INDS'11&ISTET'11@Uni-Klagenfurt.AT July 25-27, 2011

Image Edge Detection with Discretely Spaced FitzHugh-Nagumo Type Excitable Elements

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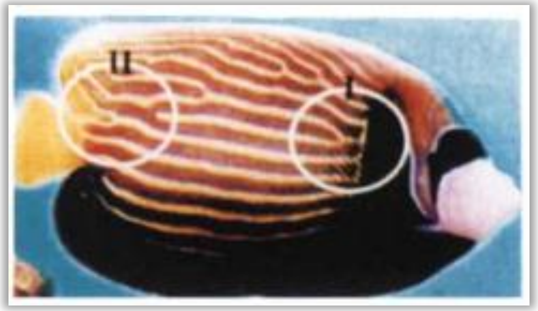
Outline

- Introduction & Background
  - Reaction-diffusion, coupled oscillators & pattern formation
  - Edge detection algorithms
- Motivation
- Edge Detection Algorithms
  - Our previous algorithm utilising coupled excitable elements
  - Proposed algorithm based on the previous algorithm
- Experimental Results
- Conclusion

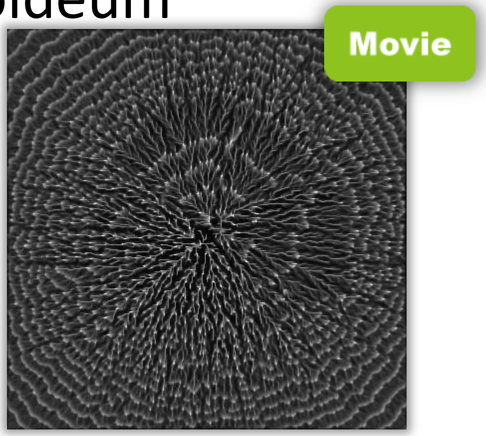
Introduction & Background:
Reaction-Diffusion, Coupled Oscillators & Pattern Formation

- Reaction-Diffusion System
  - activator and inhibitor
- Weak Inhibition
  - Chemical reaction
    - Belousov-Zhabotinsky (BZ) reaction
  - Biological system
    - signal propagation in Dictyostelium discoideum
- Strong Inhibition
  - Turing pattern

Keener & Tyson, *Physica D*, 1986



Kondo & Asai, *Nature*, 1995



Höfer et al., *Physica D*, 1995

Introduction & Background:
Previous Research Topics on Pattern Formation

	Weak Inhibition	Strong Inhibition
Experimental Study	**Belousov-Zhabotinsky (BZ) Reaction** - Zaikin & Zhabotinsky, *Nature*, 1970 **Light-Sensitive BZ Reaction** - Busse & Hess, *Nature*, 1973 - Jinguji et al., *Physica D*, 1995	**Mach Bands in *Limulus* Eyes** - Hartline et al., *J. Gen. Physiol.*, 1956 **Chemical Reaction** - Castets et al., *Phys. Rev. Lett.*, 1990 **Pattern Formation on Fish Skin** - Kondo & Asai, *Nature*, 1995
Modelling Study	**FitzHugh-Nagumo (FHN) Model** - FitzHugh, *Biophysical J.*, 1961 - Nagumo et al., *Proc. IRE*, 1962 **Reaction-Diffusion + Oregonator (BZ)** - Keener & Tyson: *Physica D*, 1986	**Pattern Formation in *Hydra*** - Turing, *Proc. Roy. Soc. Lond.*, 1952 - Gierer & Meinhardt, *Kybernetik*, 1972 **Model for Mach Bands** - Barlow & Quarles, *J. Gen. Physiol.*, 1975
Image Processing (IP) & Computer Vision	**Light-Sensitive BZ reaction** - Kuhnert et al.: *Nature*, 1986, 1989 **Autowave Principles** - Krinsky et al., *Physica D*, 1991	**Edge Detection & Segmentation** - Nomura et al., *J. Phys. Soc. Jpn.*, 2003 - Kurata et al., *Phys. Rev. E*, 2009 **Stereo Disparity Detection** - Nomura et al., *Mach. Vis. Appl.*, 2009
Cellular Neural Network (CNN)	**Autowaves for IP with Chua's Circuit** - Perez-Munuzuri et al., *IEEE CS*, 1993	**Turing Pattern with Chua's Circuit** - Goras & Chua, *IEEE CS*, 1995 **Segmentation with FHN + LEGION*** - Wang & Terman, *IEEE NN*, 1995

