UNIVERSITÀ DEGLI STUDI DI PADOVA

The Canny edge detector

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Agenda

- How to find edges?
  - A famous edge detector: the Canny algorithm

Canny edge detector

- Canny edge detector is a filter addressing the following targets:
  - Low error rate
  - Edge points well localized
  - Single edge point response

Canny edge detector

- Paper published in 1986
  - Available on moodle

IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE, VOL. PAMI-8, NO. 6, NOVEMBER 1986 679

A Computational Approach to Edge Detection

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Abstract—This paper describes a computational approach to edge detection. The success of the approach depends on the definition of a *comprehensive* set of goals for the computation of edge points. These goals must be precise enough to delimit the desired behavior of the detector while making minimal assumptions about the form of the solution. We define detection and localization criteria for a class of edges, and present mathematical forms for these criteria as functionals on the operator impulse response. A third criterion is then added to ensure that the detector has only one response to a single edge. We use the criteria in numerical optimization to derive detectors for several common image features, including step edges. On specializing the analysis to step edges, we find that there is a natural uncertainty principle between detection and localization performance, which are the two main goals. With this principle we derive a single operator shape which is optimal at any scale. The optimal detector has a simple approximate implementation in which edges are marked at maxima in gradient magnitude of a Gaussian-smoothed image. We extend this simple detector using operators of several widths to cope with different signal-to-noise ratios in the image. We present a general method, called feature synthesis, for the fine-to-coarse integration of information from operators at different scales. Finally we show that step edge detector performance improves considerably as the operator point spread function is extended along the edge. This detection scheme uses several elongated operators at each point, and the directional operator outputs are integrated with the gradient maximum detector.

Index Terms—Edge detection, feature extraction, image processing, machine vision, multiscale image analysis.

I. Introduction

EDGE detectors of some kind, particularly step edge detectors, have been an essential part of many computer vision systems. The edge detection process serves to simplify the analysis of images by drastically reducing the amount of data to be processed, while at the same time preserving useful structural information about object boundaries. There is certainly a great deal of diversity in the applications of edge detection, but it is felt that many applications share a common set of requirements. These requirements yield an abstract edge detection problem, the solution of which can be applied in any of the original problem domains.

We should mention some specific applications here. The Binford–Horn line finder [14] used the output of an edge detector as input to a program which could isolate simple geometric solids. More recently the model-based vision system ACRONYM [3] used an edge detector as the front end to a sophisticated recognition program. Shape from motion [29], [13] can be used to infer the structure of three-dimensional objects from the motion of edge contours or edge points in the image plane. Several modern theories of stereopsis assume that images are preprocessed by an edge detector before matching is done [19], [20]. Beattie [1] describes an edge-based labeling scheme for low-level image understanding. Finally, some novel methods have been suggested for the extraction of three-dimensional information from image contours, namely shape from contour [27] and shape from texture [31].

In all of these examples there are common criteria relevant to edge detector performance. The first and most obvious is low error rate. It is important that edges that occur in the image should not be missed and that there be no spurious responses. In all the above cases, system performance will be hampered by edge detector errors. The second criterion is that the edge points be well localized. That is, the distance between the points marked by the detector and the "center" of the true edge should be minimized. This is particularly true of stereo and shape from motion, where small disparities are measured between left and right images or between images produced at slightly different times.

In this paper we will develop a mathematical form for these two criteria which can be used to design detectors for arbitrary edges. We will also discover that the first two criteria are not "tight" enough, and that it is necessary to add a third criterion to circumvent the possibility of multiple responses to a single edge. Using numerical optimization, we derive optimal operators for ridge and roof edges. We will then specialize the criteria for step edges and give a parametric closed form for the solution. In the process we will discover that there is an uncertainty principle relating detection and localization of noisy step edges, and that there is a direct tradeoff between the two. One consequence of this relationship is that there is a single unique "shape" of impulse response for an optimal step edge detector, and that the tradeoff between detection and localization can be varied by changing the spatial width of the detector. Several examples of the detector performance on real images will be given.

II. One-Dimensional Formulation

To facilitate the analysis we first consider one-dimensional edge profiles. That is, we will assume that two-

Manuscript received December 10, 1984; revised November 27, 1985. Recommended for acceptance by S. L. Tanimoto. This work was supported in part by the System Development Foundation, in part by the Office of Naval Research under Contract N00014-81-K-0494, and in part by the Advanced Research Projects Agency under Office of Naval Research Contracts N00014-80-C-0505 and N00014-82-K-0334.

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IEEE Log Number 8610412.

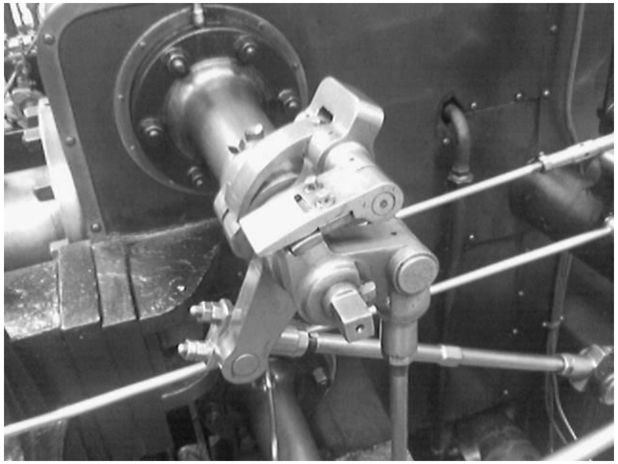
0162-8828/86/1100-0679$01.00 © 1986 IEEE

