Time varying image analysis

- Motion detection
- Motion estimation
- Egomotion and structure from motion

The problems

- Visual surveillance
  - stationary camera watches a workspace -find moving objects and alert an operator
  - moving camera navigates a workspace - find moving objects and alert an operator
- Image coding
  - use image motion to perform more efficient coding of images
- Navigation
  - camera moves through the world - estimate its trajectory
    - » use this to remove unwanted jitter from image sequence - image stabilization and mosaicking
    - » use this to control the movement of a robot through the world

Motion detection

- Frame differencing
  - subtract, on a pixel by pixel basis, consecutive frames in a motion sequence
  - high differences indicate change between the frames due to either motion or changes in illumination
- Problems
  - noise in images can give high differences where there is no motion
    - » compare neighborhoods rather than points
  - as objects move, their homogeneous interiors don't result in changing image intensities over short time periods
    - » motion detected only at boundaries
    - » requires subsequent grouping of moving pixels into objects

Motion detection

- Background subtraction
  - create an image of the stationary background by averaging a long sequence
    - » for any pixel, most measurements will be from the background
    - » computing the median measurements, for example, at each pixel, will with high probability assign that pixel the true background intensity - fixed threshold on differencing used to find "foreground" pixels
    - » can also compute a distribution of background pixels by fitting a mixture of Gaussians to set of intensities and assuming large population is the background - adaptive thresholding to find foreground pixels
  - difference a frame from the known background frame
    - » even for interior points of homogeneous objects, likely to detect a difference
    - » this will also detect objects that are stationary but different from the background
    - » typical algorithm used in surveillance systems
- Motion detection algorithms such as these only work if the camera is stationary and objects are moving against a fixed background

Example

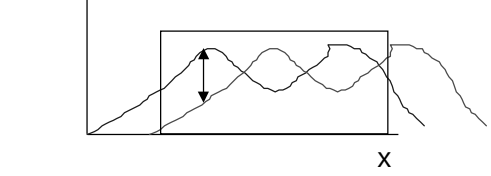
Example

Motion estimation - optic flow

- Optic flow is the 2-D velocity field induced in an image due to the projection of moving objects onto the image plane
- Three prevalent approaches to computing optic flow:
  - token matching or correlation
    - » extract features from each frame (gray level windows, edge detection)
    - » match them from frame to frame
  - gradient techniques
    - » relate optic flow to spatial and temporal image derivatives
  - velocity sensitive filters
    - » frequency domain models of motion estimation

A 1-d gradient technique

- Suppose we have a 1-D image that changes over time due to a translation of the image
- Suppose we also assume that the image function is, at least over small neighborhoods, well approximated by a linear function.
  - completely characterized by its value and slope
- Can we estimate the motion of the image by comparing its spatial derivative at a point to its temporal derivative?
  - example: spatial derivative is 10 units/pixel and temporal derivative is 20 units/frame
  - then motion is (20 units/frame) / (10 units/pixel) = 2 pixels/frame



Gradient techniques

- Assume I(x,y,t) is a continuous and differentiable function of space and time
- Suppose the brightness pattern is locally displaced by a distance dx, dy over time period dt.
  - this means that as the time varying image evolves, the image brightness of points don't change (except for digital sampling effects) as they move in the image
  - I(x,y,t) = I(x + dx, y + dy, t + dt)

Gradient techniques

- We expand I in a Taylor series about (x,y,t) to obtain

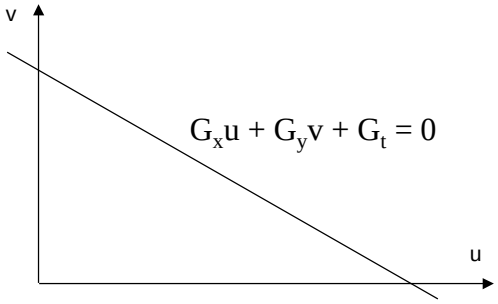
$$I(x+dx, y+dy, t+dt) = I(x, y, t) + dx\partial I / \partial x + dy\partial I / \partial y + dt\partial I / \partial t$$