*LEGION: Locally Excitatory Globally Inhibitory Oscillator Network

Introduction & Background:

Edge Detection Algorithms & Related Topics

Algorithms / Topics	Articles
Gaussian filter (LoG or DoG filter)	Marr and Hildreth: *Proc. Roy. Soc. Lond.*, 1980
Diffusion equation	Koenderink: *Biological Cybernetics*, 1984 Sunayama et al.: *Jpn. J. Appl. Phys.*, 2000
Anisotropic diffusion	Perona and Malik: *IEEE PAMI*, 1990 Nordstrom: *Image & Vis. Comp.*, 1990 Black et al.: *IEEE IP*, 1998
Edge detection & blur estimation	Elder and Zucker: *IEEE PAMI*, 1998
Evaluation methods & others	Heath et al.: *IEEE PAMI*, 1997 Martin et al.: *IEEE PAMI*, 2004, 2011 F-measure, Precision-Recall, contour detection
Review	Ziou and Tabbone, *Patt. Recog. Image Anal.*, 1998 Basu, *IEEE SMC-C*, 2002

Motivation

- Image processing with
  - reaction-diffusion systems
  - coupled excitable elements
- Inspired by
  - Long-range inhibition in visual systems
    - DoG filter
    - Mach bands effect
  - Stationary patterns in biological systems

