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ELEVATED ACTIVE CONTOUR WITH GLOBAL IMAGE ENERGY BASED ON ELECTROSTATIC FORCE

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Abstract: In this article a new modification of the well known segmentation technique, namely active contour - snake, was proposed. This modification consists in a new formulation of its external force based on the electrostatics. However the base idea of giving electric charges to the image and the snake has been already presented in several works, none of them clearly adressed the problem where the charged snake took place of a charged pixel. In this situation the electrostatic force is not defined, since the distance between charges is zero. The snake proposed in this work evolves on a plane elevated above the image, what never allows this distance to become zero. The method was implemented and verified on real microscopic images of oocytes, proving its superiority on the classic snake.

Keywords: image segmentation, active contour - snake, electrostatic force

1. Introduction

The active contour (alias snake), since its introduction by Kass [7], has been one of the most powerful and most often used techniques in the image segmentation domain. Its ability to deal with moderated local noise and discontinuities in segmented objects has been widely exploited in segmentation of many classes of objects, biomedical images being one of them [8].

Despite its robustness, the original snake suffers from some problems, including its sensibility to the parameters choice and locality in finding its optimal position (having minimum energy). The former still existing in the majority of its formulations, the latter was tried to be solved (or at least improved) in many works, cited in secion 2.

This work proposes a new formulation of the snake external energy based on the electrostatic force, where the image and the snake are given electric charges of the oposite signs. Such the global energy allows the snake to “see further”, beyond

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its local neighbourhood, potentially containing noise and smaller, less relevant structures, and correctly reach the object boudaries across them. But this formulation needs a special treatement when the charged contour takes the position of the charged pixel, because the electrostatic force between them is not defined in this situation since the distance is equal to zero - in the nature two charges never can take the same position. This problem was addressed and solved in this work.

This article is organized as follows. Section 2. gives a review of the original Kass's snake and several works improving its ability to find more distant objects, including approaches using the electrostatic force. Section 3. introduces a new formulation of the snake external energy based on the electrostatic force. Section 4. presents experiments on real biomedical images showing how the new "electric" snake overcomes problems in finding objects surrounded by different, less intensive or smaller structures.

2. Background

In its original form [7], the snake is a 2D curve $v(s) = (x(s), y(s))$ (closed or open) evolving in an environment under forces to minimize its energy, composed of two forms: internal and external (the third form proposed by Kass, energy of constraints, has been used in practice very rarely):

$$E_{snake} = \int (E_{internal}(v(s)) + E_{external}(v(s)))ds. \tag{1}$$

The internal energy (or energies) controls the snake shape, namely its tensility and rigidity by terms of its first and second spatial derivatives. The external energy drives the snake to desired regions in its evironment and in segmentation it is mainly based on image intensity or image gradient. All the energies are weighted in order to allow steering the snake behaviour, e.g. to be more smooth or to better fit an object to extract. In applications, very often the curve goes to its discrete form as an ordered collection of points and the total energy becomes sum of individual energies of each point. The minimalization process consists in iterative deplacing each point separately in quest of a position with locally minimal energy. Two strategies exist here:

- examining every possible next location of each point in its local neighbourhood and choosing this one with the lowest energy (if lower than the current point energy); potential point locations should be discrete and usually are limited to pixels;

- calculation of a resultant force acting on each point and deplacing this point accordingly to this force; points can be situated on arbitrary positions, even between pixels (image intensities on inter-pixel locations are interpolated).

In every case crutial is initialization of the snake position. In the first strategy the local neighourhood should be small (order of pixels) to avoid too fast snake evolution, in the second one the external force, being usually the local image gradient, is calculated very localy (also order of pixels). All this causes that the snake will not “see” an object to segment if it is situated outside this limited scope. Taking into consideration a natural tendence of the snake to shrink [3], initially situated outside the object to segment, the snake can successfully reach it only if there is not other objects on its way. But real images, with noise and complex scenes, very rarely have this property and the correct segmentation depends very strongly on a close and precise initialization.

Many works had as their goals to widen the ability of the snake to “see” further. In virtually every its application to the segmentation, the original image is preprocessed by the Gaussian blur filter in order to expand zones where the image gradient is not null aroung edges. It improves the segmentation but this extension still remains of order of pixels and does not help in more distant initializations.

