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Spatial Light Modulator Feedback System Configured as An Excitable Medium

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Abstract—We construct a dynamical imaging system which includes a micromirror spatial light modulator (SLM) and camera, connected in a feedback loop. This system is configured as a cellular automaton which models an excitable medium. The cells in this automaton correspond to pixels on the SLM screen, and are updated according to the Greenberg-Hastings rules [1, 2]. The cells can be excited, refractory, or quiescent. If a cell is excited, a corresponding area of the camera's detector will be illuminated. Cells will be excited if they are in a quiescent state and the intensity detected by the corresponding camera pixel is above a threshold. After firing, a cell enters a refractory period, and must wait for some number of iterations before it can fire again. Due to optical spillover, which is a characteristic of the imaging system, there is coupling between adjacent cells. This system supports spiral waves, target waves, and incoherent and synchronized firing patterns. We see patterns which display propagating fronts which coexist with global oscillations.

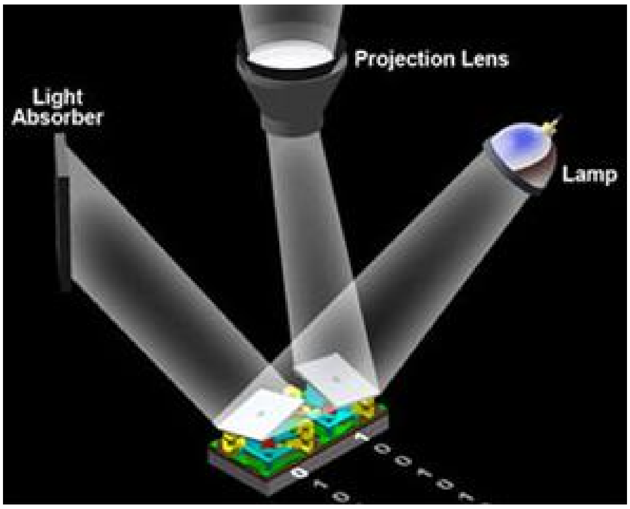


Figure 1: **Micromirror projector operation.** A light beam can be modulated by switching the micromirrors between two orientations. Image from [3].

Micromirror SLMs

Our experiments use the Pico Projector 2.0 made by Texas instruments[3]. This device uses a 480x320 array of 7.56 μm micromirrors. These mirrors can be in one of two orientations, $\pm 12°$. One of these is the "on" state, where light, which reflects light towards the projection optics, and the other is the "off" state, where light is projected toward a light absorber. In normal operation, RGB color is achieved by displaying interlaced red, green, and blue frames while the SLM is illuminated by red, green and blue LEDs. The time that a pixel spends in the "on" orientation corresponds to its intensity, so the Pico Projector achieves 60Hz 24-bit RGB color through a 1440Hz binary modulation of the micromirror array.

Greenberg-Hastings rules in an optical feedback system

The Greenberg-Hastings model is a very simplified model of an excitable medium. The medium is represented by a cellular automaton which have a state represented by an integer and are updated in discrete time. The allowed values for the state x are $x = 0, 1...m - 1$ where m is the number of states. A cell with a state $x = 0$ is resting, and $x = 1$ corresponds to the excited state. The states $2 \ldots m-1$ correspond to refractory states. An excited cell will deterministically enter a refractory state, and the transitions though the refractory states are also deterministic. When the network is updated, a cell in state $x = 1 \ldots m - 1$ will transition to $(x + 1)$ modulo m. That is, it will move to the next refractory state, or to the resting state 0 if it is in the last refractory state $m-1$. Our generalizations of this model involve the transitions from the resting state to the excited state.

In many models, the transition from 0 to 1, or the "firing" of the cell, happens either deterministically or stochastically based on the number of neighbors are excited. Thus, cells may excite their neighbors resulting in propagating activity. We couple the cells optically so that cells may excite their neighbors. We discuss two feedback systems

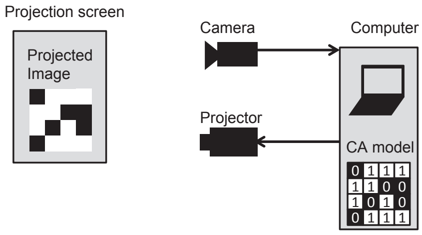


Figure 2: **Projection configuration.** A CA model is running on the computer, and coupling between the cells in this model is achieved though feedback though a projector and camera.

where cells in a numerical CA model are coupled optically.

In the first configuration, shown schematically in Figure (2), we use the Pico projector and the webcam in their "out of the box" states. The projector is arranged so that it projects an image onto a screen. The image it projects reflects the state of the CA with display pixels corresponding to cells in the CA. If a cell is excited, the corresponding pixel will be white, otherwise it will be black. Likewise, there is a mapping between camera pixels and cells in the model. Cells will fire, or make the transition from states 0 to 1 if the intensity at the corresponding camera pixel exceeds a threshold. Thus, optical coupling is achieved.