The FitzHugh-Nagumo Type Excitable Element

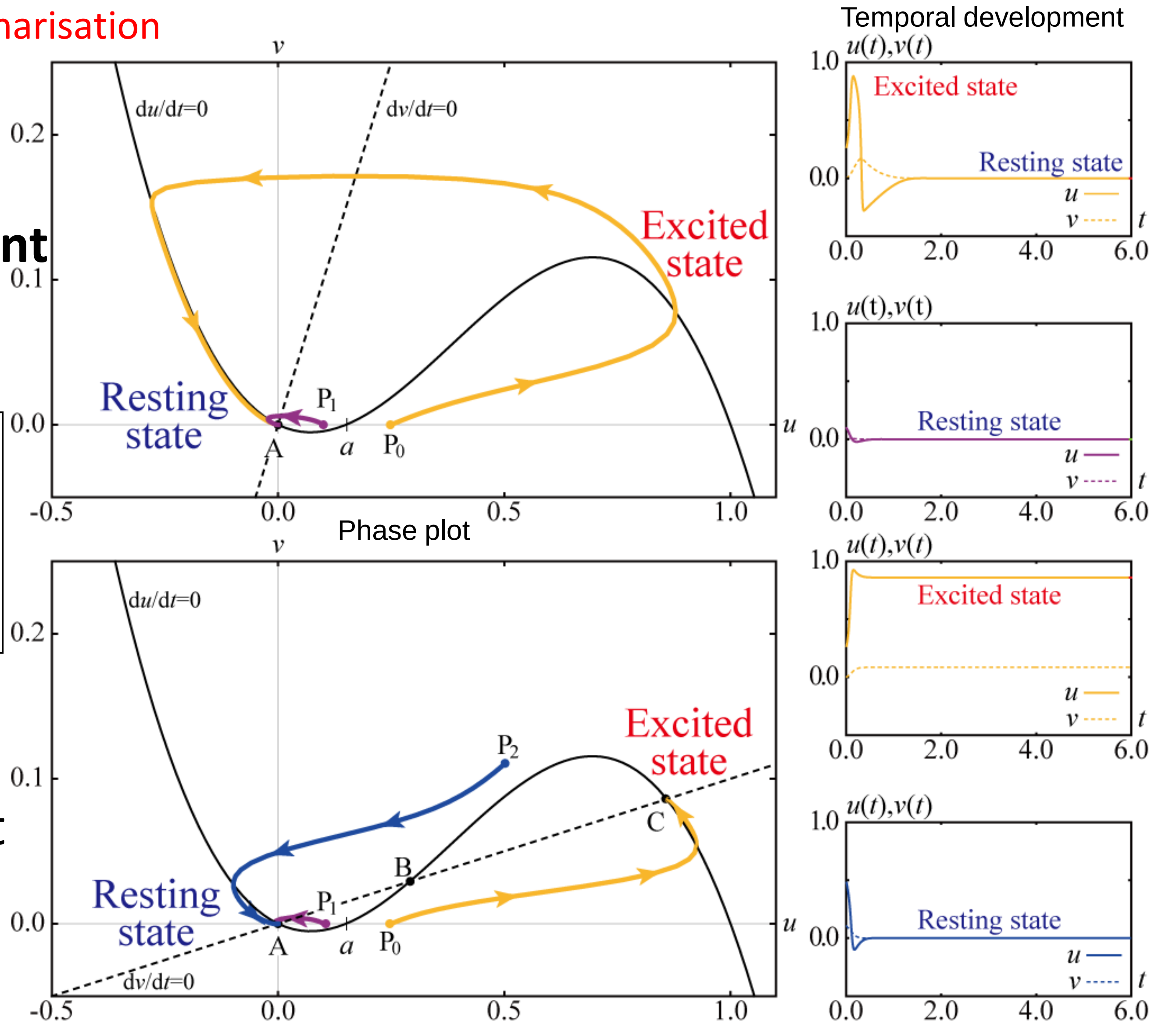
Threshold level *a* for binarisation

(a) **Uni-stable element**

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{1}{\varepsilon}\left[u(u-a)(1-u)-v\right]$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} = u - bv$$

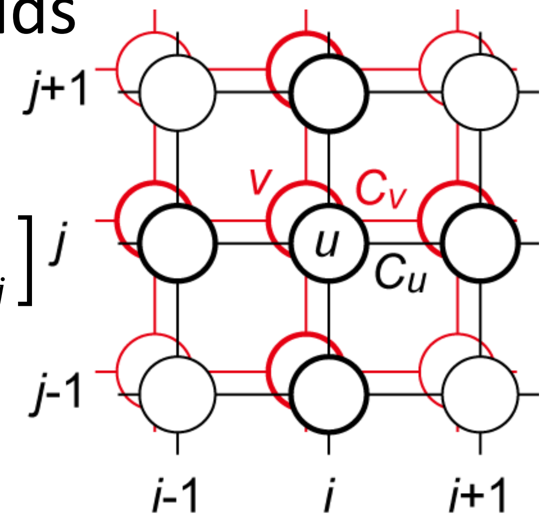
(b) Bi-stable element



Previous algorithm:

Spatially Coupled Uni-stable Excitable Elements

- Uni-stable elements placed at image grids
  - Nomura et al., *J. Phys. Soc. Jpn.*, 2003
  - Kurata et al., *Phys. Rev. E*, 2009



$$\frac{du_{i,j}}{dt} = C_u \left[\overline{u_{i,j}} - 4u_{i,j} \right] + \frac{1}{\varepsilon} \left[u_{i,j}(u_{i,j} - a)(1 - u_{i,j}) - v_{i,j} \right]$$

$$\frac{dv_{i,j}}{dt} = C_v \underbrace{\left[\overline{v_{i,j}} - 4v_{i,j} \right]}_{\text{Spatial coupling}} + u_{i,j} - bv_{i,j}$$

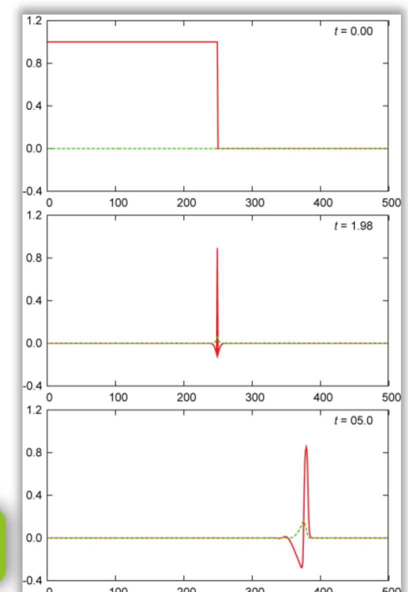
$\overline{u_{i,j}}, \overline{u_{i,j}}$: averages in the nearest four points.