One of the first improvements to the original snake was the Cohen’s balloon [3]. Additional force, pushing the snake points outside, simply inverts its natural tendence to shrink and makes it growing, like a balloon inflated with air. This force allows to initially place the contour inside an object to extract, what in many cases is more convenient than starting the evolution from its outside. Although this modification can help the snake in many cases to reach its goal, it still has drawbacks inherited from the original snake:

- the initial countour should be placed completely inside the object to extract; if the entire initial shape or its part is situated outside, it will grow and will not converge to the object;
- the method is still very sensitive to its parameters; moreover, there is one parameter more, i.e. the weight of the balloon force; its choise is crucial to good segmentation and very often depends on many factors (e.g. scale, object and image intensities): too low will prevent the snake to reach the object (it will stop on a noise/other smaller object or because of its natural shrinking tendence), too high will cause the snake to overgo the object.

Gunn and Nixon [5] propose an interesting method to extract the most distinct object in some region by placing two classical active contours: one completely inside and one completely outside the object to segment. They evolve independently until they reach their local minima. Then, this one with higher total energy is pushed toward the better placed one (with lower energy) by adding for a moment a supplementary force, similar to the Cohen's balloon force, in order to get it out from the local minimum. The segmentation ends when two contours converge to the same position. This technique works well, but it demands to place two initial contours, what can be sometimes troublesome. Also comparing global snake energies (to decide which contour will be given the supplementary force) can push the snake out from locally well extracted regions, if it has higher total energy.

A very eficient method of extending the snake ability to see distant objects can be found in the work of Xu and Prince [10], where the active contour evolves under a new force field - Gradient Vector Flow. This force replaces the original external force (the image gradient), and it is its extension to the image regions with the gradient magnitude close to zero. In an iterative pre-processing stage (consisting in solving the generalized diffusion equation) the gradient is propagated from the object boudaries and along its local directions to empty image parts. Thus the snake in every position is given a direction to an edge (high gradient region) and it can move to it. The most often it is the closest edge, but in concave forms this force leads to more distant, “internal” object fragments. This ability to correctly segment concave objects (inversely to the classical snake) is pointed out as the next main advantage of this technique. Also, the initial contour does not need to be placed completely inside or completely outside the object - it will always see the edges. However, the real images very rarely have the empty regions. Beside the object to extract, they contain other ones, as well as noice and artefacts. Even if less intensive, they will attract the being propagated gradient and consequently - the snake. To work well, the technique would demand some extra pre-processing, e.g. zeroing too small gradient by thresholding, what will introduce a new parameter - the threshold value.

The idea to give the snake and the image electric charges is not new. Jalba et al. [6] introduced the charged-particle model (CPM) composed of free particles positively charged and evolving independently in the electric field given by the negatively charged image pixels. The pixel charge values are based on the image gradient. The particles are not organized in an ordered collection, conversely to the classic snake, and each of them evolves in the electric field independently, however influenced (repulsed) accordingly to the electrostatic force by other equally charged particles. This repulsion plays role of the internal forces in the original snake and replaces them. Only after the convergence the continuous contour (or surface in 3D) is reconstructed. That model has ability allowing it to be placed in almost arbitrary initial position, e.g. outside and beside the object or even in the form of regular mesh evenly distributed on the entire image. Once the object boudary is reached, in at least one its fragment, the particles are evenly distributed along the edges (not encountering obstacles from the external electric field) by the repulsion force to cover the entire shape. In the electrostatic force calculation the pixel (charge) from the position occupied by the being simulated particle is simply temporarily removed to avoid this partial force to be undefined (distance zero). This action is a deviation from the physical model, but apparently it was not reported as a problem in the whole process.

The CPM behaves worse, as pointed out Yand et al. [11], when some part of the object egdes is weaker or blurred, resulting in a non-continuous final contour. They blame the internal nature of the CPM, where not ordered particles constantly leave those regions attracted by close more distinct edges. To solve this problem they proposed to incorporate the electrostatic force in the frame of the standard active contour (however, under form of the geodesic one), which always guarantees the continuous result. Their electric field, driving the contour, is also dynamic, changing locally when some part of the contour reached strong edges: the bondary competition force starts to repulse other its fragments pushing them to other undiscovered regions. The geodesic formulation of the contour as the zero level set of the higher dimension function (instead of the discrete snake) allows not to address the problem where the charged snake takes the same position with the charged pixel.

Chang and Valentino [12] proposed an electrostatic deformable model as a charged fluid model to segment medical images. A propagating front is composed of fluid elements (cells), and each of them is filled with elementary electric charges moving freely between these cells (so only on this front) and defining the electric field. This field is summed with the image gradient field and the resulting one drives the whole front evolution. Thus there is not direct interaction charged particles-charged pixels, no need to calculate the electrostatic force and no problem with the zero distance.