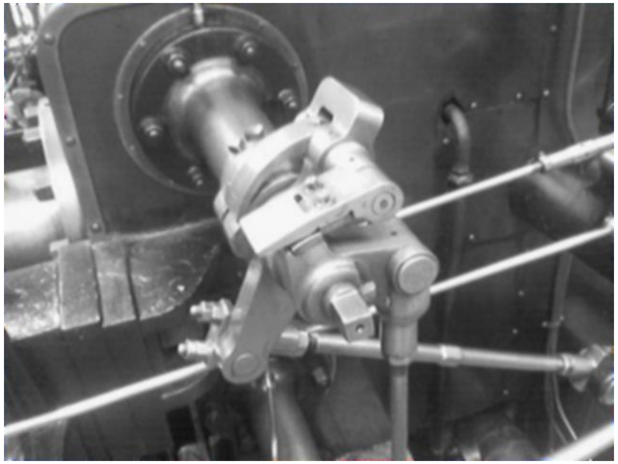
Canny edge detector

- Canny algorithm
  1. Smoothing with a Gaussian filter
  2. Gradient computation (magnitude and phase)
  3. Quantize the gradient angles
  4. Non-maxima suppression
  5. Hysteresis thresholding

Step 1: smoothing

- Smoothing is often employed before evaluating edges
  - Noise reduction



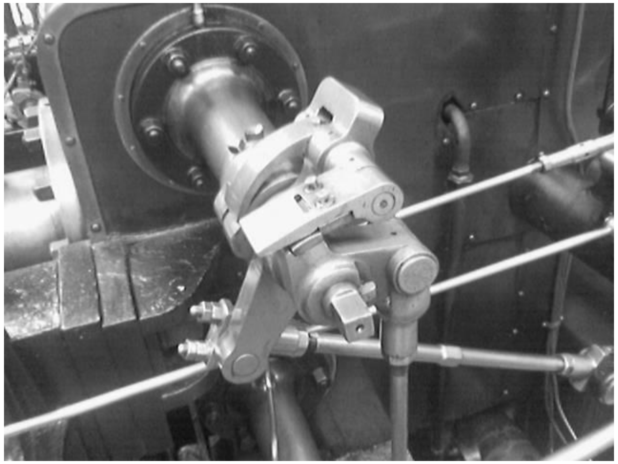


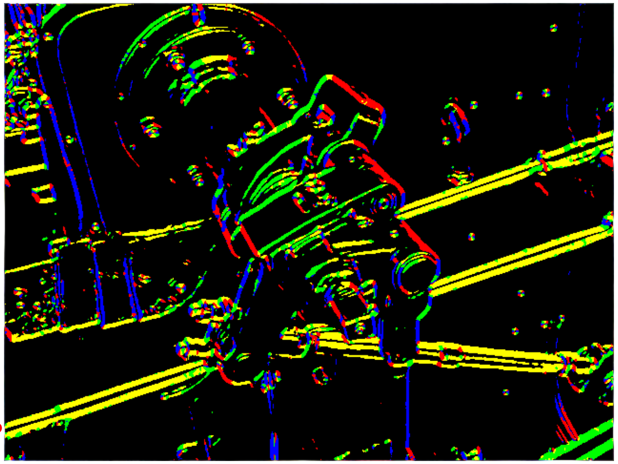
Step 2: gradient computation

- Edges are calculated using vertical, horizontal and diagonal masks
  - Edge direction is also calculated
- Recall:

$$\|\nabla f(x,y)\| = \sqrt{g_x^2 + g_y^2}$$

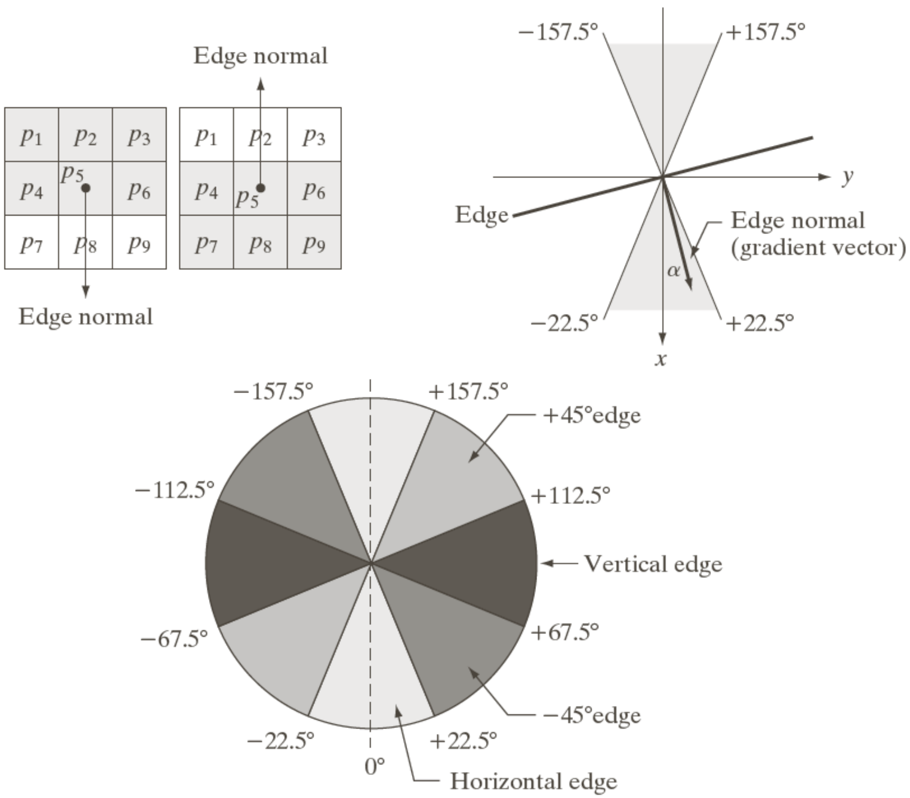
$$\theta = \tan^{-1}\left(\frac{g_y}{g_x}\right)$$





Step 3: Edge quantization

- Group orientations (θ) into ranges
  - "bins" of 45°



a b
c

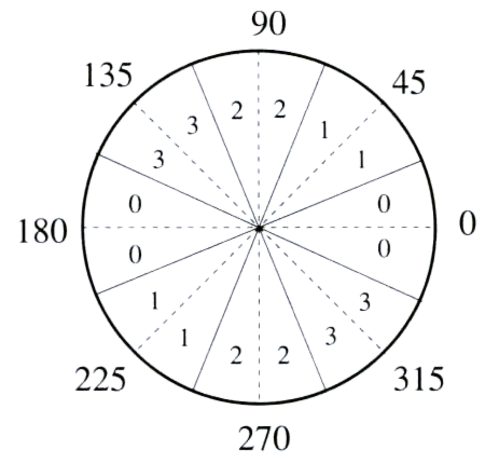
FIGURE 10.24
(a) Two possible orientations of a horizontal edge (in gray) in a 3 × 3 neighborhood. (b) Range of values (in gray) of α, the direction angle of the *edge normal*, for a horizontal edge. (c) The angle ranges of the edge normals for the four types of edge directions in a 3 × 3 neighborhood. Each edge direction has two ranges, shown in corresponding shades of gray.

