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Self-Organized Control for Visual Sensor Networks

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1. Introduction

A visual sensor network consisting of embedded visual sensor nodes, e.g. wireless cameras, is promising as a monitoring and surveillance system for the high visibility and the amount of information that video images provide. However, it suffers from limitations on the wireless communication capacity and the computational capacity [1]. For the limited bandwidth, an attempt to collect high-quality video data from all camera nodes to a monitoring center always fails and it results in corruption of perceived video images. Although mechanisms such as bandwidth allocation, retransmission control, and FEC (Forward Error Correction) have been proposed to maintain the quality of video images in a lightly loaded and moderately congested wireless network, they do not help much when the volume of video traffic is, for example, twice as much as the capacity of the network. Therefore, we need application-level control to regulate the amount of video traffic in addition to network-level congestion control. Furthermore, the mechanisms should be simple and light enough so that it can be easily implemented on powerless embedded nodes.

From a viewpoint of applications, not all video images are equally important. It implies that we can consider such a mechanism where the quality of video images is high at a camera node detecting a target, e.g. a suspicious person, while keeping the quality low at the other nodes to control the amount of video traffic not to exceed the network capacity [2,3]. At the same time, network-level congestion control is required to mitigate buffer overflow and packet loss caused by the heterogeneous and unbalanced video traffic. Such congestion control can be accomplished by allowing a node who has more packets in a buffer to have the higher transmission rate than other nodes [4]. Although it might be possible that a single central node determines and dictates the video quality and the transmission rate to all camera nodes, it involves the considerable control overhead in collecting the up-to-date information about the location of targets and the buffer occupancy and to disseminate the control message to all nodes. As such it works only in a small-scale network.

In this paper, we propose mechanisms of video quality control and congestion control which are scalable to the number of camera nodes and adaptive to the number, location, and velocity of targets. In our proposal, each node determines the video quality and the transmission rate based on local information that it obtains by exchanging messages with neighbors. As a consequence of mutual interaction among nodes, the globally organized application-level and network-level control emerges. That is, self-organization [5]. In a self-organizing system, the global pattern appears as a result of mutual interaction among simple agents behaving based on local information. We adopt a reaction-diffusion model [6] as the fundamental theory of self-organized control mechanisms on both of application and network levels in this paper. With our mechanisms, each node only need to evaluate the reaction-diffusion equations based on the information about itself and neighbors for video quality and congestion control.

2. Reaction-Diffusion Model

A reaction-diffusion model expresses chemical reactions of morphogens intra- and inter-cells. Alan Turing explained self-organization of periodic patterns on the surface of body of fishes and mammals by using the model [6]. A general form of a reaction-diffusion model of two virtual morphogens called activator and inhibitor is formulated by a pair of temporal differential equations as follows.

$$\begin{cases} \dfrac{\partial u}{\partial t} = F(u,v) + D_u \nabla^2 u \\ \dfrac{\partial v}{\partial t} = G(u,v) + D_v \nabla^2 v \end{cases}$$

where u and v are the concentrations of morphogens. The first term of the right-hand side is called a reaction term corresponding to chemical reactions within a cell formulated by functions F and G. The second term is called a diffusion term corresponding to chemical interactions between neighbor cells. D_u and D_v are the diffusion rates and ∇^2 is the Laplacian operator.

Depending on the form of reaction-diffusion equations and their parameters, a variety of patterns, such as stripes, maze, and spots, can be generated. In the reaction-diffusion model, the following two conditions must be satisfied to generate patterns. First, the activator activates itself and the inhibitor, whereas the inhibitor restrains itself and the activator. Second, the inhibitor diffuses faster than the activator ($D_v > D_u$). Now assume that the concentration of activator slightly increases in the field of homogeneous morphogen concentrations, the concentrations of activator and inhibitor are increased around the point by being activated by the activator. The generated inhibitor diffuses faster than the activator and restrains generation of activator at further areas. On the other hand, the activator stays at the point and the concentration of activator is kept higher than that of inhibitor. Consequently, the diversity in the concentration of activator emerges and a pattern of heterogeneous morphogen concentrations appears.