+ higher order terms

$$dI / dt = [I(x+dx, y+dy, t+dt) - I(x, y, t)] / dt =$$
$$(dx / dt)(\partial I / \partial x) + (dy / dt)(\partial I / \partial y) + \partial I / \partial t$$

  - valid only if temporal change is due entirely to motion
- Can rewrite this as $dI/dt = G_x u + G_y v + G_t = 0$. The G's are derivatives measured from the image sequence, and u and v are the unknown optic flow components in the x and y directions, respectively

Motion constraint line

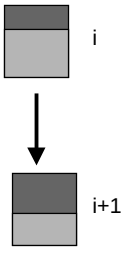


- So, the spatial and temporal derivatives at a point in the image only provide a linear constraint on the optic flow

$G_x u + G_y v + G_t = 0$

Motion constraint line

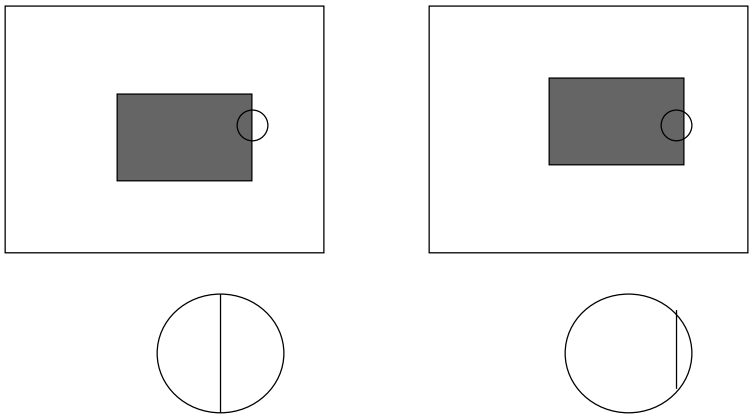
- If G_x and G_y are small, then motion information cannot be accurately determined
  - places in the image where the gray level is almost constant are difficult places to estimate motion
    - » G_t will also be small in these places
- If $G_x = 0$, then $-G_t = G_y v$, so that v is determined, but u is unknown
  - If $G_x = 0$, we have a horizontal edge, so we can't measure its motion along the edge



Motion constraint line

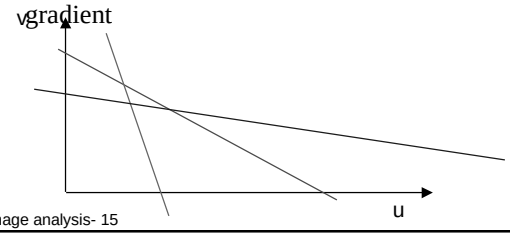
- If H and L denote the gradient and level directions at a pixel then
  - H = tan-1 G_y/G_x
  - L is perpendicular to H
  - $G_L = 0$
- Then $G_t = -G_H dH/dt$, where dH/dt is the displacement in the gradient direction
  - dH/dt can be recovered by measuring G_t and G_H. It is called **normal flow**
  - but dL/dt cannot be recovered, since $G_L = 0$
  - this is called the aperture problem

Aperture problem



Recovering u and v

- Solve for u and v separately, ignoring their coupling through 2-D motion
  - $u = -G_t/G_x$
  - $v = -G_t/G_y$
- Solve system of linear equations corresponding to motion constraints in a small image neighborhood
  - assume u and v will not vary in that small neighborhood
  - requires that neighborhoods have edges with different orientations, since slope of motion constraint line is determined by image gradient