3. Elevated electric snake

Global external force

This work proposes a new formulation of the external electric force, which similarly to the GVF replaces its original form based on the image gradient. This new force is based on the electrostatic force, attracting two point electric charges of opposite signs proportionally to the product of their values and inversely proportionally to the square distance between them:

$$F_{electrostatic} \sim \frac{q_1 q_2}{r^2} \tag{2}$$

where q_1, q_2 - values of two electric charges, r - distance between them.

The same relation is also given by the gravitational force, but the latter is limited to attracion, while the former describes two directions of the influence: attraction (when two charges are of opposite signs) and repulsion (charges of the same signs).

In the proposed technique the contour is discrete - composed of N points: $p(i) = (x_p(i), y_p(i))$, $i = 0..N-1$, constituting a closed curve. Each such point is given a unitary electric charge of the same sign, let's say positive one: $q_p(i) = 1$. These points evolve in the electric field defined by the image in the following manner: each pixel $I(x,y)$ of the image I is given the negative electric charge $q_I(x,y)$ with the value corresponding to the gradient magnitude in this position:

$$q_I(x,y) = -|\nabla I(x,y)|. \tag{3}$$

Each such the fixed charge $q_I(x,y)$ attracts every single snake point $p(i)$ with the force $\overrightarrow{f}(i,x,y)$ of magnitude proportional to the product of these two charges ($q_I(x,y)$ and $q_p(i)$) and inversely proportional to the square distance between the pixel and the snake point. Since the snake point charge is unitary, only the pixel charge remains in the numerator:

$$f(i,x,y) = \frac{|\nabla I(x,y)|}{\|\overrightarrow{p(i)-(x,y)}\|^1}. \tag{4}$$

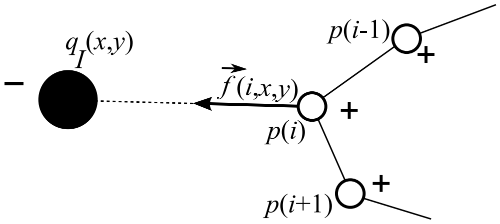


Fig. 1. Force attracting a snake point to a single pixel in the image.

Each snake point is attracted simultaneously by all the charges in the images. The vector sum of all these single forces defines the external force driving the snake in this point:

$$\overrightarrow{F}_{external}(i) = \sum_{x,y} \overrightarrow{f}(i,x,y). \tag{5}$$

Such the formulation allows the snake to see, and be attracted by, distant high gradient regions and to neglect close, low gradient obstacles. But the electrostatic force is defined only for two charges separated by some distance. The closer they are each to other, the stronger this force becomes , tending to infinity while the distance tends to zero. The goal of each snake point is the highest gradient region, what means the situation when two charges will take the same position, where the electrostatic force between them would be not defined. To resolve this contradiction, two surfaces: the image itself and the snake evolution plane, are separated by some distance *h* by elevating the latter above the image (Fig. 2). Thus the snake points can move only on this elevated plane, parallel to the image, and will never touch the image pixels. The external force (Equations 4 and 5) becomes in this way 3D.

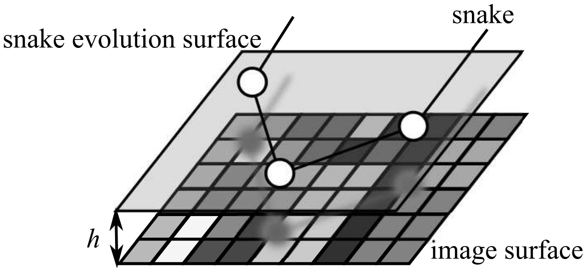


Fig. 2. Two surfaces: image and the snake evolution plane, are separated by distance *h*.

Snake energies and evolution

The snake evolution here consists in searching in the local neighbourhood of every of its points in order to find a new position with lower energy. Thus, the snake points locations are limited to the image pixels and every point should be given its energy instead of force.

The internal energies from the Equation 1 are responsible for the contour form: its regularity and smoothness. In this work the original Kass's formulations (based on spatial derivatives) were replaced by invariant to scale ones. Marking a vector from $p(i)$ to $p(i-1)$ by $\overrightarrow{v}_{i,i-1}$:

- the point regularity energy is expressed as normalized difference between actual distance to the previous point and the mean inter-point distance *d* in the whole contour:
$$E_{regularity}(i) = \frac{|d - \|\overrightarrow{v}_{i,i-1}\| \,|}{d}; \tag{6}$$
- the point smoothness energy is equal to cosinus of the angle between two vectors going to the neighbour points (in practice it is calculated as scalar product of

these normalized vectors):

$$E_{smoothness}(i) = \cos(\angle(\overrightarrow{v}_{i,i-1}, \overrightarrow{v}_{i,i+1})) = \frac{\overrightarrow{v}_{i,i-1}}{\|\overrightarrow{v}_{i,i-1}\|} \cdot \frac{\overrightarrow{v}_{i,i+1}}{\|\overrightarrow{v}_{i,i+1}\|}. \tag{7}$$