- **Strong inhibition: $C_u<<C_v$**

  ⇒ Stationary pulses at edge positions

- Weak inhibition: $C_u<<C_v$

  ⇒ Propagating pulses



Initial states
u and *v*

u and *v*
($C_u<<C_v$)

u and *v*
($C_u > C_v$)

Movie

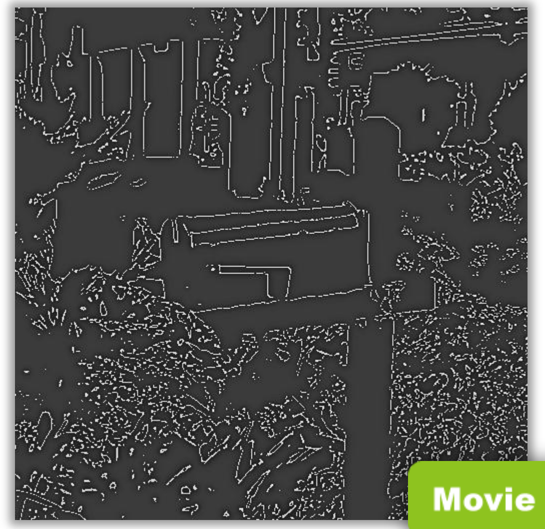
Previous algorithm:

Examples for a Real Image

- Initial states:
  - $u_{i,j}(0)$=“image intensity distribution” and $v_{i,j}(0)=0.0$
- Pulses are self-organised at edges.
  - $C_u << C_v$: pulses are stationary at the edges.
  - $C_u > C_v$: pulses propagates and develop as spiral waves.

Real image (512×512 pixels)
Initial state of $u_{i,j}(t=0)$.

$u_{i,j}(t=10)$ with $C_v=0.0$



$u_{i,j}(t=10)$ with $C_v=20.0$

Courtesy of Heath et al.: “Edge detector comparison”, http://marathon.csee.usf.edu/edge/edge_detection.html

Other parameter settings:
$C_u=4.0$, $a=0.05$, $b=1.0$, $\varepsilon=1.0\times10^{-2}$, $\delta t=1/10000$

Our previous algorithm:

Edge Detection for Grey Level Image

- Two pairs of coupled elements

The 1st pair

$$\begin{cases} \dfrac{\mathrm{d}u_{i,j}^{0}}{\mathrm{d}t} = C_u\left[\overline{u_{i,j}^{0}} - 4u_{i,j}^{0}\right] + \dfrac{1}{\varepsilon}\left[u_{i,j}^{0}(u_{i,j}^{0} - a_{i,j}^{0})(1-u_{i,j}^{0}) - v_{i,j}^{0}\right] + \underbrace{\dfrac{\mathrm{d}u_{i,j}^{1}}{\mathrm{d}t}\Theta\left(-\dfrac{\mathrm{d}u_{i,j}^{1}}{\mathrm{d}t}\right)} \\ \dfrac{\mathrm{d}v_{i,j}^{0}}{\mathrm{d}t} = C_v\left[\overline{v_{i,j}^{0}} - 4v_{i,j}^{0}\right] + u_{i,j}^{0} - bv_{i,j}^{0} \end{cases}$$

The 2nd pair

$$\begin{cases} \dfrac{\mathrm{d}u_{i,j}^{1}}{\mathrm{d}t} = C_u\left[\overline{u_{i,j}^{1}} - 4u_{i,j}^{1}\right] + \dfrac{1}{\varepsilon}\left[u_{i,j}^{1}(u_{i,j}^{1} - a_{i,j}^{1})(1-u_{i,j}^{1}) - v_{i,j}^{1}\right] \\ \dfrac{\mathrm{d}v_{i,j}^{1}}{\mathrm{d}t} = C_v\left[\overline{v_{i,j}^{1}} - 4v_{i,j}^{1}\right] + u_{i,j}^{1} - bv_{i,j}^{1} \end{cases}$$

- Edge map

$$M(t) = \left\{(i,j) \mid u_{i,j}^{0} > \theta\right\}$$

Weak point:

Edges of narrow dark areas are not detected.

Nomura et al., *International Journal of Circuits, Systems and Signal Processing*, 2011

Proposed Edge Detection Algorithm

- For detecting edges of narrow dark areas,
- Utilise an original image $I_{i,j}$ and its intensity inverted version $\neg I_{i,j}$.
- Apply our previous edge detection algorithm to both of the images $I_{i,j}$ and $\neg I_{i,j}$.
- Obtain two edge maps $M_I(t)$ and $M_{\neg I}(t)$.
- Compute a final edge map.

$$M(t)=M_I(t) \cup M_{\neg I}(t)$$

Experimental results:

Performance Evaluation of Edge Detection Algorithms

- Tested algorithms:
  - Our previous Algorithm:
    - Nomura et al., *International Journal of Circuits, Systems and Signal Processing*, 2011
  - Proposed algorithm
  - Canny Algorithm: Canny, *IEEE PAMI*, 1986
  - Anisotropic Diffusion Algorithm: Black et al., *IEEE IP*, 1998

For program codes of the Canny algorithm and the anisotropic diffusion algorithm, courtesy of Heath et al., http://marathon.csee.usf.edu/edge/edgecompare_main.html

- Accuracy measures:
  - P: Precision
  - R: Recall
  - F-measure

$$P = \frac{1}{|M_t|} |M_t \cap M_o|$$

$$F = \frac{2PR}{P+R}$$

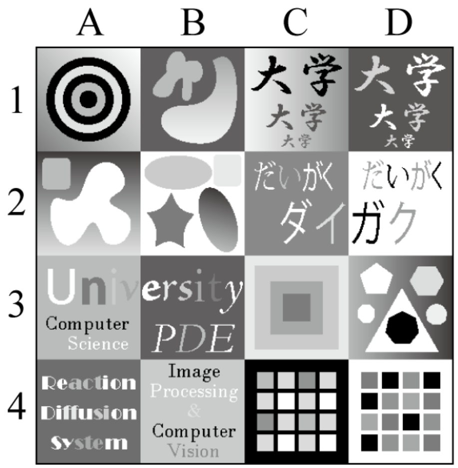
$$R = \frac{1}{|M_o|} |M_t \cap M_o|$$

M_o: obtained edge map
M_t: true edge map

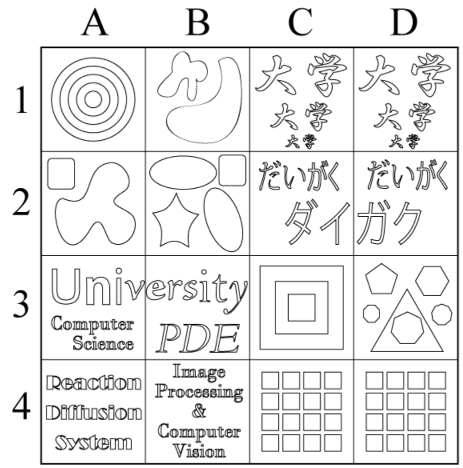
Martin et al.: *IEEE PAMI*, 2004, 2011

Experimental results:

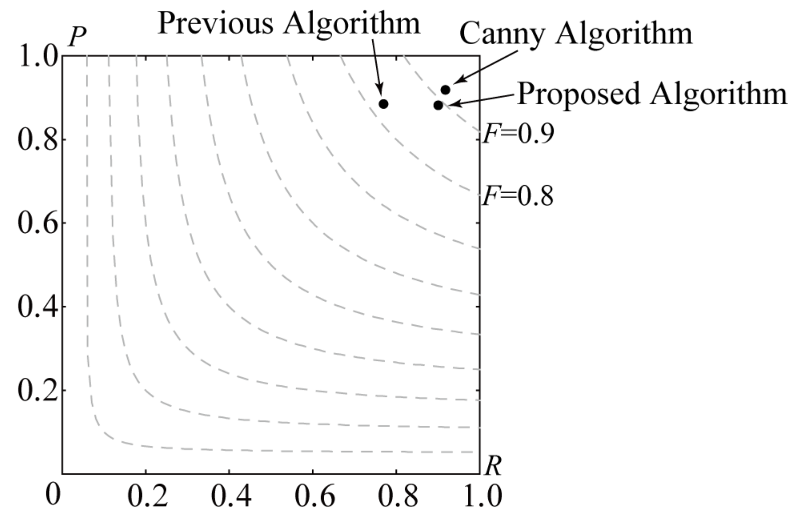
Results of Performance Evaluation for Noiseless Image