Recovering u and v

- If the constraint lines in a neighborhood are nearly parallel (i.e., the gradient directions are all similar), then the location of the best fitting (u,v) will be very sensitive to errors in estimating gradient directions.
- More generally, one could fit a parametric model to local neighborhoods of constraint lines, finding parameters that bring constraint lines “nearest” to the estimated motion assigned to each pixel.
  - for example, if we assume that the surface we are viewing in any small image neighborhood is well approximated by a plane, then the optical flow will be a quadratic function of image position in that image neighborhood

Token and correlation methods

- Gradient based methods only work when the motion is “small” so that the derivatives can be reliably computed
  - although for “large” motions, once can employ multiresolution methods
- Tracking algorithms can compute motion when the motion is “large”
  - correlation
  - feature tracking
- Correlation
  - choose a kxk window surrounding a pixel, p, in frame i.
  - compare this window against windows in similar positions in frame i+1
  - The window of best match determines the displacement of p from frame i to frame i+1

Correlation

- Correlation
  - sum of squared gray level differences
  - sum of absolute intensity differences
  - “robust” versions of these sensitive to outliers
- Drawbacks of correlation
  - matching in the presence of rotation is computationally expensive since all orientations of the window must be matched in frame i+1
  - if motion is not constant in the kxk window then the window will be distorted by the motion, so simple correlation methods will fail
    - » this suggests using smaller windows, within which motion will not vary significantly
    - » but smaller windows have less **specificity**, leading to matches more sensitive to noise

Tracking

- Apply a feature detector, such as an edge detector, to each frame of the sequence
  - want features to be distinctive
  - example: patterns of edges or gray levels that are dissimilar to their surrounds
  - Match these features from frame to frame
  - might assume that nearby features move similarly to help disambiguate matches (but this is not true at motion boundaries)
  - integrate the matching with assumptions about scene structure - e.g., features are all on a plane moving rigidly

Multiresolution methods

- Consider using edges as features for a tracking algorithm for motion estimation. What should the scale of the edge detector be?
  - small scale
    - » many edges are detected
    - » easily confused with one another
    - » computationally costly matching problem
  - coarse scale
    - » relatively few edges identified
    - » localized only poorly, so motion estimates have high errors
    - » simple matching problem
- Multiresolution - process the image over a range of scales, using the results at coarser scales to guide the analysis at finer scales
  - detect edges at a coarse scale
  - estimate motion by tracking
  - use these estimates as initial conditions for matching edges at next finest scale

Multiresolution methods

- These are also called **focusing** methods or **scale space** methods
  - can also apply to gradient based motion estimators

3-D motion and optical flow

- Assume a camera moving in a static environment
- A rigid body motion of the camera can be expressed as a translation and a rotation about an axis through the origin.
- Let
  - **t** be the translational component of the camera motion
  - ω be the angular velocity
  - **r** be the column vector $[X\ Y\ Z]^T$
- Then the velocity of r with respect to the XYZ coordinate system is

  $\mathbf{V} = -\mathbf{t} + \omega \times \mathbf{r}$
- Let the components of
  - **t** $= [U\ V\ W]^T$
  - **w** $= [A\ B\ C]^T$

3-D Motion and Optic Flow

- Rewrite in component form:

  $X' = -U - BZ + CY$

  $Y' = -V - CX + AZ$

  $Z' = -W - AY + BX$

  where the differentiation is with respect to time
- The optic flow at a point (x,y) is (u,v) where

  $u = x'$, $x = fX/Z$

  $v = y'$, $y = fY/Z$
- Differentiating x and y with respect to time, we obtain

  $u = X'/Z - XZ'/Z^2 = (-U/Z - B + Cy) - x(-W/Z - Ay + Bx)$

  $v = Y'/Z - YZ'/Z^2 = (-V/Z - Cx + A) - y(-W/Z - Ay + Bx)$

3-D Motion and Optic Flow

- These can be written in the form

  $u = u_t + u_r$

  $v = v_t + v_r$
- (u_t, v_t) denotes the translational component of the optic flow
- (u_r, v_r) denotes the rotational component of the optic flow

