

Quiz 3 — 01/31/2024

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Credit Statement

I discussed solution ideas with:

1. Ivy (Aiwei) Zhang
2. Angelic McPherson

However, all typed work is my own, with reference to class notes especially on homographies and transformations. I also referred to some of my earlier notes on linear algebra (from **MATH 22**) on the interpretations of matrices and their null-spaces, column-spaces, and row-spaces.

Problem 1.

Given a set N of points $\mathbf{p}_i = (x_i, y_i), i \in \{1, \dots, N\}$, in the image plane, we wish to find the best line passing through those points.

- (i) One way to solve this problem is to find (a, b) that most closely satisfy the equations $y_i = ax_i + b$, in a least-squares sense. Write these equations in the form of a *heterogeneous* least-squares problem $A\mathbf{x} = \mathbf{b}$, where $\mathbf{x} = (a, b)^T$, and give an expression for the least-squares estimate of \mathbf{x} . Give a geometric interpretation of the error being minimized, and use a simple graph to visualize the error. Does this make sense when fitting a line to points in an image?

The set of N points satisfies the following system of equations:

$$y_1 = ax_1 + b$$

$$y_2 = ax_2 + b$$

$$\vdots$$

$$y_N = ax_N + b.$$

We can rewrite the system as the following heterogeneous *least-squares* problem:

$$\underbrace{\begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_N & 1 \end{bmatrix}}_A \underbrace{\begin{bmatrix} a \\ b \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}}_{\mathbf{b}}.$$

We would like to multiply both sides by the inverse of the matrix, but the matrix is not square. To get around this, left-multiply both sides by A^T so that the matrix on the left becomes square, then solve the normal equations $A^T A \mathbf{x} = A^T \mathbf{b}$.

$$\underbrace{\begin{bmatrix} x_1 & x_2 & \cdots & x_N \\ 1 & 1 & \cdots & 1 \end{bmatrix}}_{A^T} \underbrace{\begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ \vdots & \vdots \\ x_N & 1 \end{bmatrix}}_A \underbrace{\begin{bmatrix} a \\ b \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} x_1 & x_2 & \cdots & x_N \\ 1 & 1 & \cdots & 1 \end{bmatrix}}_{A^T} \underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}}_{\mathbf{b}}$$

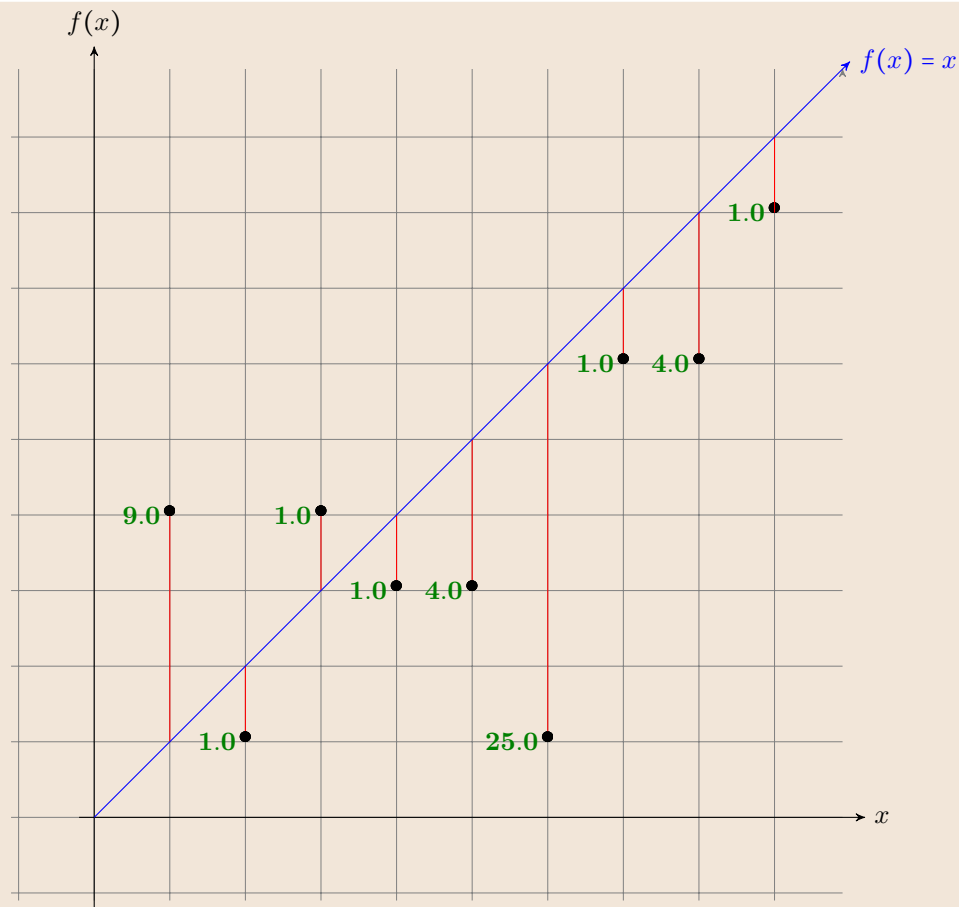
$$\underbrace{\begin{bmatrix} \sum_{i=1}^N x_i^2 & \sum_{i=1}^N x_i \\ \sum_{i=1}^N x_i & N \end{bmatrix}}_{A^T A} \underbrace{\begin{bmatrix} a \\ b \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} \sum_{i=1}^N x_i y_i \\ \sum_{i=1}^N y_i \end{bmatrix}}_{A^T \mathbf{b}}$$