The external point energy is based on the “electrostatic” resultant force (Equation 5). For a single, stationary snake point it is assumed to be zero and only its deplacement can cause incrementing or decrementing it. This relative energy change is calculated as a negative scalar product of the electrostatic force and the vector of the examined point potencial deplacement $\overrightarrow{(\Delta x, \Delta y)}$ (Figure 3):

$$\Delta E_{external}(i, \Delta x, \Delta y) = -\overrightarrow{F}_{external}(i) \cdot \overrightarrow{(\Delta x, \Delta y)}. \tag{8}$$

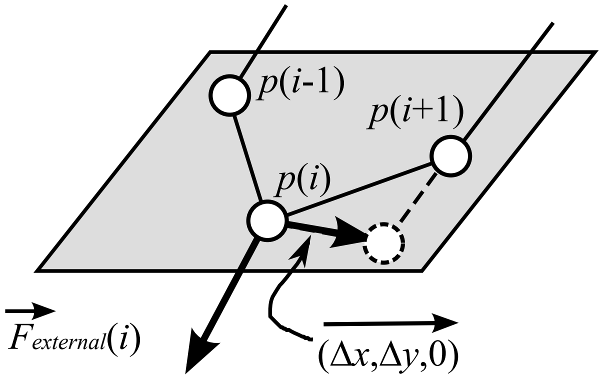


Fig. 3. Calculating the external energy change from the “electrostatic” force and the snake point potential deplacement.

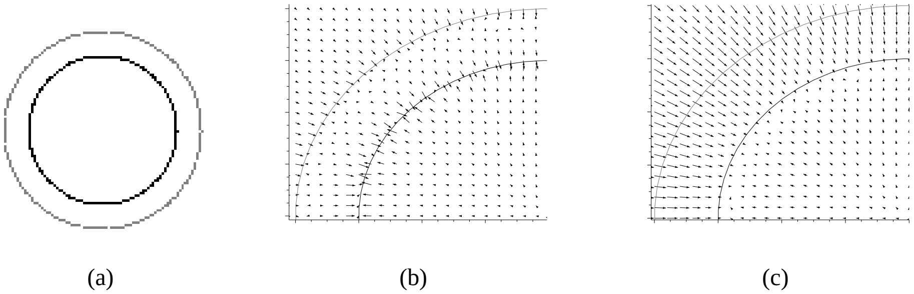
If the point deplacement is close to the force direction, then the product will be positive and the energy change negative, so the deplacement (in the energy minimalization process) will be probably accepted (if no better one is found). If it is going in the opposite direction, the energy change will be positive and it will be certainly rejected. Finally, if the force is completely vertical, all examined deplacements will be perpendicular to it and they will give the energy change equal to zero, so no better than the current position.

The overall segmentation procedure is organized as follows:

1. The initial countour is placed in the image by an operator. It does not need to be very close to the object to segment, but on its way to this object it can not find bigger objects having higher gradient and it should contain the object to segment in its inside (see Section 4.).

2. In every iteration step, each snake point is examined separately: if its deplacement in its local neighbourhood gives the energy decrementation, then this point is moved to this new position.
3. If in the current iteration no points are deplaced, the procedure can be finished.

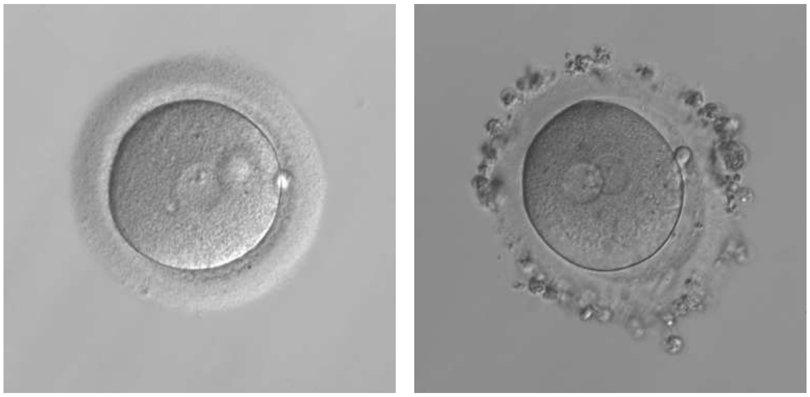
Snake elevation h



(a) (b) (c)

Fig. 4. Snake elevation steers its scope of view: (a) - the darker internal circle represents an object to segment while the brighter external one - an obstacle to cross; (b) - zoom on the upper-left part - the electric field on a lower level ($h = 1$, only x and y components shown) points toward the outer circle from both its sides; (c) - zoom on the upper-left part - the electric field on an upper level ($h = 9$, only x and y components shown) points everywhere toward the inner circle.