  $u_t = [-U + xW]/Z$

  $v_t = [-V + yW]/Z$

  $u_r = Axy - B(x^2 + 1) + Cy$

  $v_r = A(y^2 + 1) - Bxy - Cx$
- Notice that the rotational part is independent of Z - it just depends on the image location of a point
- So, all information about the structure of the scene is revealed through the translational component

Mosaicing from a rotating camera

- If we take a camera and rotate it, we can combine all of the images into a p

Special case of a plane in motion

- Suppose we are looking at a plane while the camera moves
  - $Z = Z_0 + pX + qY$
- Then for any point on this plane
  - $Z - pX - qY = Z_0$
  - $1 - p(X/Z) - p(Y/Z) = Z_0/Z$
  - $1/Z = [1-pX/Z - qY/Z]/Z_0 = [1- px - qy]/Z_0$
- So, we can rewrite the translational components of motion for a plane as:

  $u_t = [-U + xW][1- px - qy]/Z_0 = [-U/Z_0 + xW/Z_0] [1- px - qy]$

  $v_t = [-V +yW][1- px - qy]/Z_0 = [-V/Z_0 + xW/Z_0] [1- px - qy]$
- These are quadratic equations in x and y
- So, if we can compute the translational component of the optic flow at "enough" points from a planar surface, then we can recover the translational motion (with unknown scaling) and the orientation of the plane being viewed.

Pure translation

- When camera motion is only translation, then we have

  $u_t = [-U + xW]/Z$

  $v_t = [-V + yW]/Z$
- Consider the special point (u,v) = (U/W, V/W).
  - This is the "image" of the velocity vector onto the image plane
  - The motion at this point must be 0 since the surface point along this ray stays on the ray as the camera moves (also our equations evaluate to 0 at (U/W, V/W))
- Consider the line connecting any other (x,y) to $(x + u_t, y + v_t)$
  - The slope of this line is $v_t/u_t = [x-u]/[y-v]$
  - So, the line must pass through (u, v)
- All of the optic flow vectors are concurrent, and pass through the special point (u,v) which is called the **focus of expansion (contraction)**

Pure translation

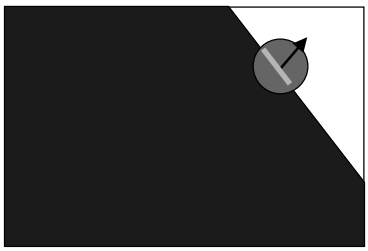
- Another way to look at it
  - Let $\Delta t = 1$, so that the image center at time t moves from (0,0,0) to (U,V,W) at time t+1
  - Think of the two images as a stereo pair
  - The location of the projection of (U,V,W), the lens center at time t+1 (the "right" image), in the image at time t (the left image) is at location (U/W, V/W) = (u,v)
  - All conjugate lines at time t must pass through this point
  - So, given a point (x,y) at time t, the location of its corresponding point at time t+1 in the **original** coordinate system must line on the line connecting (x,y) to (u,v)
- So, if we know the optic flow at two points in the case of pure translation, we can find the focus of expansion
  - in practice want more than two points

Pure translation

- Can we recover the third component of motion, W?
- No, because the same optic flow field can be generated by two similar surfaces undergoing similar motions (U,V and W always occur in ratio with Z).

Normal flows and camera motion estimation

- If we can compute optic flow at a point, then the foe is constrained to lie on the extension of the optic flow vector
- But the aperture problem makes it difficult to compute optic flow without making assumptions of smoothness or surface order
- Normal flow (the component of flow in the gradient direction) can be locally computed at a pixel without such assumptions
- Can we recover camera motion from normal flow?