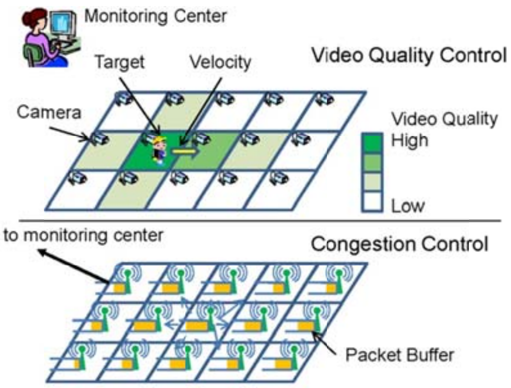

Fig. 1: Visual Sensor Network.

3. Reaction-Diffusion based Self-organized Control for Visual Sensor Network

Figure 1 illustrates our system model. Camera nodes with capability of wireless communication and motion detection are distributed in a monitored region. It is not necessary that nodes are arranged in a grid as far as a wireless network is connected where there is no isolated node, but we hereafter assume a grid layout for the ease of explanation. Each square corresponds to the area that a camera observes. A camera node can communicate with four neighbors in up, right, down, and left directions. It has a packet buffer for each of neighbors. Video images obtained by camera nodes are collected at a monitoring center, which is behind a wired connection, through multi-hop wireless communication among nodes.

Now, there is a target moving toward the right. The video quality at a camera node which has a target in its observation area must be as high as possible to have detailed video images of the target. A camera node of the neighbor area in the moving direction should provide high-quality images preparing for the future movement. Surrounding nodes also set the video quality at the moderate level, so that they can deal with the sudden and irregular movement of the target.

Consequently, we see a spatial pattern of heterogeneous distribution of video quality, i.e. a spot centered at the node detecting the target. Here, we can directly adopt the reaction-diffusion model in order to autonomously generate the spot pattern through local interaction among neighbors. Nodes maintain and calculate virtual morphogen concentrations and set the video quality in accordance with the concentrations. However we need to extend the model to have a spot spreading toward the moving direction of a target while keeping the total amount of video traffic within the wireless network capacity. In our mechanism, a node detecting a target in its observation area adds the small and constant amount of activator, called stimulus, in the reaction-diffusion equation to increase the activator concentration and generate a spot centered at the node. The stimulus propagates to neighbors and further nodes in the moving direction of a target while decreasing the amount.

As a result of the above-mentioned video quality control, there appears the concentration of video traffic on the path from the spot to the monitoring center. Then, packet losses would occur at a node on the path by exceeding the capacity of the packet buffer for the next-hop node to the monitoring center, while local buffers for the other neighbors and buffers of the other neighbors have room for more packets. Therefore, it is effective to distribute the load among local buffers and among neighbors to suppress packet loss. We can easily combine these two mechanisms by using the reaction-diffusion model. From a mechanistic viewpoint, the reaction term corresponds to local control within a node and the diffusion term realizes mutual interaction between neighbors.

We briefly explain the basic behavior of node adopting the reaction-diffusion model for video quality control and congestion control. A node monitors the buffer occupancy and the observation area by a camera. The state information is exchanged among neighbors by being embedded in a HELLO message at a regular HELLO interval. The information contains the concentrations of virtual morphogens, the amount of stimulus, and the total number of packets stored in buffers. A node evaluates two reaction-diffusion models, i.e. one for video quality control and the other for congestion control, based on the information of itself and neighbors. Equations are spatially and temporally discretized and transformed to integer arithmetic. For video quality control, the morphogen concentrations are updated and a node sets the video quality accordingly. If there is a target in the observation area, a node sets the stimulus. For congestion control, by the reaction term a node determines weights of the WRR (weighted round robin) scheduler to give more weight to a packet buffer with more packets than others and let packets leave the buffer more often. The diffusion term determines CW_{min} (the minimum of contention window) of IEEE 802.11 CSMA/CA in accordance with the relative buffer occupancy, where a node with more packets has a smaller CW_{min} and obtains more chances to find the available channel than neighbors.

4. Conclusions

In this paper, we briefly explain our idea to adopt the reaction-diffusion model to control both of video quality and congestion in a self-organized manner in visual sensor networks. Self-organization must lead to the scalability, adaptability, and robustness of the system. Although our preliminary results prove the performance of our idea, not shown for space limitation, we need to evaluate our proposal from the above aspects rather than the performance.

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