Besides the standard active contour parameters (mainly weights of the energies terms), the proposed technique adds one more: elevation h of the snake evolution surface above the image (Figure 2). In spite of complicating the whole model it can be also used to steer the snake scope of view. The higher is snake lifted, the farther it can look beyond smaller local obstacles. This feature is visualized in Figure 4, where the inner, darker circle plays role of an object to segment and the outside one, brigther is an obstacle (Figure 4a). If the elevation h of the snake is small ($h = 1$), the electric



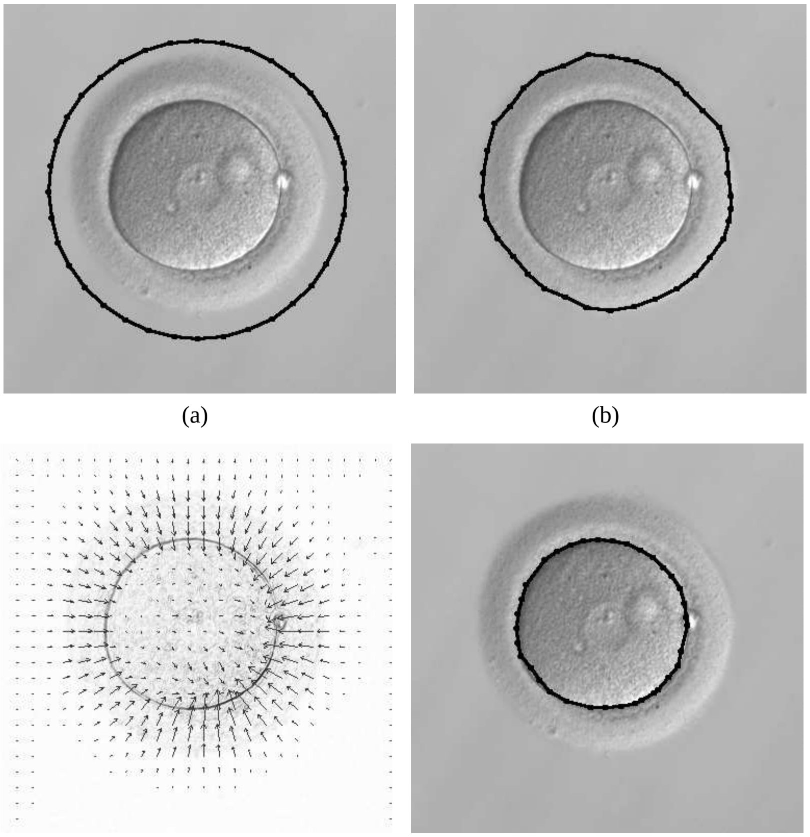
(a) (b)

Fig. 5. Microscopic images of oocytes in different stage of their evolution.

field from the outside of this configuration leads the active contour only to the outer shape (Figure 4b shows only x and y components of the 3D field) - it can not cross the outer circle because the field in its inside points toward it and not toward the inner, stronger circle. When the elevations is higher ($h = 9$, Figure 4c), the electric field, even between circles, points toward the inner, stronger one.

4. Experiments

The proposed method, implemented in Java, was verified on real microscopic images of oocytes. These images are especially well suited to show its advantages since they