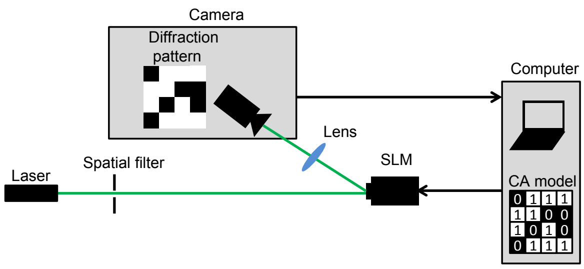


Figure 3: **Diffraction configuration.** As in the first configuration, A CA model is running on the computer, and coupling between the cells in this model is achieved though feedback with an SLM and camera.

In the second configuration, shown schematically in Figure (3), we have removed the imaging optics from webcam and the projection optics from the projector. We illuminate the micromirror array with light from a laser pointer, and a diffraction pattern is formed on the camera's detector. As before, SLM pixels and camera pixels are both mapped to specific cells in the CA model. If a cell is excited, the corresponding pixel of the SLM will direct light towards the camera, otherwise it will not. Also, like the first configuration, cells in this configuration will fire if the intensity at the corresponding camera pixel exceeds a threshold. Thus, in both configurations, the update algorithm can be summarized as follows:

- If $x_{ij}^t = 1 \ldots m-1$, $x_{ij}^{t+1} = (x_{ij}^t + 1)$ modulo m
- If $x_{ij}^t = 0$ and $I_{ij}^t > \Theta$, $x_{ij}^{t+1} = 1$
- If $x_{ij}^t = 0$ and $I_{ij}^t \leq \Theta$, $x_{ij}^{t+1} = 0$

Where x_{ij}^t is the state of pixel i, j at iteration t, I_{ij}^t is the intensity at the corresponding camera pixel at time t, and Θ is the intensity threshold. Note that I_{ij}^t is not a function of the X_{ij}^{t-1}. It takes several tenths of a second for an image to be transmitted from the camera to the computer. This introduces a time delay in the dynamics, and so I_{ij}^t is a function of $X_{ij}^{t-\tau}$, where τ is a time delay that depends on the camera settings.

Extensions

We explore some extensions of the this model. Which allow for more complex dynamics. The transitions though the refractory states remain unchanged: these extensions are modifications of the circumstances under which a cell "fires" (transitions from 0 to 1). The control software for the feedback system allows each of these extensions to be turned on an off independently. These can also be implemented in either of the feedback configurations shown in Figures (2) and (3).

Global coupling

In addition to being excited by their neighbors, cells may fire due to stimulation from the mean field. This tends to lead to global oscillatory dynamics, which can coexist with propagating wave fronts or other patterns. In each iteration, we compute $\langle I \rangle^t$, the average intensity of light falling on the camera screen. The coupling to the mean field is described by a constant ϵ_0. Cell i, j can fire if $I_{ij}^t + \epsilon_0 \langle I \rangle^t >$ exceeds a threshold. Note that ϵ_0 may be positive or negative. Positive ϵ_0 is excitatory coupling: cells are more likely to fire if there is more activity in the network. Conversely, negative ϵ_0 is inhibitory. Setting $\epsilon_0 = 0$ removes global coupling entirely.

Global Coupling with two groups

We achieve more complex dynamics by treating the cells as members of two distinct groups. The left half of the lattice is group 1, and the right half is group 2. In general one needs 4 coupling constants to describe this configuration. However, we have focused our attention on the symmetric case, in hope that some interesting asymmetry might develop. Populations of coupled oscillators can support chimera states in which coexisting synchronized and unsynchronized populations exist in spite of completely symmetric coupling [4, 5, 6]. These states have been seen in populations of populations of coupled oscillators with community structure [5]. It is possible that our system will show similar dynamics. The two population case is then described by two coupling constants ϵ_1 and ϵ_2: the coupling within groups and between groups, respectively. If the averaged intensities on the two halves of the camera screen are $\langle I \rangle_1^t$ and $\langle I \rangle_2^t$, then the conditions under which a cell can fire are:

- For cells in group 1: $I_{ij}^t + \epsilon_1 \langle I \rangle_1^t + \epsilon_2 \langle I \rangle_2^t > \Theta$
- For cells in group 2: $I_{ij}^t + \epsilon_2 \langle I \rangle_1^t + \epsilon_1 \langle I \rangle_2^t > \Theta$.

Again, positive values of ϵ are excitatory coupling and negative values of ϵ are inhibitory.