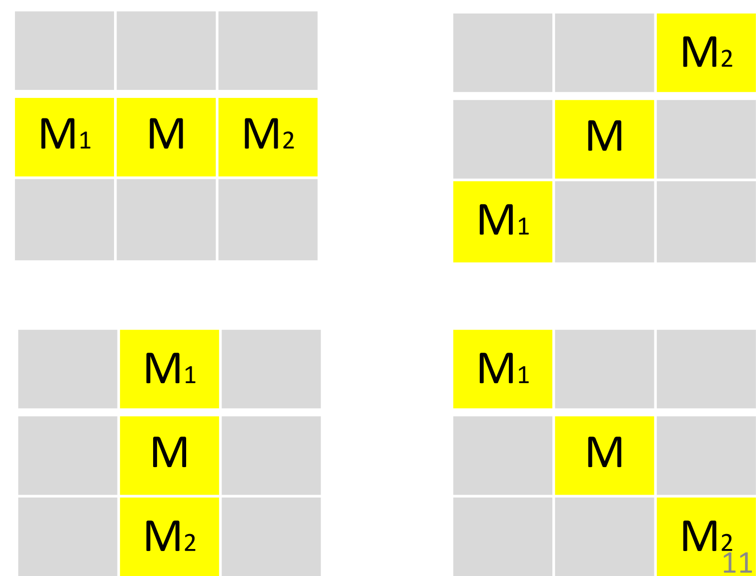
Step 4: non-maxima suppression

- Non-maxima suppression reduces the edge thickness
- Thin edges are desirable
  - Reduce a gradient to a single edge line
  - Accurate location of the edge point
- Non-maxima suppression is a process that
  - Crosses an edge
  - Selects the strongest point

Step 4: non-maxima suppression

- Consider a neighborhood (e.g., 3×3)
- Take the quantized direction d_k (closest to θ_k)
- If (module @ central pixel < at least one of the neighbors along d_k)
  - Gradient set to 0 (suppressed)





Step 5: hysteresis thresholding

- Hysteresis thresholding is used to:
  - Keep strong edges
  - Keep weak edges connected with strong edges
  - Reject isolated weak edges
- Edge strength is measured by means of gradient magnitude
- Low-level tools used
  - Thresholding
  - The use of masks

Step 5: hysteresis thresholding

- Hysteresis thresholding is based on two thresholds: T_L and T_H
- Two images are obtained: I_L and I_H

Step 5: hysteresis thresholding

I_H

0	0	0	0	0	0	0	3
0	0	0	0	1	1	3	0
0	0	2	1	1	0	0	0
0	0	3	0	0	0	0	0
0	3	2	0	0	0	0	0
0	1	0	0	0	1	0	1
0	3	0	0	1	0	1	0

gaps filled from T_l

I_L

0	0	0	0	0	0	0	3
0	0	0	0	1	1	3	0
0	0	2	1	1	0	0	0
0	0	3	0	0	0	0	0
0	3	2	0	0	0	0	0
0	1	0	0	0	1	0	1
0	3	0	0	1	0	1	0

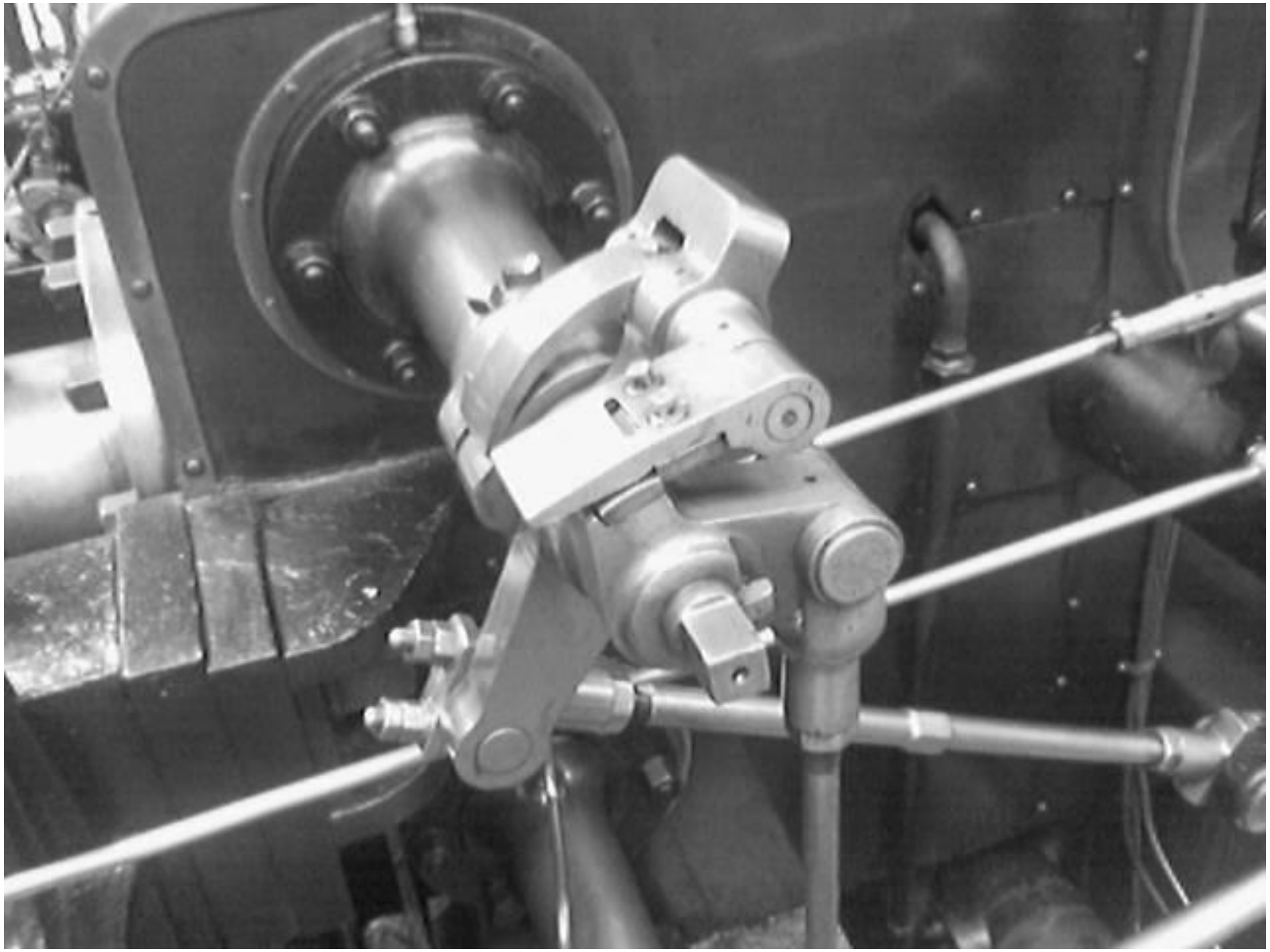
1. Consider all pixels in I_H as edge
2. For each pixel in I_H
   mark as valid all neighbors in I_L
3. Ignore all non-valid pixels in I_L

