

Distance and Direction Sensing with Excitable Chemical Medium

Joanna N. GORECKA,¹ Jerzy GORECKI,² Kenichi YOSHIKAWA,³
Yasuhiro IGARASHI³ and Hiroki NAGAHARA³

¹*Institute of Physics, Polish Academy of Sciences,
Al. Lotnikow 36/42, 02-668 Warsaw, Poland*

²*Institute of Physical Chemistry, Polish Academy of Science,
Kasprzaka 44/52, 01-224 Warsaw, Poland*

and

*Faculty of Mathematics and Natural Sciences,
Cardinal Stefan Wyszyński University,
Dewajtis 5, 01-815 Warsaw, Poland*

³*Department of Physics, Graduate School of Science,
Kyoto University, Kyoto 606-8502, Japan*

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We demonstrate a strategy of sensing the distance between an observer and a small source of periodic oscillations in a nonlinear chemical medium. The information about the distance is returned in the firing numbers of pulses excited in the set of sensor channel. The same method can be also applied to recognize the direction of a train of plane excitation waves. The idea of chemical sensor is tested in simulations based on the Rovinsky-Zhabotinsky model and the results are confirmed by experiments with Belousov-Zhabotinsky reaction.

§1. Introduction

Exploring the environment for the optimum living conditions and resources of food is one of the most important problems a living organism should solve. At the level of very simple organisms sensing the environment is related to the chemical processes proceeding in a cell. It is well known¹⁾ that an excitable chemical medium is responsible for transmission of information along the nerves. Therefore, the question on how an excitable chemical system can acquire information coming from outside can help in better understanding of chemical aspects of sensing in the living organisms. It is expected that the information on the direction from which the excitations arrive or on how distant is their source is very important. We demonstrate that such information can be obtained with the use of a simple chemical system.

A possible strategy of direction sensing with the use of chemical excitable medium has been recently presented by Nagahara et al.²⁾ The authors considered a simplified environment represented by an excitable semiplane. The stimulus comes to an observer as a pulse of chemical excitation. The sensor described in Ref. 2) uses the coincidence of pulses to recognize the direction of a single arriving excitation. It is formed by a ring of a highly excitable medium. Half of the ring is located in the environment. The other half belongs to the observer and a number of coincidence detectors linked with sensor channels are placed around it. An excitation coming from the environment hits the ring at a point located such that the wave vector of the

excitation is oriented along the radius. It generates two pulses on a ring propagating in the opposite directions. The pulses meet again in the observer part of the ring and excite the nearest coincidence detector. Of course, the meeting point is placed on the same diagonal as the wave vector of the arriving excitation, so information about its direction is returned as a pulse propagating in a specific channel.

§2. The chemical sensor

Here we present an alternative strategy of chemical sensing. Our method is based on the fact that the frequency of a periodic train of excitation pulses can change after crossing the barrier of non excitable medium.³⁾⁻⁶⁾ The change in frequency depends on the angle between the wave vector of arriving pulses and the normal to the barrier. Therefore, the firing number (defined as the ratio between the number of pulses that crossed the barrier and the number of pulses that arrived at it) can be used to obtain information on the direction of arriving pulse. Figure 1 shows the sensor in contact with environment (the upper dark gray part of the picture). The sensor is composed of a number of similar excitable channels (in Fig. 1 they are numbered 1-4) that are wide enough to ensure a stable propagation of pulses. The sensor channels are separated one from another by parallel non-excitable stripes that do not allow for the interference between pulses propagating in the neighboring channels. All sensor channels are separated from the environment M by a non excitable gap G. The width of this gap is crucial for sensor sensitivity. If the gap is too wide then no excitation of M can generate a pulse in sensor channels. If the gap is too narrow then any excitation can pass G and create a pulse in every channel, so signals in sensor channels are identical. The width of the gap should be selected such that the firing number strongly depends on the angle between wave vector characterizing a pulse arriving at the gap and the normal to the gap. It is also very important that the gaps between the active area M and each channel are exactly the same.

