>
</tr>
<tr>
<td>1</td>
<td>0.249</td>
<td>-0.283</td>
</tr>
<tr>
<td>2</td>
<td>0.431</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.249</td>
<td>0.283</td>
</tr>
<tr>
<td>4</td>
<td>0.036</td>
<td>0.108</td>
</tr>
</tbody>
</table>

Table 1: Simoncelli’s 5-point Matched/Balanced Kernels
summed over time. Equation 6 shows the meaning of $\vec{v}$ which is the vector of the 3D velocity components ($V_x$, $V_y$, and $V_z$).

$$\vec{v} = (V_x, V_y, V_z) \quad (6)$$

Now we need to introduce a new scalar value called $V_{\text{norm-total}}$ which means to get the total $L_2$ norm of every single velocity at each frame $i$ as following:

$$V_{\text{norm-total}} = \sum_{i=1}^{n} ||\vec{v}_i||_2 \quad (7)$$

Another scalar value called total displacement ($D_{\text{total}}$) is computed as the $L_2$ norm of the sum of every single velocity vector at each frame as following:

$$D_{\text{total}} = ||\sum_{i=1}^{n} \vec{v}_i||_2 \quad (8)$$

Now, the rate of displacement change, $D_{\text{rate}}$ is computed as:

$$D_{\text{rate}} = D_{\text{total}} - D_{\text{total,-1}} \quad (9)$$

Where $i$ denotes to the current frame number, and obviously $(i-1)$ is the previous frame number.

The total elongation of the corn seedling stem/leaf can be approximated by the displacement value based on a sum of velocities. Error in this measure is introduced when the stem/leaf is bent, when the tip starting point projection changes with time.

Furthermore, because the seedling sometimes just sways about while it is growing, it is inaccurate to measure the $L_2$ norm of the image velocity components at the corn seedling tip but rather measuring the displacement over a significant time interval would give a better approximation for the seedling elongation. In this way, negative and positive values of the $x$, $y$ and $z$ components of image velocity will cancel each other out when summed.

4.5 Plant Elongation

One way to measure the elongation of the corn seedling involves projecting the tip starting point onto the current growing plant seedling. Figure 3 shows this projection from the tip starting point $P_{t_1}$ to a projected point $P_{p_1}$ on the corn seedling at time (frame) $i$, where $i$ is the current frame number.

We define $P_{p_1}$ by first getting $P_{c_i}$ which is the intersection of the lines $P_{t_1}P_{t_i}$ and $P_{c_i}P_{f_i}$ lines, where $P_{t_1}$ and $P_{t_i}$ are pixels measured in the bottom row of the corn seedling in frames 1 and $i$ respectively.

Now $r$, the distance from $P_{c_i}$ to either $P_{p_1}$ or $P_{t_1}$, is equal as it is the distance swept along the arc from $P_{t_1}$ to $P_{p_1}$:

$$r = ||P_{t_1}P_{c_i}|| = ||P_{p_1}P_{c_i}|| \quad (10)$$

Then $L$, the stem elongation as:

$$L = ||P_{t_1}P_{c_i}|| - ||P_{p_1}P_{c_i}|| \quad (11)$$

Given the intersection point of lines $P_{t_1}P_{f_1}$, and $P_{c_i}P_{f_i}$, i.e. $P_{c_i}$, we can compute the projection point $P_{p_i}$ as the point on the ray given by:

$$P_{p_i} = P_{c_i} + \frac{P_{p_1}P_{f_1}}{||P_{c_i}P_{f_1}||} \cdot r \quad (12)$$

In the event that “bends” appear in the stem, if those bend points can be detected, then this elongation method can easily be extended to handle them.

![Figure 3: Measuring the corn seedling elongation as the stem sways: we want to measure elongation of the stem only.](image)

4.6 Plant Area Change

A second way to measure corn seedling growth is to measure the area extension of the plant from frame 1 to frame $i$, as shown in Figure 4. As in the previous section, we compute $P_{p_i}$, the projection of $P_{t_1}$ onto the line $P_{c_i}P_{f_i}$. From that point (upwards) we
compute whether a pixel belongs to a plant stem or
the background by a simple threshold on grayvalue
(30). A simple count of these stem pixels gives a
rough estimate of area increase. Note here that we
are assuming that the stem areas below $P_1$ and $P_p$
are equal; actually the area under $P_p$ will probably
be a bit bigger because of subsequent growth.

![Diagram](image)

Figure 4: Another way to measure the growth by
computing the area extension of the corn seedling.

For a corn seedling stem/leaf we can also count
the number of pixels comprising its surface. This
involves use a threshold $\tau$ (we use value 30) to separate
background pixels from stem/leaf pixels. The total
area then represents the total growth:

$$A_{\text{total}} = \text{Count}(P(i, j)), \text{ such that } P(i, j) \geq \tau,$$

where $P(i, j)$ is the pixel at location $(i, j)$, also
$P(i, j)$ pixels should be above the $P_p$ (Projection
Point) position to be counted in the area computa-
tions as shown in Figure 4.

The initial value for $\tau$ is 10.0 then we change it
when the lighting condition changes because at that
time the plant pixel intensities would change also
and would give a rise or a decrease in the total com-
puted area, so to compensate that change, we tune
the value $\tau$ by decreasing or increasing it, to cancel
out the light intensity change affection. We use a
binary search method to get the best new $\tau$ to can-
cel out the intensity effect. This mostly happens in
frame number 150 and 300 when the light condition
change from dark to light and vice versa.