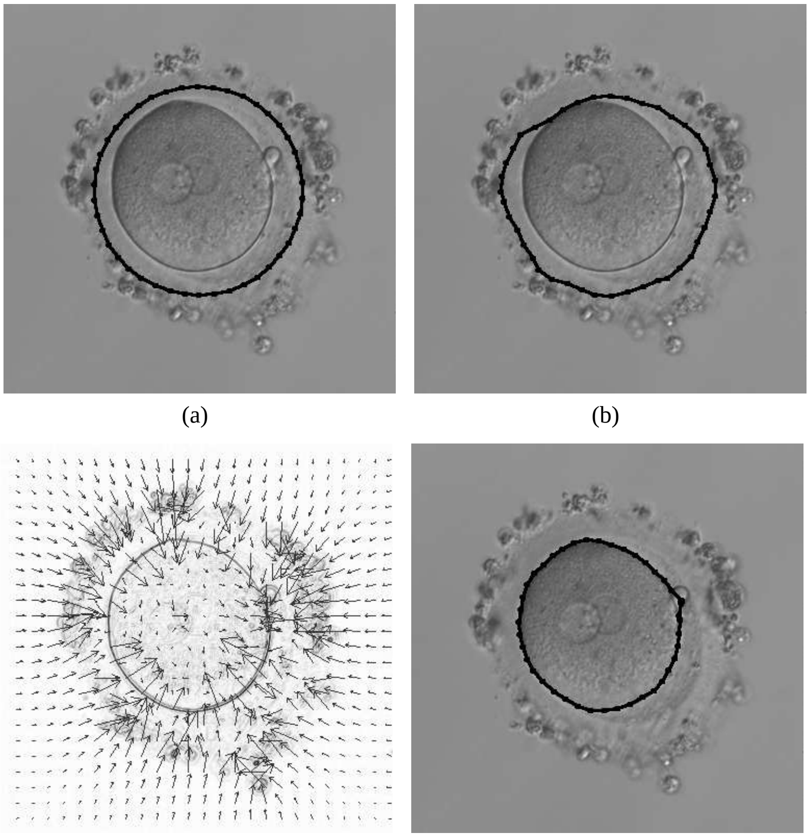


(a) (b)

(c) (d)

Fig. 6. Experiments with image 5a: (a) - initial contour (in black); (b) - result of the classic snake segmentation (in black); (c) - "electrostatic" force vector field superimposed on the image gradient; (d) - result of the "electric" snake (in black).

they contain one well distinguished shape surrounded by less distinct structures. In other works the oocytes (and other reproductive cells in general) were segmented using various techniques, including deformables models. Pastorinho et al. [9] used two deformable models: Active Shape Model to detect the nucleus and GVF snake to detect the whole zooplankton gonad. Alén et al. [1] applied and compared two techniques to segment and count fish oocytes form histological images: region growing and edge-based one, where unstructured detected edges are modelled with ellipses. Giusti et al. [4] segmented zygote (fertilized ovum - evolved from an oocyte) in very interesting manner, exploiting artefacts from the optical imaging to improve segmentation. The original zygote image, converted to the polar coordinated, defines a directed acyclic graph with arcs values computed using the image characteristics. The minimum-cost path in this graph traces the zygote limits. The same approach is



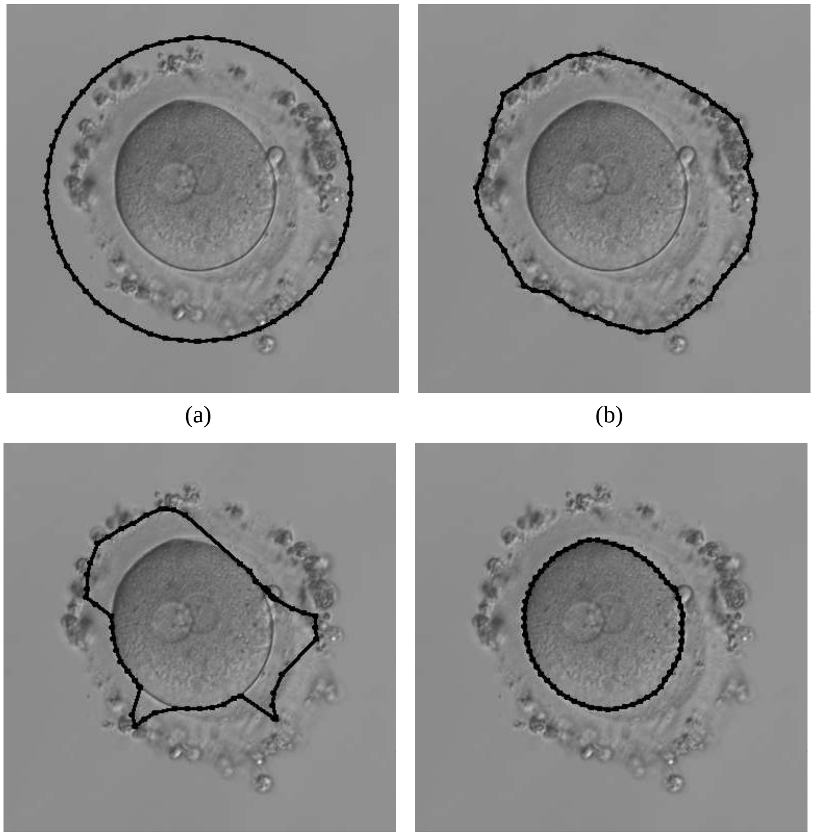
(a) (b)

(c) (d)

Fig. 7. Experiments with image 5b: (a) - initial contour situated between the oocyte and adjacent structures (in black); (b) - result of the classic snake segmentation (in black); (c) - “electrostatic” force vector field superimposed on the image gradient; (d) - result of the “electric” snake (in black).

also used to segment pronuclei inside the zygote. Basile et al. [2] used morphological operators in microscopic images to segment a single cell of an arbitrary shape and the Hough transform to identify its circular cytoplasm-nucleus boundary before applying a texture analysis to the segmented regions.