Let us consider a small source of a periodic train of excitation pulses S in M. If the source is close to the array of sensor channels then the wave vectors characterizing excitations in front of various channels will be different. Thus, we expect different frequencies of excitations in various channels. On the other hand, if the source of excitations is far away from the gap G then the wave vectors in front of different channels should be almost identical and so, the frequencies of excitations in different

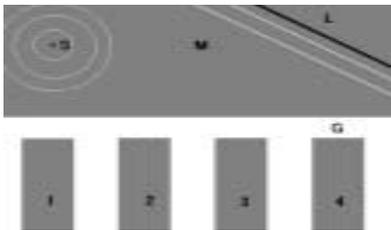


Fig. 1. The geometry of a chemical sensor composed of four channels (1-4). The gray areas are excitable, the white is non-excitable. The sensor is in contact with the environment M. We consider excitations generated alternatively by a small, compact source S (distance sensing) or by a line L (direction sensing). Thin white lines show the shapes of pulses generated by S and L.

channels would not differ. Therefore, the device shown in Fig. 1 can sense the distance separating it from the source of excitations and returns information about it in a set of firing numbers. We can also expect that the sensor can recognize a slow motion of the source with respect to the observer, because when the differences in firing numbers between neighboring channels decrease then the source of excitations moves away (and vice versa).

The sensor can also give information about the wave vector characterizing a train of plane pulses of excitation. The line L in Fig. 1 shows a source of such pulses. As mentioned above the firing number in a channel depends on the angle between the wave vector and the normal to the gap. Observing the time difference between excitations of the most left and the most right channels the sensor can detect if the pulse arrived from the left or from the right.

In numerical simulations of the sensor performs we have used a well known, simple Rovinsky-Zhabotinsky (RZ) model of ferroine catalyzed Belousov-Zhabotinsky (BZ) reaction.⁷⁾ The variables: x and z , corresponding to the dimensionless concentrations of the activator HBrO_2 and of the oxidized form of catalyst $\text{Fe}(\text{phen})_3^{3+}$. If ferroine is immobilized on a flat membrane then in the excitable regions the time evolution is described by:

$$\frac{\partial x}{\partial \tau} = \frac{1}{\epsilon} \left[x(1-x) - \left(2q\alpha \frac{z}{1-z} + \beta \right) \frac{x-\mu}{x+\mu} \right] + \nabla_{\rho}^2 x, \quad (2.1)$$

$$\frac{\partial z}{\partial \tau} = x - \alpha \frac{z}{1-z}. \quad (2.2)$$

The non excitable regions are the areas of space where the catalyst is absent so, $z = 0$ and the evolution of x is described by:

$$\frac{\partial x}{\partial \tau} = -\frac{1}{\epsilon} \left[x^2 + \beta \frac{x-\mu}{x+\mu} \right] + \nabla_{\rho}^2 x. \quad (2.3)$$

All variables and coefficients in Eqs. (2.1)–(2.3) are dimensionless and relationship with the real variables can be found in the literature.⁸⁾ In numerical calculations we use the same values of parameters α , β , ϵ , μ as in the previous works.^{8),10),11)} Equations (2.1)–(2.3) for the distribution of excitable and non excitable areas shown in Fig. 1 are solved on a square grid of points equally distant in x- and y- directions ($\Delta = 0.2885$). We considered excitations generated by a small source S which was 5 grid points wide and 15 grid points high with the concentration of activator 0.02 as well as plane pulses of excitations generated by a line of points with the same concentration of activator.

Simulations have confirmed that the proper choice of the gap is crucial for sensor work. For the considered excitable system, the size and the strength of the source we observe a strong dependence of the firing number on the direction of wave vector of the incoming pulse for the gap 2.885 distance unit wide. The response of the sensor to excitations generated by the small source described above is shown in Fig. 2. The period of excitations in the environment was 34.8. Figure 2(A) shows the time evolution of x at points centrally located within the signal channels 1, 2, 3 and 4 for the source placed 8.655 unit above the channel 1. For the considered position