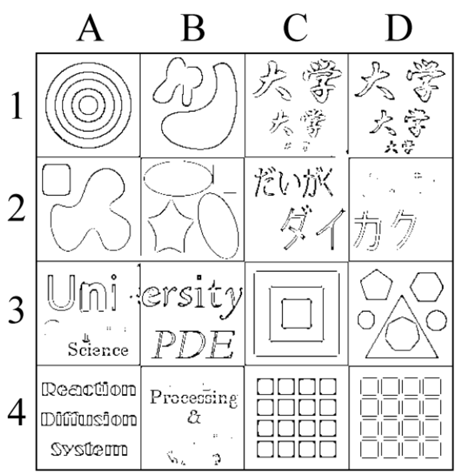
Noise-less Image



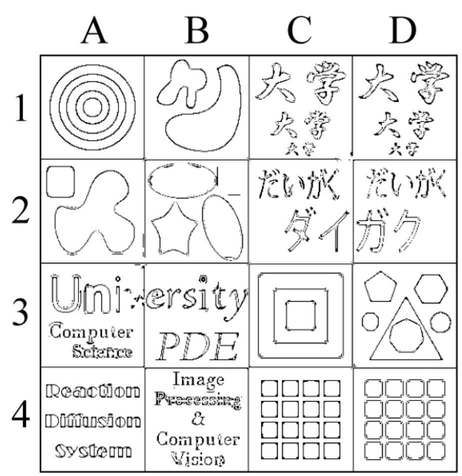
Ground-Truth



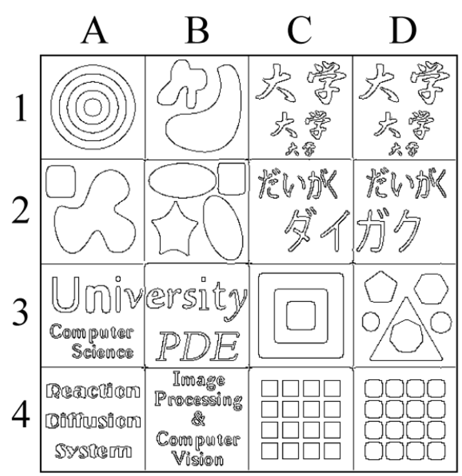
Evaluation with F-measure



Previous Algorithm
P=0.886, R=0.769
F=0.823



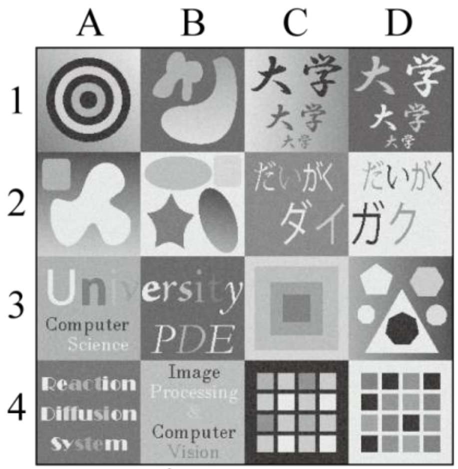
Proposed Algorithm
P=0.883, R=0.901
F=0.892



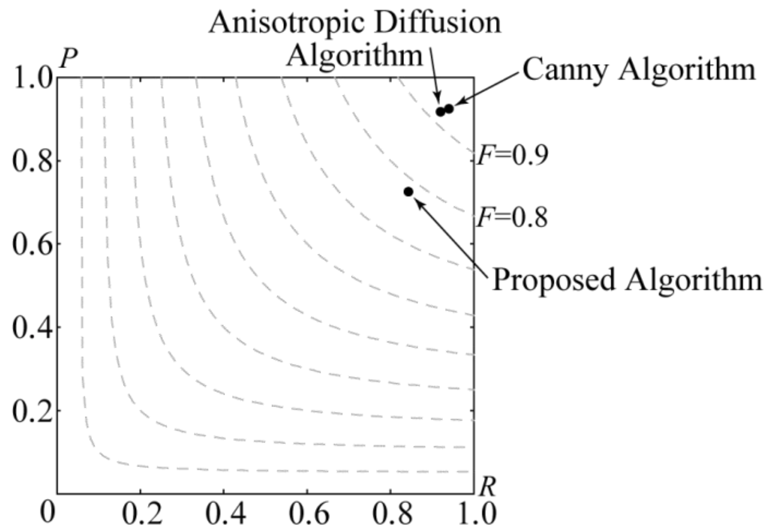
Canny Algorithm
P=0.919, R=0.918
F=0.919

Experimental results:

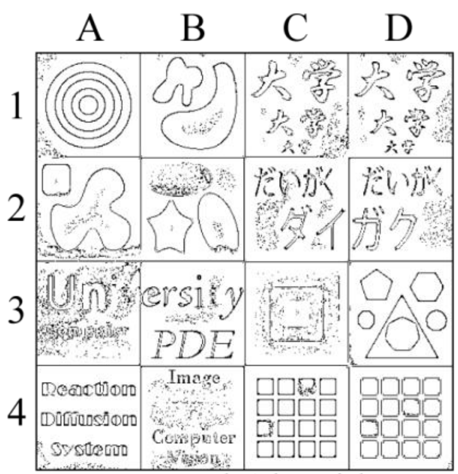
Results of Performance Evaluation for Noisy Image