In the first image (Figure 5a) the oocyte is much more distinct than the surrounding structure. The initial contour was initialized outisde both the cell and the structure (Figure 6a). Despite lower intensity of that structure, the classic Kass's snake stopped its evolution on it and did not reach the cell itself (Figure 6b). The "electrostatic" force vector field (Figure 6c) gives correct direction toward the cell boundaries through adjacent structure from the outside of the cell. Thus, the "electric" snake easily crossed that structure and correctly segmented the cell (Figure 6d).



(a) (b)

(c) (d)

Fig. 8. Experiments with image 5b: (a) - initial contour situated outisde the oocyte and adjacent structures (in black); (b) - result of the classic snake segmentation (in black); (c) - result of the "electric" snake (in black), *h*=1; (d) - result of the "electric" snake (in black), *h*=2.

The image shown on Figure 5b seems harder to segment because of more distinct structures around the oocyte - their intensities are comparable to the oocyte intensity. Initialized between them (Figure 7a), the classic snake was attracted by the closest edges: somewhere - the oocyte, elsewhere - the adjacent structures, and sometimes, initialized on noise, did not move at all (Figure 7b). The "electrostatic" force vector field (Figure 7c) points toward the actual cell boundaries, even through intensive local obstacles (their "charge" is smaller than the cumulative "charge" of the boundaries) and the "electric" snake correctly segmented the oocyte (Figure 7d).

Sight range

For the "electric" snake its sight range can be controlled by its elevation *h* above the image (Figure 2). The snake situated close to the image (smaller elevation *h*) will be more attracted by local pixels than by distant ones, even more intensive. Going up, it will acquire ability to look beyond local pixels to see (and reach) more intensive structures in its neighbourhood. Example of this behaviour can be observed on Figure 8. The initial snake was placed outside the oocyte and adjacent structures (Figure 8a). Certainly, the classic snake failed to extract the oocyte ((Figure 8b), but so did the "electric" snake evolving on the plane too close to the image (*h*=1, Figure 8c). Only after elevating it higher (*h*=2) it was able to correctly extract the cell passing over the adjacent intensive structures (Figure 8d). However, the "electric" snake elevated too high will become too global - it will focus on only few image locations with the highest gradient. Only to these regions will lead the "electrostatic"

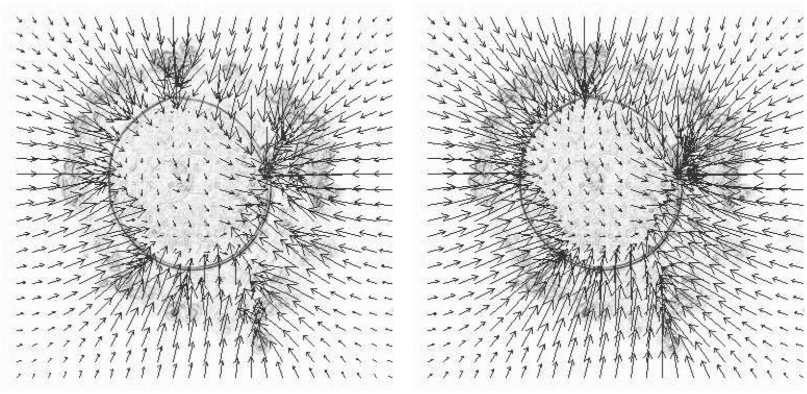
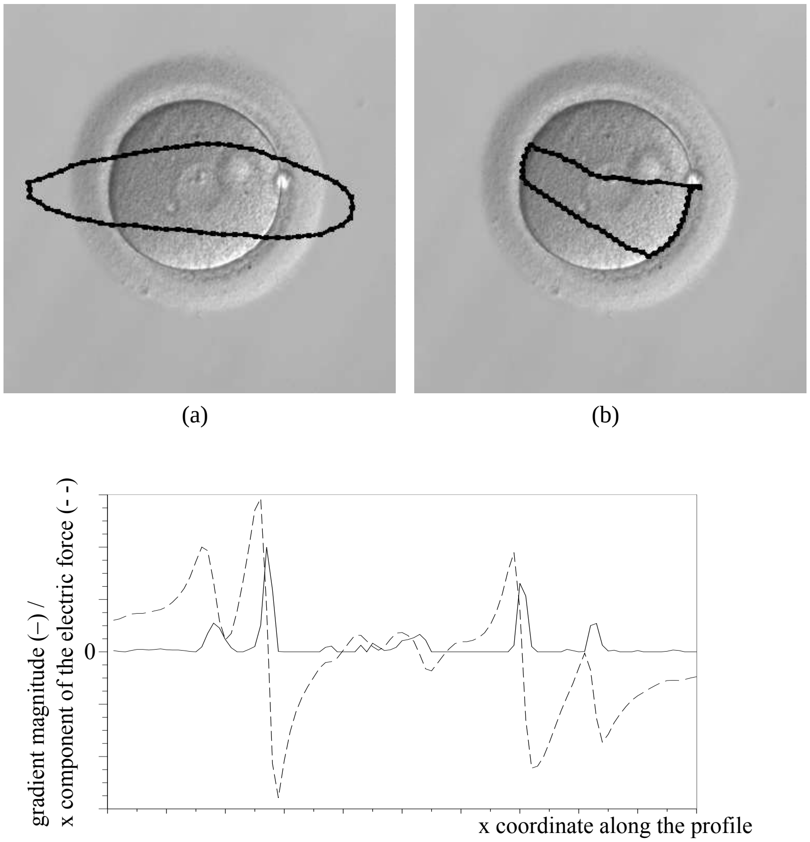