Square matrix on the left is invertible,^a so we can solve for \mathbf{x} by left-multiplying both sides by its inverse:

$$\underbrace{\begin{bmatrix} a \\ b \end{bmatrix}}_{\mathbf{x}} = \underbrace{\begin{bmatrix} \sum_{i=1}^N x_i^2 & \sum_{i=1}^N x_i \\ \sum_{i=1}^N x_i & N \end{bmatrix}}_{(A^T A)^{-1}}^{-1} \underbrace{\begin{bmatrix} \sum_{i=1}^N x_i y_i \\ \sum_{i=1}^N y_i \end{bmatrix}}_{A^T \mathbf{b}}$$

The error being minimized is the sum of the square *vertical* distances of each point from the line, or equivalently, the sum of the square of how much each point deviates from the line.

$$\mathcal{E} = \sum_{i=1}^N \left\| y_i - \begin{bmatrix} a & b \end{bmatrix} \begin{bmatrix} x_i \\ 1 \end{bmatrix} \right\|^2.$$



$$\mathcal{E} = 0 + 9.0 + 1.0 + 1.0 + 1.0 + 4.0 + 25.0 + 1.0 + 4.0 + 1.0 = 47$$

FIGURE 1. Graph of points, fitted line, and error measures.

The error associated with each point varies quadratically; twice the offset results in four times the error. This is often desirable when fitting a line to points in an image since it penalizes points that are farther from the line by a greater scale than points that are closer to the line. *However, if there are outliers in the dataset, then using this method to fit a line to points in an image can result in one outlier point having a large effect on the fitted line and making it less accurate.*

^aIf the matrix is not invertible, then the system of equations has either no solution (i.e. is inconsistent) or infinitely many solutions.

- (ii) Another way to solve this problem is to find $\ell = (a, b, c)$, defined up to scale, that most closely satisfies the equations $ax_i + by_i + c = 0$, in a least-squares sense. Write these equations in the form of a *homogeneous* least-squares problem $A\ell = 0$, where $\ell = (a, b, c)^T$ and $\ell \neq 0$. This problem has a trivial solution (zero vector) which is not of much use. Describe some ways of avoiding this trivial solution and corresponding algorithms for solving the resulting optimization problem. Is this approach more or less useful than the previous one? Why?

Hint: Think about how we can express the distance of a point from a line.