Identifying the FOE from normal flow

- Assume that the foe is within the field of view of the camera
- For each point, p, in the image

  For each normal flow vector, **n**,

  If p lies in the "correct" halfplane of **n**, then score a vote for p

  The FOE is the centroid of the connected component of highest scoring points (might be a single pixel, but ordinarily will not be).
- Alternative code - maintain an array of counters in register with the image

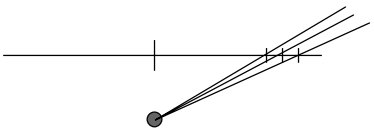
  For each normal flow vector,**n**,

  Increment the counters corresponding to all pixels in the "correct" halfplane of **n**

  Search the array of counters for the connected component of highest vote count
- For an image containing N normal flow vectors and mxm pixels, both algorithms are (m^2N), but (2) is more efficient

Identifying the FOE from normal flow

- What if the FOE is outside the field of view of the camera?
- The image plane is a bad place to represent the FOE to begin with
  - FOE indicates the direction of translational motion
  - Pixels in a perspective projection image do not correspond to equal angular samples of directions
    - » in the periphery, a pixel corresponds to a wide range of directions
  - Solution - represent the array of accumulators as a sphere, with an equiangular sampling of the surface of the sphere
    - » Each normal vector will then cast votes for all samples in a hemisphere
    - » Simple mathematical relationship between the spherical coordinate system of the array of counters, and the image coordinate system



Structure from motion

- If we can compute the 3D motion parameters of an image sequence then we can compute the (scaled) range to visible points in the scene
  - So, if the camera motion is a simple translation, then the Z coordinate of a point is inversely proportional to the length of the optical flow vector - just like disparity for stereo.
- Practical problems
  - motion is not simple translation, but also includes rotation
    - » small rotations about the y axis are easy to confuse with translations in x
  - computing optical flow more difficult than normal flow

Structure from motion

- More practical problems
  - discontinuities in range
    - » optical flow algorithms integrate information over small image neighborhoods. If those neighborhoods overlap a boundary between an object and the background, then the assumptions on which the algorithm is based (e.g., planar surface) are violated and the result will be wrong.
  - Independently moving objects
    - » will confuse the algorithms that estimate 3D motion parameters because their motion is inconsistent with the rigid camera motion

Structure from motion

Structure from motion

A regularization approach

- Many vision problems such as stereo reconstruction of visible surfaces and recovery of optic flow are instances of **ill posed** problems.
- A problem is well posed when its solution:
  - exists
  - is unique, and
  - depends continuously on its initial data
- Any problem that is not well posed is said to be ill posed
- The optic flow problem is to recover both degress of freedom of motion at each image pixel, given the spatial and temporal derivatives of the image sequence
  - but any solution chosen at each pixel that locally satisfies the motion constraint equation can be used to construct an optic flow field consistent with the derivatives measured
  - therefore, the solution is not unique - how to choose one?

A regularization approach

- Solution - add a priori knowledge that can choose between the solutions
- Formally, suppose we have an ill posed problem of determining z from data y expressed as
  - Az = y, where A is a linear operator (e.g., projection operation in image formation)
- We must choose a quadratic norm || || and a so-called stabilizing functional || Pz || and then find the z that minimizes:
  - $||Az-y||^2 + \lambda ||Pz||^2$
  - λ controls the compromise between the degree of regularization and the closeness of the solution to the input data (the first term).
- T. Poggio, V. Torre and C. Koch, Computational vision and regularization theory, *Nature*, **317**, 1984.

A regularization approach

- For optic flow:
  - the first term is $[dx/dt \ \partial I/\partial x + dy/dt \ \partial I/\partial y + \partial I/\partial t]^2 = [dI/dt]^2$
    - » this should, ideally, be zero according to the theory
  - the second term enforces a smoothness constraint on the optic flow field :$\varepsilon = (\partial u/\partial x)^2 + (\partial v/\partial x)^2 + (\partial u/\partial y)^2 + (\partial v/\partial y)^2$
  - The regularization problem is then to find a flow field that minimizes $[dI/dt]^2 + \lambda \varepsilon \, dx \, dy$
  - This minimization can be done over the entire image using various iterative techniques