Time Delay

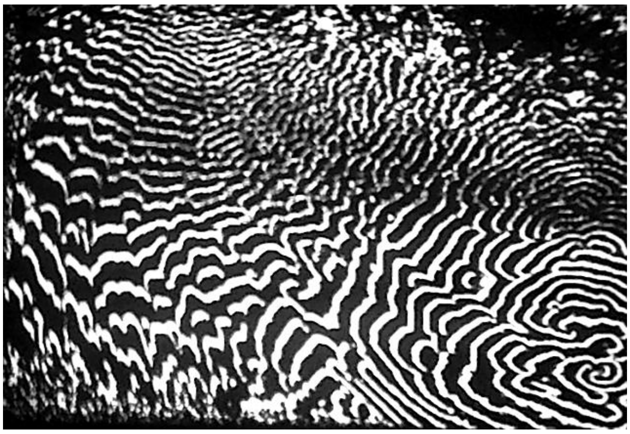
The imperfect synchronization of the SLM and the camera introduces a time delay in the dynamics. Cells are updated based not on the intensity in the previous iteration, but on the intensity which occurred several iterations earlier. This effect is difficult to remove, but easy to exaggerate. We can explore the effects of a long time delay by buffering the images recorded by the camera, and updating based on an image which occurred a proscribed number of iterations in the past. The time delay qualitatively changes the character of the patterns that form. The system often displays dynamics that are periodic with the same period as the time delay.

Stochastic firing

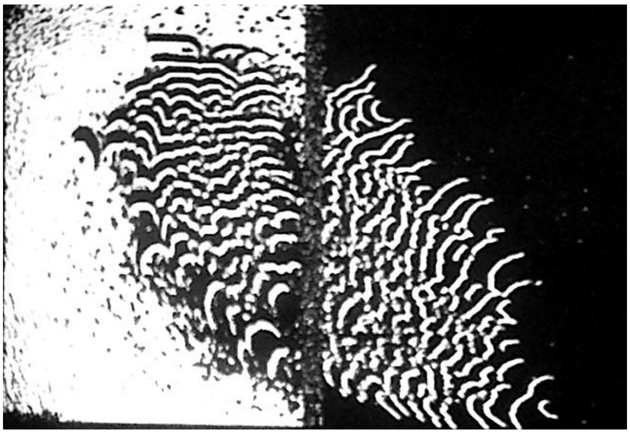
Finally, we allow cells to either spontaneously fire without stimulation with a probability p_s or to fail to fire with a probability p_f. Spontaneous firing allows the system to show activity in a regime where it is otherwise quiescent. The possibility for cells to randomly fail to fire will effect the level of synchrony observed in the presence of global coupling.

Examples

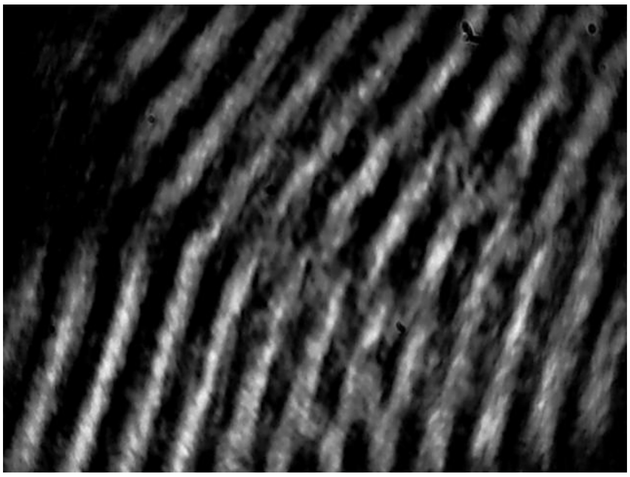
Finally, we show some examples of the kinds of dynamics that can be achieved with this system. Unless otherwise noted, all of the extensions discussed earlier are turned off. The camera aquisition parameters(Gain, exposure time, etc.) are also very important, but are kept constant while the configuration is unchanged. The correct values of these parameters is sensitive to setup and the ambient lighting conditions. Figure (4a) shows propagating wavefronts observed in the projection configuration. Small spiral patterns are also seen in the bottom-right corner. These patterns depend critically on the alignment of the camera's field of view with the projected image. Also, either the camera or projector must be defocused so that cells may be coupled to their neighbors.



(a)



(b)



(c)

Figure 4: **Examples.** (a) Propagating wavefronts in the projection configuration. $m = 5$, $\Theta = 0.2$, $p_s = 0.1$ (b) Projection configuration: Propagating wavefronts in the presence of global oscillations in a 2-group system. $m = 5$,Θ=0, p_s=0.1, ϵ_1=0.1, ϵ_2=-0.5 (c) Period-2 stripe pattern in the diffraction configuration. $m = 2$, $\Theta = .1$, $p_s = .6$, $\epsilon_0 = -0.1$

Figure (4b) shows another snapshot taken in the projection configuration. Here, the two-community structure has been imposed. There is inhibitory coupling between the left and right groups, and excitatory coupling within the groups. From this coupling, global oscillations develop. The two groups are out of phase: one group fires while the other is silent. For the given parameter values, propagating waves coexist with these global oscillations.

In the diffraction configuration, the cells are coupled over a much larger range than in the projection configuration. Global oscillations are easy to observe, but propagating wavefronts occur more rarely. When they do occur, they lack the intricate structure of the other two examples. Another kind of pattern formation can be observed, however. Figure (4c) shows a standing stripe pattern observed in the diffraction configuration. The stripes are periodic with a period of 2 iterations.

Acknowledgements

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