The set of N points satisfies the following system of equations:

$$\begin{aligned} ax_1 + by_1 + c &= 0 \\ ax_2 + by_2 + c &= 0 \\ &\vdots \\ ax_N + by_N + c &= 0. \end{aligned}$$

We can rewrite the system as the following homogeneous *least-squares* problem:

$$\underbrace{\begin{bmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ \vdots & \vdots & \vdots \\ x_N & y_N & 1 \end{bmatrix}}_A \underbrace{\begin{bmatrix} a \\ b \\ c \end{bmatrix}}_{\ell} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{\mathbf{0}}.$$

On Avoiding the Trivial Solution

This equation has a trivial solution $\ell = \mathbf{0}$, which is not useful and can be avoided by normalizing the vector ℓ so that $\|\ell\| = 1$.

On Finding the Solutions We solve the equation $A\mathbf{x} = 0$ by converting A into its singular value decomposition

$$A = U\Sigma V^T$$

so that

$$U\Sigma V^T \ell = 0.$$

From the singular value decomposition, we compute V (the transpose of V^T) and find the column corresponding to the smallest singular value. This column contains the coefficients of the conic fitting the points.

On Comparative Utility of Approaches:

In the examples above, it is clear that using homogeneous least squares to fit a line to points in an image is much

simpler to solve than using the heterogeneous approach, especially since in the homogeneous approach, the right-hand side of the equation is zero.

Problem 2.

The equation for a conic in the plane using inhomogeneous coordinates (x, y) is

$$ax^2 + bxy + cy^2 + dx + ey + f = 0. \quad (2.1)$$

- (a) Suppose you have a given a set of inhomogeneous points $\mathbf{x}_i = (x_i, y_i)$, $i \in \{1, \dots, N\}$. Derive an expression for the least squares estimate of a conic $\mathbf{c} = (a, b, c, d, e, f)$ passing through those points.

Note: your expression may take the form of a null vector or eigenvector of a matrix. If so, you must provide expressions for the matrix elements.

To determine the matching conic, we need to solve the equation $A\mathbf{x} = \mathbf{0}$:

$$\underbrace{\begin{bmatrix} x_1^2 & x_1x_2 & x_2^2 & x_1 & x_2 & 1 \\ x_2^2 & x_2y_2 & y_2^2 & x_2 & y_2 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_N^2 & x_Ny_N & y_N^2 & x_N & y_N & 1 \end{bmatrix}}_{\mathbf{A}} \underbrace{\begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix}}_{\mathbf{c}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{\mathbf{0}}$$

We solve the equation $\mathbf{A}\mathbf{c} = \mathbf{0}$ by converting \mathbf{A} into its singular value decomposition

$$A = U\Sigma V^T$$

so that

$$U\Sigma V^T \mathbf{x} = \mathbf{0}.$$

From the singular value decomposition, we compute V (the transpose of V^T) and find the column corresponding to the smallest singular value. This column contains the coefficients of the conic fitting the points.

- (b) In general, what is the minimum value of N that allows a unique solution for \mathbf{c} ?

The minimum value of N is 5.

Since there are five unknowns in \mathbf{c} — a, b, c, d, e — we need at least five equations to solve for \mathbf{c} . Therefore, the minimum value of N is 5.

Note that f can be moved to the right-hand side of the equation.

- (c) Homogenize equation 2.1 by making the substitutions $x \leftarrow x_1/x_3$ and $y \leftarrow x_2/x_3$, and show that in terms of homogeneous coordinates ($\mathbf{x} = (x_1, x_2, x_3)$) the conic can be expressed in matrix form

$$\mathbf{x}^T \mathbf{C} \mathbf{x} = 0,$$

where \mathbf{C} is a symmetric matrix.

By substituting $x \leftarrow x_1/x_3$ and $y \leftarrow x_2/x_3$, and simplifying the resulting equation, we get:

$$ax^2 + bxy + cy^2 + dx + ey + f = 0$$

$$a \left(\frac{x_1}{x_3} \right)^2 + b \frac{x_1 x_2}{x_3 x_3} + c \left(\frac{x_2}{x_3} \right)^2 + d \frac{x_1}{x_3} + e \frac{x_2}{x_3} + f = 0$$

$$\frac{x_1^2}{x_3^2} a + \frac{x_1 x_2}{x_3 x_3} b + \frac{x_2^2}{x_3^2} c + \frac{x_1}{x_3} d + \frac{x_2}{x_3} e + f = 0$$