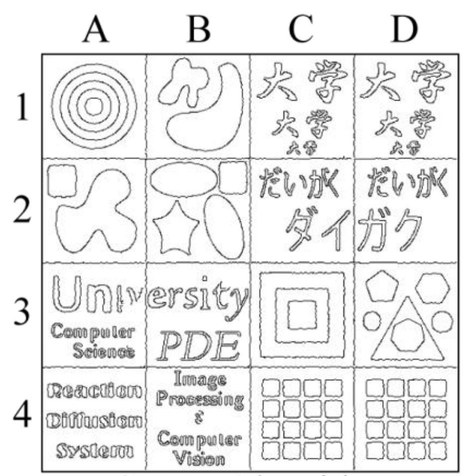
Noisy Image



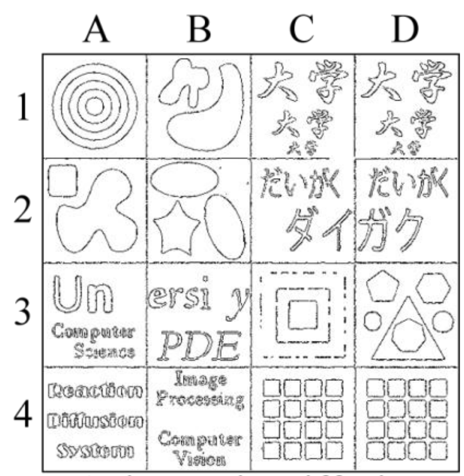
Evaluation with *F*-measure



Proposed Algorithm
P=0.726, R=0.843
F=0.780



Canny Algorithm
P=0.926, R=0.941
F=0.933

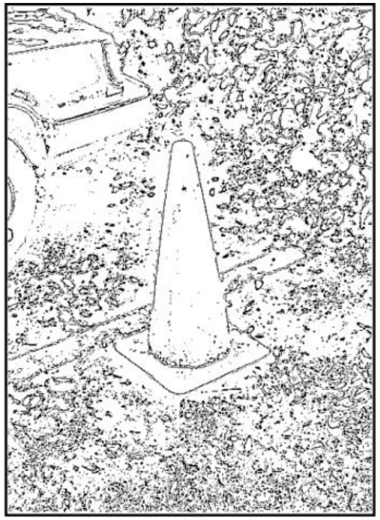


Anisotropic Diffusion Algorithm
P=0.917, R=0.920
F=0.919

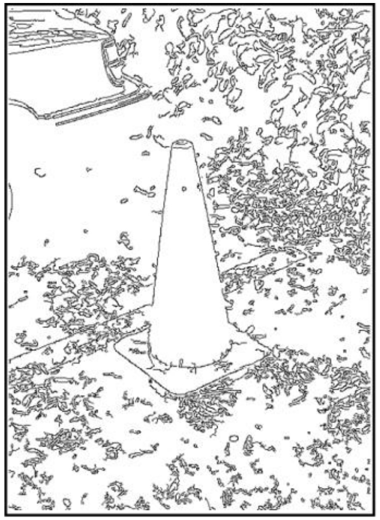
Experimental results:

Results for Real Images

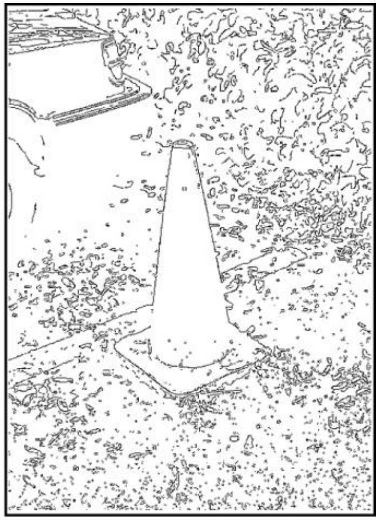
Real Image



Proposed Algorithm



Canny Algorithm

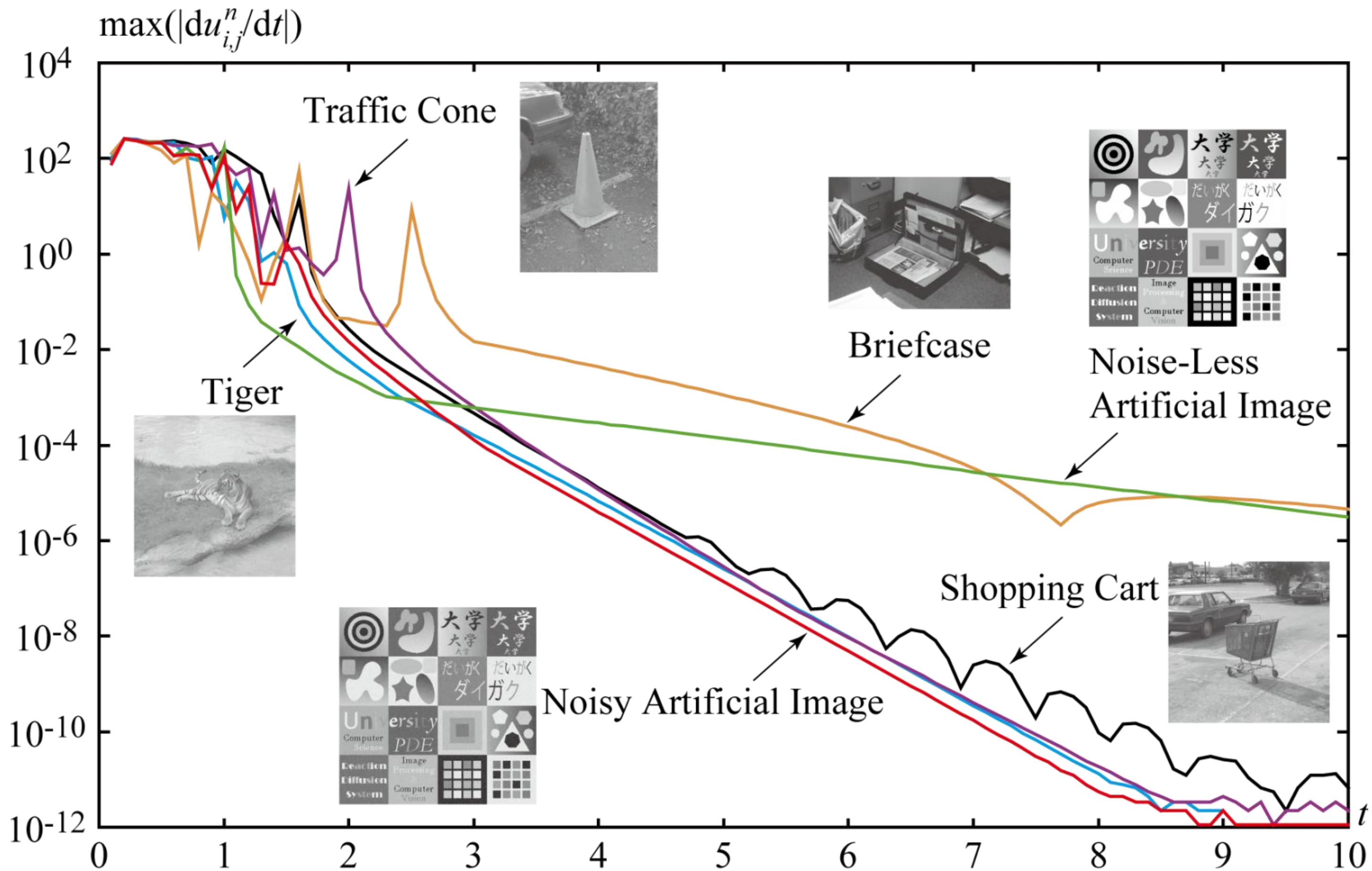


Anisotropic Diffusion Algorithm

More Results

Experimental results:

Convergence of the Proposed Algorithm



Conclusion

- Edge detection algorithm for grey level image
  - FitzHugh-Nagumo excitable elements
  - Discretely spaced elements
  - Original image and its inverted version
- Experimental results
  - Artificial and real images
  - Comparison with the Canny algorithm and the anisotropic diffusion algorithm
  - Convergence

Thank you for your attention!

Any Question ?

Acknowledgment:
The present study was supported in part by the Grant-in-Aid for Scientific Research (C) (No. 23500278) from the Japan Society for the Promotion of Science.