The rate of area change can be specified as:

$$A_{\text{rate}} = A_{\text{total}} - A_{\text{total},-1}.$$

5 Experimental Results

Figure 5 shows the result of LEAF-LDL experiment
when we measure the area (Figure 5.a) and when we
measure the elongation (Figure 5.b). In Figure 5.a
the white coloured pixels are those with grayvalue
over threshold $\tau \geq 30$. In Figure 5.b we see several
things: the jagged lines show the path of the seedling
tip as it grows, the straight lines are the displacement
vectors, $D_{\text{total}}$, the straight horizontal lines mark 50
image intervals and the curved arc-like lines are the
paths of the projections of $P_1$ in the front and side
views to $P_p$ in those views.

Figure 6 shows the elongation rate, $L_{\text{rate}}$, and
the total elongation, $L_{\text{total}}$, of LEAF-LDL experiment,
as a function of the frame number. Figure 7 shows
the area rate, $A_{\text{rate}}$, and the total area, $A_{\text{total}}$, as a
function of the frame number.

![Diagram](image)

Figure 5: LEAF-LDL experiment where we show
how we measure (a) the area and (b) the elongation.

![Diagram](image)

Figure 6: Elongation rate and total elongation for
the LEAF-LDL experiment measured as a function
of frame number.

Figure 8 shows normalized elongation rate and
area rate, computed by dividing the original rates
measures by the rate averages over the total frame
period (450 frames). This makes the two measures
have the same minimums and maximums and al-
ows comparison. The two measures are very similar,
Pearson’s Correlation Coefficient is 0.66
Figure 7: Area rate and total area for the LEAF-LDL experiment measured as a function of the frame number.

Figure 8: LEAF-LDL experiment showing normalized elongation and area rate, $l_{rate}$ and $A_{rate}$. Pearson’s Correlation Coefficient is 0.66

5.1 Corn Seedling Leaf Growth
Corn seedling stem and leaf growth do not seem that different, although a leaf appears to grow much faster in the light than the dark. Figure 9 shows the growth paths for a leaf totally in the light and totally in the dark while Figure 10 shows the growth paths for a leaf in DLD and LDL lighting conditions. The leaf in the fully lighted scene is drawn to the light source. LDL or DLD lighting conditions seem to have little effect, as for the stem.

5.2 Overall Statistics
Figure 11 shows the average growth for all our experiments in the warm or in the cold (or some combination of these) for all lighting conditions. The dark parts (purple) at the top of the pole are the standard deviations while the lighter parts (cyan) represent the average values. Figure 12 shows the average growth for all out experiments in the light and in the dark (or some combination of these) for all root temperatures. These experiments show that the rate of growth is fastest for warm root temperatures, slowest for the cold root temperatures and in-between and about the same for the CWC and WCW sequences. Lighted stems grow faster than dark stems and when the lighting is mixed the growth rate is in-between; LDL sequences show slightly more growth than DLD sequences (which makes sense as they are exposed to more light).

Figure 9: The growth of a leaf in light and in dark.

Figure 10: The growth of a leaf in a DLD or LDL sequence.

Figure 11: Average stem growth rate according as a function of root temperature, C, W, CWC or WCW.
Corn seedling leaf overall growth statistics are not much different than those for a corn seedling stem. Figure 13 shows this.

5.3 Castor Oil Bean Leaf Growth

In this section we examine the divergence of optical flow as a means to measure leaf growth. Figure 14 shows an image of a Castor oil bean leaf. This leaf is moving as it grows and we verified that the leaf moves with the computed flow. Jähne et al. [14] also investigated the use of optical flow to measure motion in dynamic processes, like castor oil bean leaf growth via divergence. They used a 2 frame calibration technique to correct for camera defects. Nevertheless, we obtained similar results to them using our near-infrared camera. We first tried to measure optical flow using Lucas and Kanade’s least squares method [3] but we found the flows too sparse. We report Horn and Schunck’s method [4] with the Lagrange multiplier $\alpha$ set to 10 and using 100 iterations.

Figure 15 which shows the flow for frame number 100 from the 450 frames sequence.

Figure 14: An image of the Castor Oil leaf in frame number 100.

Figure 15: Horn and Schunck result using $\alpha = 10$. This one is for frame 100.

We compute the image velocity divergence as:

$$Divergence = \sqrt{\left(\frac{\partial v_x}{\partial x}\right)^2 + \left(\frac{\partial v_y}{\partial y}\right)^2}$$

are computed using Simoncelli’s filters on the $(v_x, v_y)$ computed via the Horn and Schunck iterations. Like Jähne et al. [14] we hypothesize that high absolute values of Divergence correspond to positions of growth (but we have no way of verifying this at the present). Figure 16 shows the divergence image. The black spots indicate high divergence and made indicate leaf growth.
6 Conclusions and Future Work

We have shown that optical flow may be a useful measuring tool for plant growth. Stem/leaf elongation seems to be good metrics for corn seedling growth. Corn seedling stems/leaves seem to grow faster when their root temperature is warmer or when they are exposed to more light. These expected results are confirmed by our growth measurements. Lastly, we hypothesized that the divergence of an optical flow field of a moving/growing leaf might be a means of measuring leaf growth.

Future work includes, using longer time sequences (simulating a day which is warm in the light and cold in the dark), using “older” plants where lighting conditions would produce more pronounced growth effects, measuring leaf growth and correlating this to surface area growth and measuring divergence on plants with many overlapping leaves.

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References