Canny edge detector

- Recall: Canny algorithm
  1. Smoothing with a Gaussian filter
  2. Gradient computation (magnitude and phase)
  3. Quantize the gradient angles
  4. Non-maxima suppression
  5. Hysteresis thresholding
- Next slides: intermeditate algorithm results

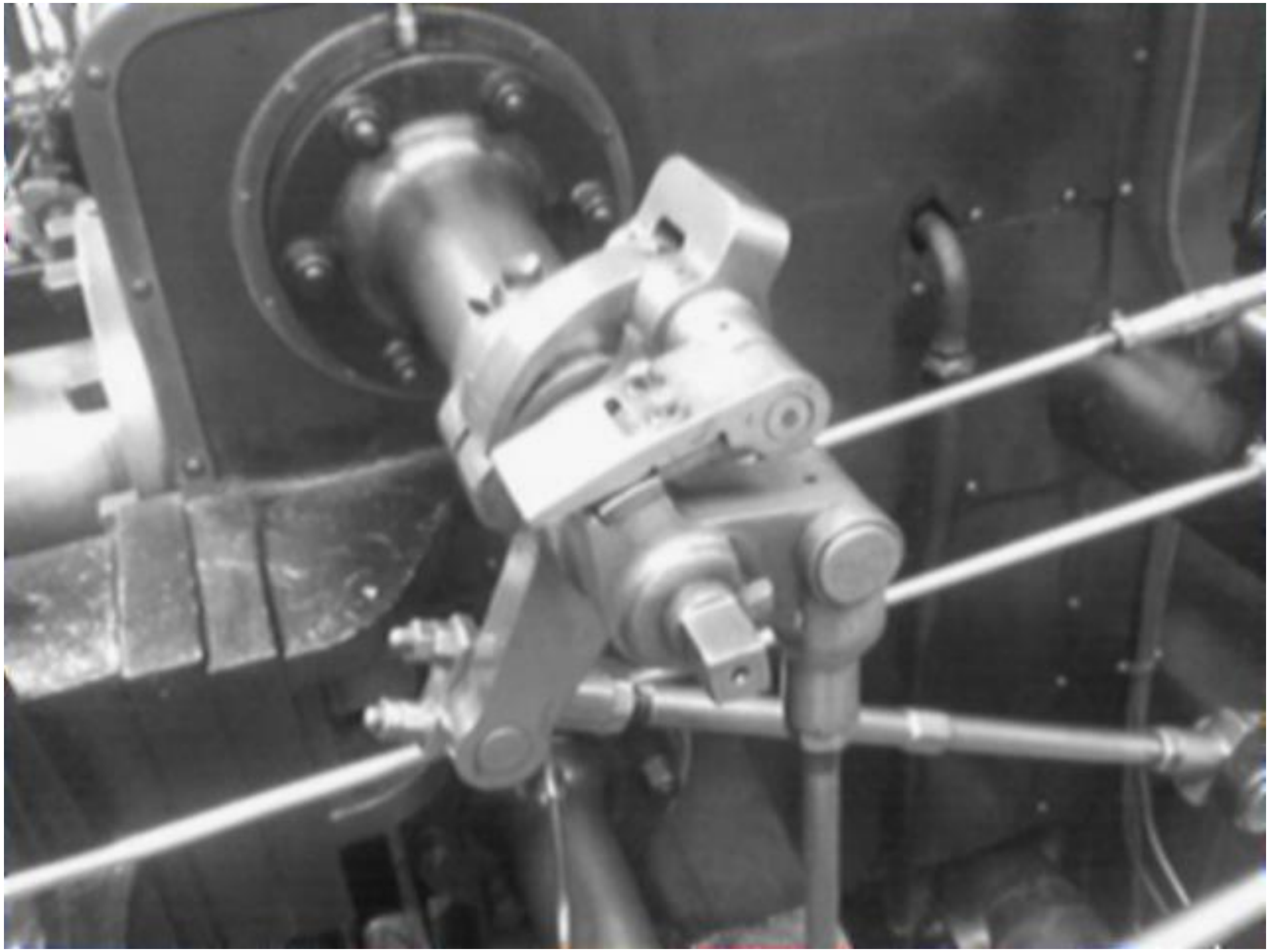
Canny - example

- Original image



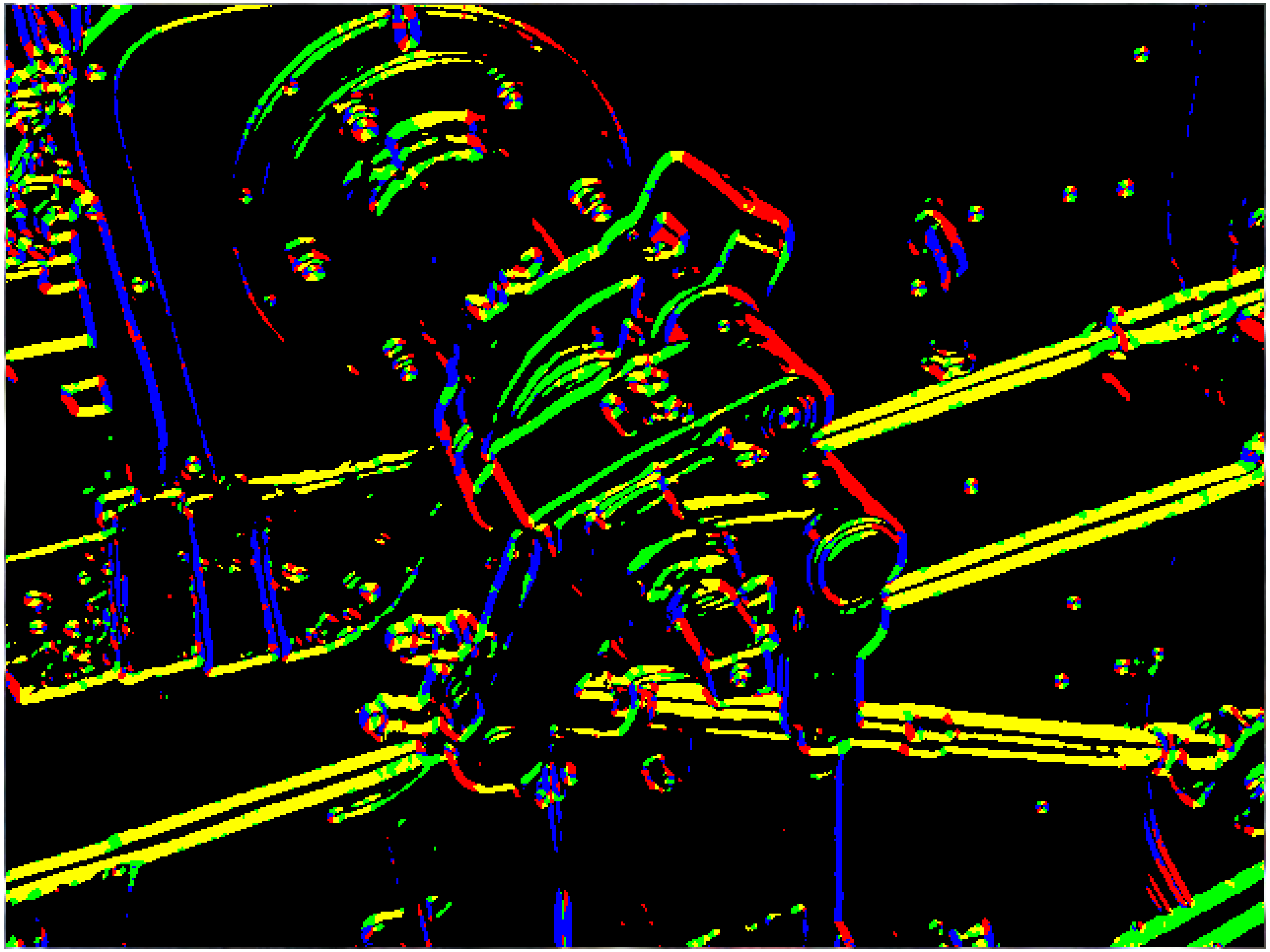
Canny - example

- Gaussian smoothing