(a) (b)

Fig. 9. Influence of the "electric" snake elevation on the "electrostatic" force vector field: (a) - elevation *h*=10; (a) - elevation *h*=20.

force vector field, ignoring the rest of the object to segment (Figure 9) - all snake points will move there. So the elevation value should be adjusted correctly, what unfortunatly adds a new parameter to the model.



(a)

(b)

(c)

Fig. 10. Results of initialization inside the oocyte : (a) - initial contour; (b) - final contour; (c) - horizontal profiles (y=1/2 height) of gradient (solid line) and x-component of the electric force (dashed line).

Unfortunatly, the proposed model fails when initialized (even partialy) inside the oocyte (Figures 10a and 10b). Relatively high and in big quantity gradient inside the cell “hides” the border and the electric field points to the actual oocyte border only in its local neighbourhood. Figure 10c presents two profiles along horizontal line crossing the oocyte center (y=1/2 image height). The solid line marks the image gradient, with two higher inner peaks on the oocyte border an two lower outer ones on the adjacent structures border. The dashed line marks the x-component of the electric field: outside the peaks it points to the image center (positive on the left side, negative on the right side), as well as between the higher and lower peeks pairs (between the oocyte and the adjacent structures), but inside the cell (the profil center) it is influenced by the cell interior and does not point to the border.

5. Conclusion

The proposed in this work elevated electric snake improves significantly ability of the active contour to segment objects when it is initialized in some distance from them (however - it can not be placed in an arbitrary position in the image, e.g. on one side of the object to segment). It differs from other deformables models using the electrostatics by taking into account that two electric charges can not be placed in the same position. It is done by elevating the contour above the image. Thanks to it, it can also pass over local obstacles (other structures, noise) even with comparable intensities (under condition that they are smaller, or in other words - their cumulative "charge" is smaller). This technique behaves worse when initialized inside circular objects filled with significant gradient (internal structures, noise). The GVF snake, also aiming to attract the snake by distant object edges, can not work with obstacles on its way - the "elevated electric snake" can do it, even if they are of comparable intensity.

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PODNIESIONY AKTYWNY KONTUR Z GLOBALNĄ ENERGIĄ OBRAZU OPARTĄ NA SILE ELEKTROSTATYCZNEJ

Streszczenie: W artykule tym zaprezentowana jest nowa modyfikacja techniki segmentacji znanej pod nazwą aktywnego konturu - węża. Polega ona na nowym sformułowaniu siły zewnętrznej opartej na sile elektrostatycznej. W istniejących pracach, w których obrazow i kontur posiadały ładunek elektryczny, omijano problem konturu zajmującego pozycję naładowanego piksela. W takiej sytuacji siła elektrostatyczna jest niezdefiniowana, gdyż odległość między ładunkami jest zerowa. Proponowany w tej pracy kontur operuje na płaszczyźnie wyniesionej ponad obraz, co sprawia, że odległość ta nigdy nie spada do zera. Metoda została zaimplementowana i zweryfikowana na rzeczywistych obrazach mikroskopowych oocytów, gdzie wykazała swoją wyższość nad klasyczną techniką węża.

Słowa kluczowe: segmentacja obrazów, aktywny kontur - wąż, siła elektrostatyczna