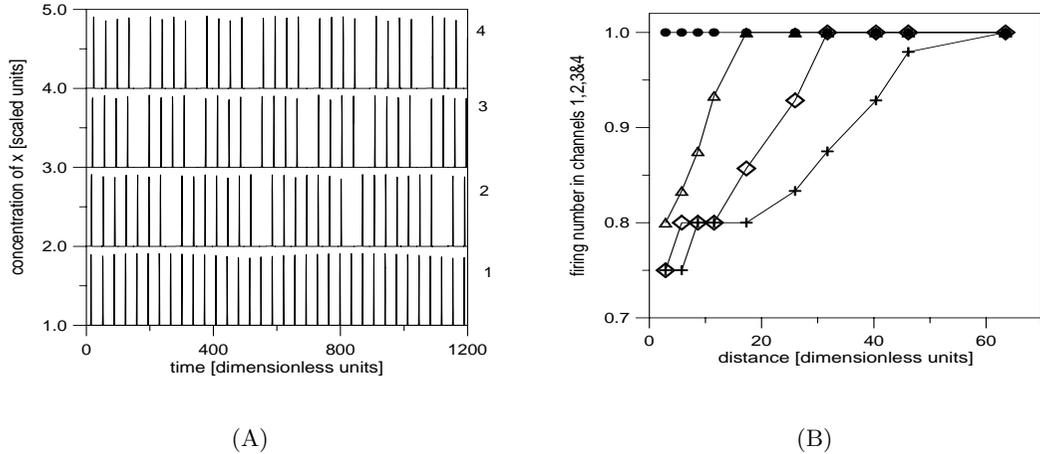


Fig. 2. (A) The concentration of x in the mid points of channels 1,2,3 and 4 as functions of time for the gap width $\Delta_G = 2.885$ and the source of excitations placed 8.655 units above the channel 1. (B) The firing number in channels 1 (dots), 2 (triangles), 3 (squares) and 4 (crosses) as functions of distance from the source.

of the source the firing numbers in channels 1-4 are 1, $7/8$, $4/5$ and $4/5$, respectively. The largest firing number is observed in the channel 1, because the wave vector of arriving excitations is normal to the gap and it decreases in the subsequent channels as the angle between the wave vector and the normal increases. If the source of excitations is closer to the sensor then the differences between firing numbers in different channels should be larger than those shown in Fig. 2(A). On the other hand, when the source is far away the firing numbers become identical. The firing numbers in all channels as functions of source distance are presented in Fig. 2(B). If the set of firing numbers is known, then the distance separating sensor from the source can be estimated. It is important that information about the distance is coded in a set of frequencies of pulses propagating in a number of channels. Changes in frequencies corresponding to changes in distance from the excitation source can be detected by frequency filters constructed with excitable medium,⁹⁾ so distances can be sensed chemically.

The signal transformation on a barrier depends on the frequency of incoming pulses.^{4),5)} We considered the influence of this effect on the work of distance sensor performing simulations for a source of excitations characterized by lower frequency of excitations. It comes out that in such case the width of gap G should be adopted (increased) for the new frequency.

We have also simulated the response of the sensor to plane pulses with different wave vectors. Such pulses were generated by a line L (see Fig. 1) of points with the increased concentration of activator. Using the sensor formed by two stripes we observed the firing numbers $1, 2/3$ and $1/2$ for the cases when the tangent of the angle between L and x -axis was $-1, -2$ and -3 respectively. This result confirms that the presented sensor can distinguish the direction of incoming train of pulses.

The experiments on the distance sensing were performed using a photosensitive

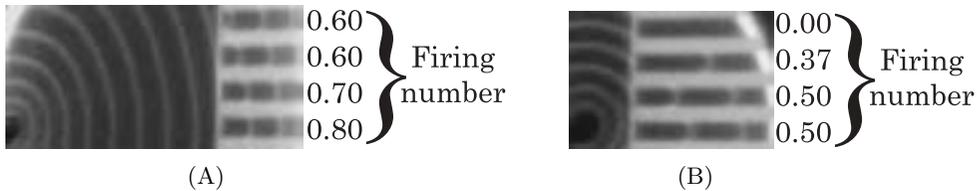


Fig. 3. The firing numbers (given right to a corresponding channel) observed in experiments with Ru-catalyzed BZ reaction. The system is illuminated such that the dark areas are excitable and the light gray areas are not. The sensor channels and gaps between them are 1 mm wide. In (A) the source of excitations (a silver wire) was 12 mm away from the sensor and in (B) it was placed 2 mm away from the sensor gap.

Ru-catalyzed BZ reaction. The reaction was studied on a membrane filter and the geometrical distribution of excitable and non excitable regions was introduced by illumination (the experimental setup was described in Ref. 10)). We have obtained a qualitative agreement with simulations (Fig. 3). The firing numbers observed in different sensor channels confirm predictions of numerical simulations: if the source of excitations is close to the sensor gap the differences between firing numbers observed in neighboring channels are large whereas when the source of excitations is far away from the sensor the frequencies in different channels become similar.

§3. Conclusions

We have demonstrated both in numerical simulations and in experiments that by setting a proper geometrical arrangement of excitable and non excitable regions one can construct a chemical device that can recognize a distance from the source of periodic excitations as well as the wave vector of plane periodic excitations. The information is returned in a set firing numbers describing excitations in sensor channels. The width of sensor gap has the decisive role on its function. Extensive simulations¹¹⁾ have shown that in order to operate at various frequencies of incoming pulses the sensor should have a mechanism of adaptation that adjusts the gap to pulse frequency. It can be also shown¹¹⁾ that the shape of junction separating sensor channels from the environment has an important effect on the range and accuracy.

Acknowledgements

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