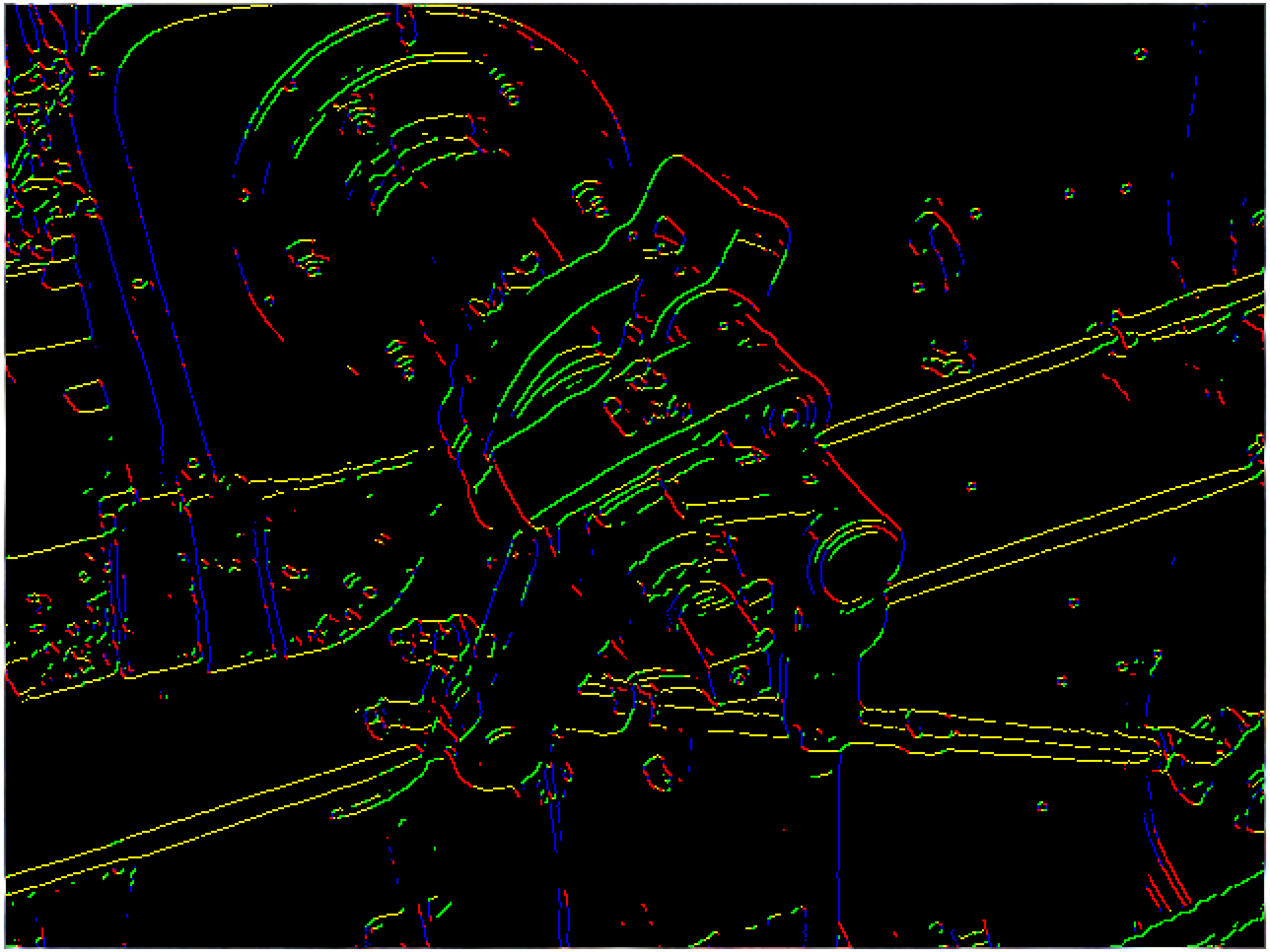
Canny - example

- Gradient



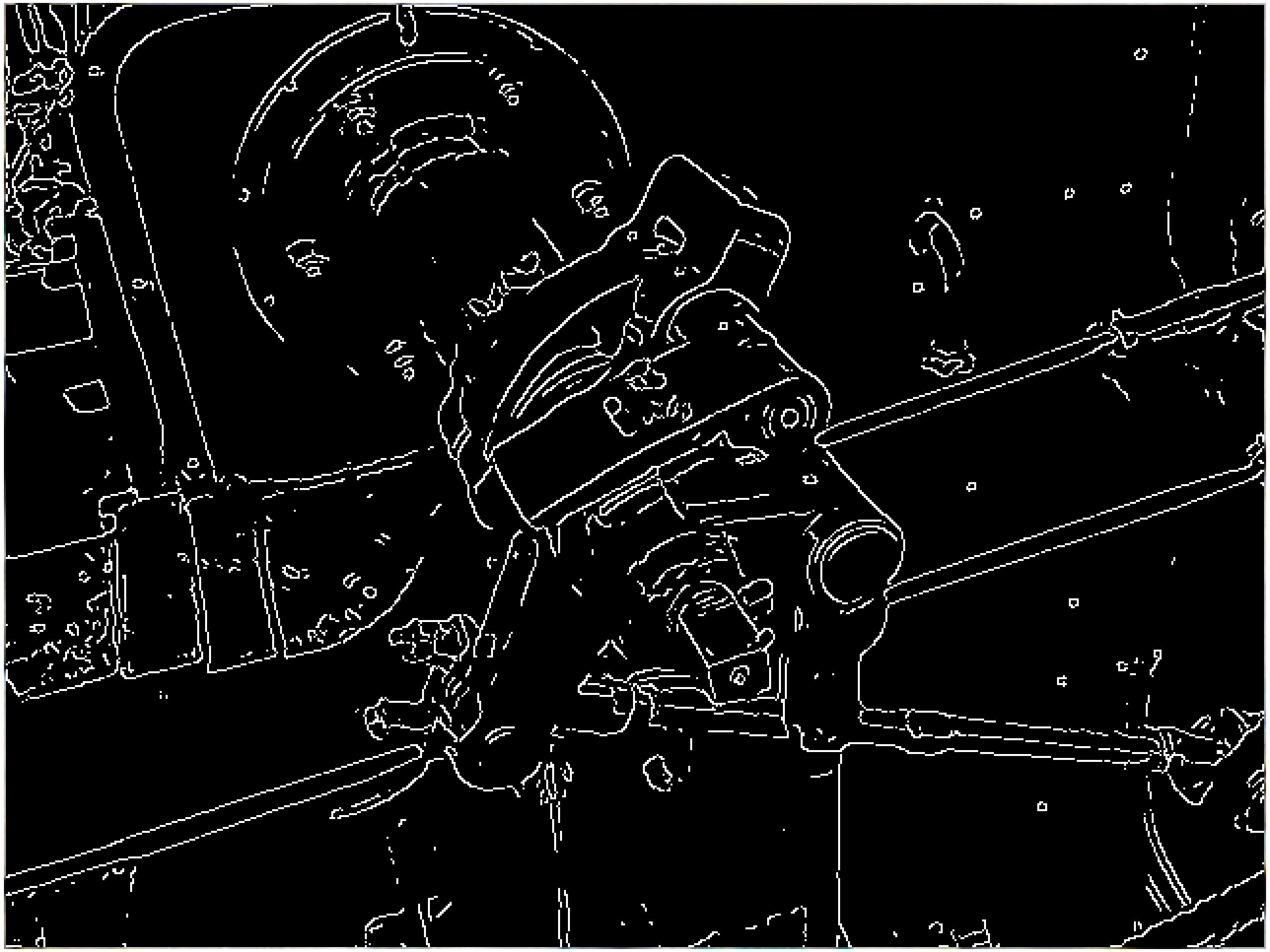
Canny - example

- Non-maxima suppression



Canny - example

- Output



Effect of Gaussian kernel size (σ)