$$\frac{x_1^2}{x_3^2} (a) + \frac{x_1 x_2}{x_3 x_3} (b/2 + b/2) + \frac{x_2^2}{x_3^2} (c) + \frac{x_1}{x_3} (d/2 + d/2) + \frac{x_2}{x_3} (e/2 + e/2) + f = 0$$

$$\begin{bmatrix} (a) \frac{x_1}{x_3} & (b/2) \frac{x_1}{x_3} & (d/2) \frac{x_1}{x_3} \\ (b/2) \frac{x_2}{x_3} & (c) \frac{x_2}{x_3} & (e/2) \frac{x_2}{x_3} \\ d/2 & e/2 & f \end{bmatrix} \begin{bmatrix} \frac{x_1}{x_3} \\ \frac{x_2}{x_3} \\ 1 \end{bmatrix} = 0$$

$$\begin{bmatrix} \frac{x_1}{x_3} & \frac{x_2}{x_3} & 1 \end{bmatrix} \begin{bmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{bmatrix} \begin{bmatrix} \frac{x_1}{x_3} \\ \frac{x_2}{x_3} \\ 1 \end{bmatrix} = 0$$

$$\underbrace{\begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}}_{\mathbf{x}^T} \underbrace{\begin{bmatrix} a & b/2 & d/2 \\ b/2 & c & e/2 \\ d/2 & e/2 & f \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}}_{\mathbf{x}} = 0$$

- (d) Suppose we apply a projective transformation to our points $\mathbf{x}'_i = \mathbf{H}\mathbf{x}_i$. The transformed points x'_i will lie on a transformed conic represented by a new symmetric matrix \mathbf{C}' . Write an equation that specifies the relationship between \mathbf{C}' and \mathbf{C} in terms of the homography \mathbf{H} .

$$\mathbf{x}'^T \mathbf{C}' \mathbf{x}' = 0$$

$$(\mathbf{H}\mathbf{x})^T \mathbf{C} (\mathbf{H}\mathbf{x}) = 0$$

$$\mathbf{x}^T \underbrace{\mathbf{H}^T \mathbf{C} \mathbf{H}}_{\mathbf{C}'} \mathbf{x} = 0 \quad (\text{since } (\mathbf{AB})^T = \mathbf{B}^T \mathbf{A}^T)$$

The transformed conic satisfies the equation $\mathbf{x}^T \mathbf{C}' \mathbf{x} = 0$ where

$$\mathbf{C}' = \mathbf{H}^T \mathbf{C} \mathbf{H}$$

Problem 3.

The affine transform in heterogeneous coordinates is given by

$$\begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix}. \quad (3.1)$$

Affine transformations are combinations of:

- (i) Arbitrary linear transformations with 4 degrees of freedom (a, b, d, e) .
- (ii) Translations with 2 degrees of freedom (c, f) .

Does affine transformation apply translation first followed by arbitrary linear transformation, or the other way around? Prove your answer mathematically.

Hint: check if

$$\begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & c \\ 0 & 1 & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a & b & 0 \\ d & e & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} a & b & 0 \\ d & e & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & c \\ 0 & 1 & f \\ 0 & 0 & 1 \end{bmatrix}$$

By computing the matrix products, we see that:

$$\begin{bmatrix} 1 & 0 & c \\ 0 & 1 & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a & b & 0 \\ d & e & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \quad (3.2)$$

$$\begin{bmatrix} a & b & 0 \\ d & e & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & c \\ 0 & 1 & f \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} a & b & ac + bf \\ d & e & dc + ef \\ 0 & 0 & 1 \end{bmatrix} \quad (3.3)$$

Our desired affine transformation matrix (3.1) matches the first matrix product (3.2). Since matrices multiply from right to left (i.e. $\mathbf{ABc} = \mathbf{A}(\mathbf{Bc})$), the linear transformations (rotation, shear, scaling, etc.) are applied first before the translation. Intuitively, this makes sense because translating first would result in the image points being at the wrong coordinates during transformation.