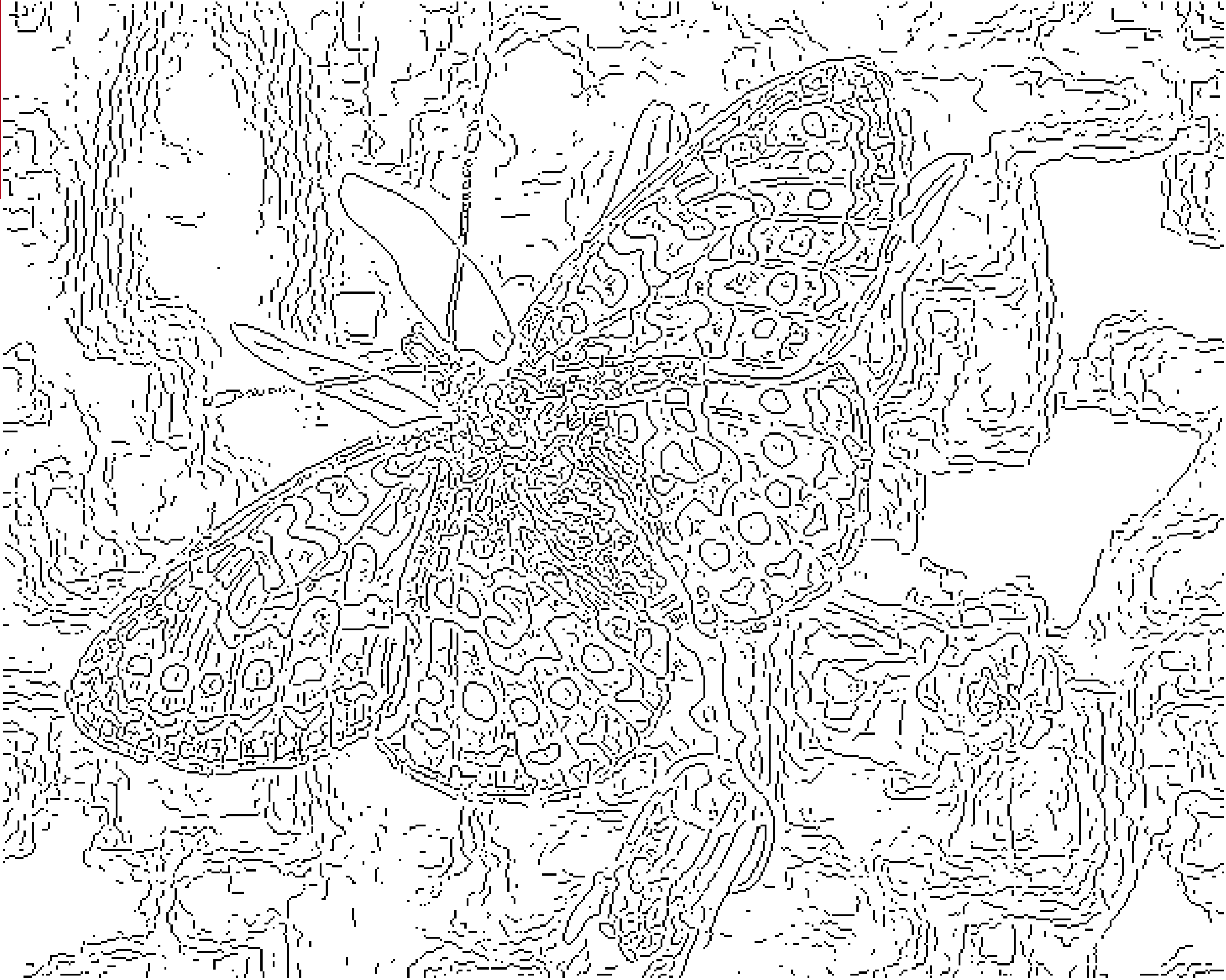
- Large σ: large-scale edges
- Small σ: finer details

Original

Canny, σ=1

Canny, σ=2

Original



Fine scale (small σ) + high thresholds

Coarse scale (large σ) + high thresholds

Coarse scale (large σ) + low thresholds

Edge detector comparison

- An edge detector algorithm is more than a derivative filter
- See the difference comparing
  - A gradient image
  - Canny edge detector
  - Marr-Hildreth edge detector
    - Another edge detector algorithm

Gradient vs Canny vs M&H

Gradient + threshold

Marr & Hildreth

Canny

a b
c d

FIGURE 10.25
(a) Original image of size 834 × 1114 pixels, with intensity values scaled to the range [0, 1].
(b) Thresholded gradient of smoothed image.
(c) Image obtained using the Marr-Hildreth algorithm.
(d) Image obtained using the Canny algorithm. Note the significant improvement of the Canny image compared to the other two.

Gradient vs Canny vs M&H

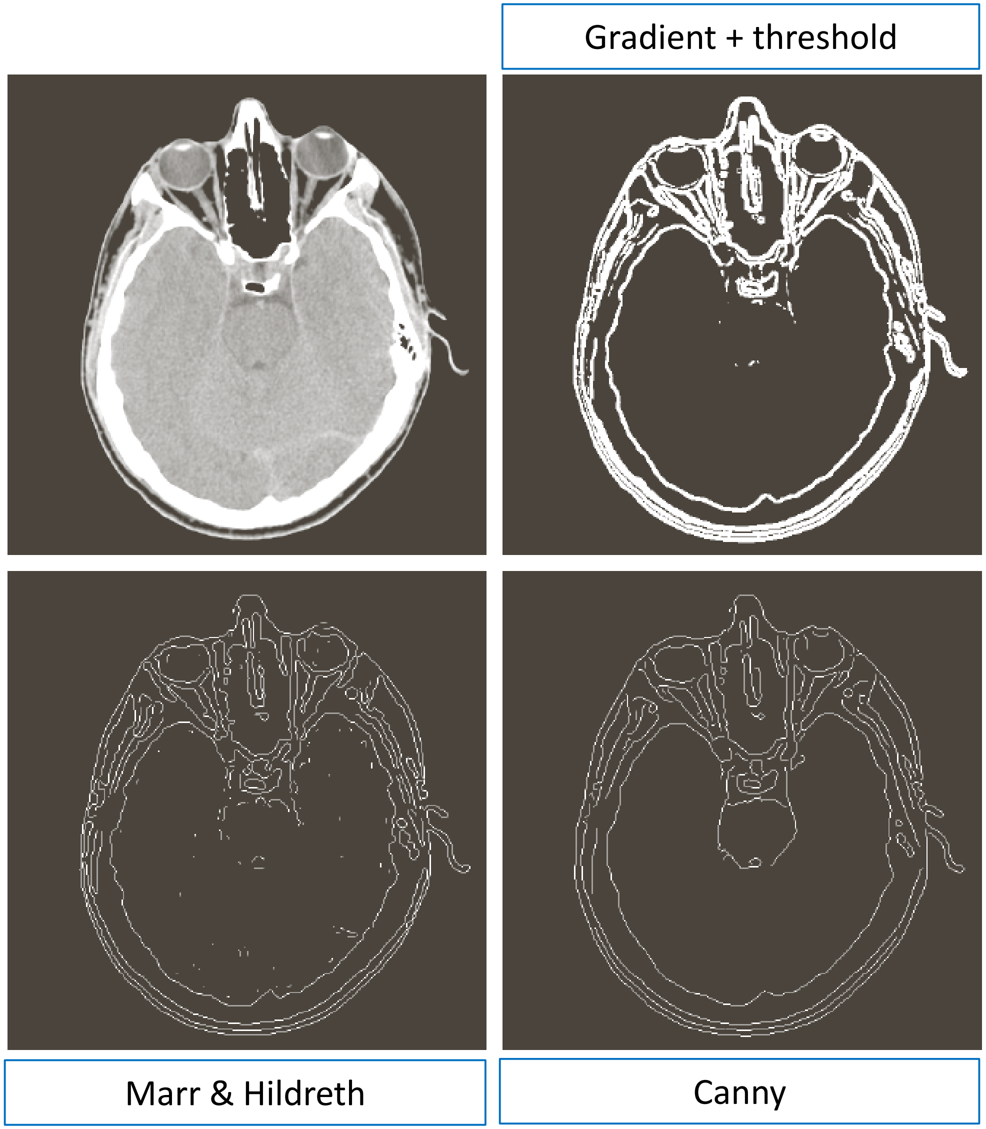
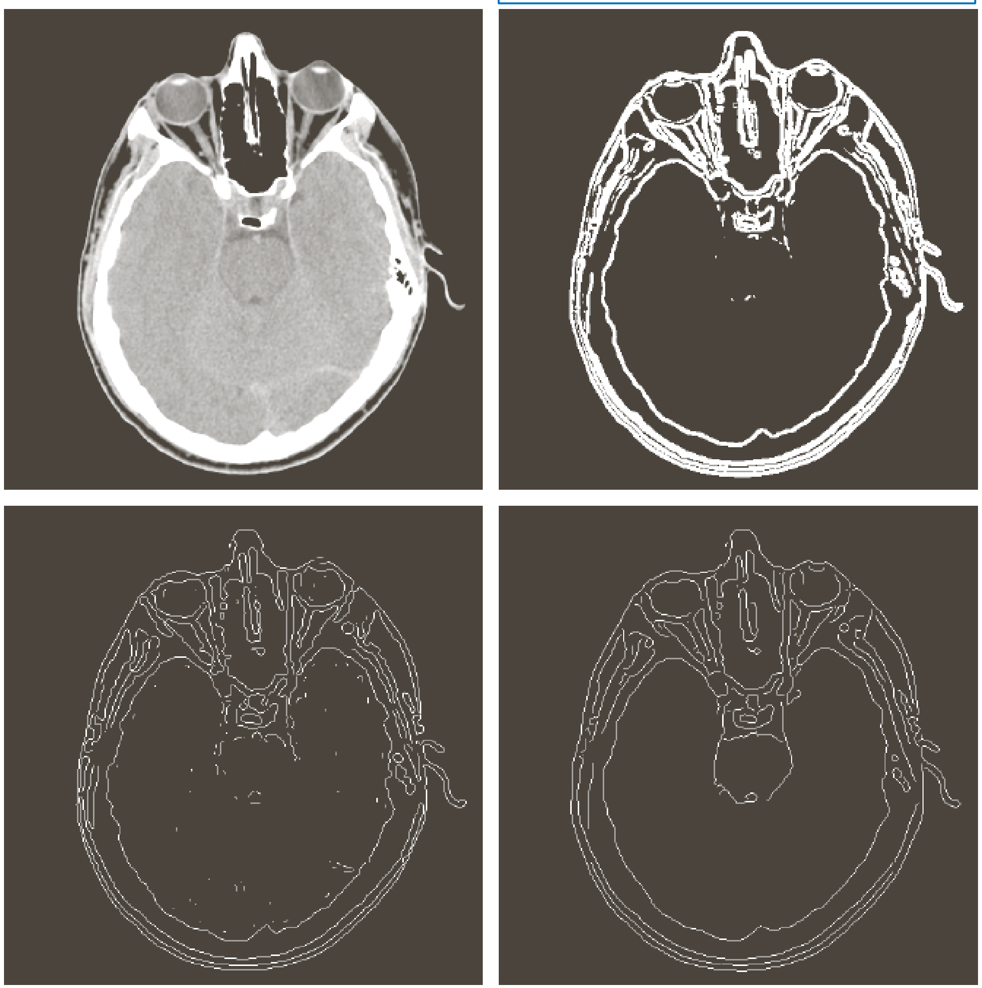


FIGURE 10.26 (a) Original head CT image of size 512×512 pixels, with intensity values scaled to the range [0, 1]. (b) Thresholded gradient of smoothed image. (c) Image obtained using the Marr-Hildreth algorithm. (d) Image obtained using the Canny algorithm. (Original image courtesy of Dr. David R. Pickens, Vanderbilt University.)

Gradient vs Canny vs M&H

Gradient + threshold



Marr & Hildreth

Canny

- Describe the differences you can recognize

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