Signal Processing: *Image Communication* 28 (2013) 745–752

Contents lists available at SciVerse ScienceDirect

Signal Processing: *Image Communication*

journal homepage: www.elsevier.com/locate/image

Depth image enlargement using an evolutionary approach

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ARTICLE INFO

Article history:
Received 22 September 2012
Received in revised form
1 February 2013
Accepted 22 March 2013
Available online 30 March 2013

Keywords:
Depth map
Image enlargement
Ant colony optimization

ABSTRACT

Accurate depth map at high resolution is required in many 3D video display concepts. Given a low-resolution depth map, this paper studies how to enhance its resolution with a registered high-resolution color image. The idea of the proposed approach is that pixels with similar color values and small distances should have similar depth values. Therefore, the known depth values in input depth map can be propagated to estimate the unknown depth values of their neighboring pixels with similar color values and small distances in high-resolution depth map. Different from conventional approaches, the proposed approach utilizes the *ant colony optimization* (ACO) technique to dispatch artificial ants moving on a coupled graph, which consists of a depth map and a color image. Then these artificial ants propagate the known depth information from the observed low-resolution depth map to its up-sampled counterpart. Experimental results show that the proposed approach achieves high-resolution depth map with more desirable quality than that of several conventional approaches.

1. Introduction

The multi-view video plus depth format [1], where the video data is associated with a corresponding depth map, is one of promising techniques to provide immersive video services flexible for different types of multi-view displays. It is important to provide accurate depth information in these 3D video applications. It has been observed in [2,3] that coding of depth map at reduced resolution provides better rate-distortion performance than the utilization of full-resolution depth maps in many coding scenarios. For that, the depth map can be down-sampled at the encoder before compression to save network bandwidth. However, the down-sampled depth map is required to be up-sampled at the decoder to provide accurate depth information for synthesizing the viewpoint video.

This paper hence focuses on enhancing the resolution of a given non-ideal low-resolution depth map. For that, various depth map up-sampling approaches have been proposed in the literature, such as edge-adaptive image interpolation methods [4–9]. Their results contain errors around object boundaries, since they interpolate depth values without the consideration of color discontinuities. In view of this, many techniques have been developed to combine the low-resolution depth map with the registered high-resolution image. Diebel and Thrun [10] proposed an interpolation method using the *Markov random field* (MRF) and designed a weighting function that is adaptive according to the color image gradient. Yang et al. [11] refined the input low-resolution depth map using an iterative joint bilateral filtering scheme [12], where depth values are calculated using weights based on pixel distance and color difference. In addition, several edge-preserving functions have been proposed in [13–16], instead of using a quadratic function in the energy function.

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http://dx.doi.org/10.1016/j.image.2013.03.005

This paper proposes a new depth map enlargement approach based on the observation that the pixels with similar color values and small distances should have similar depth values. The proposed approach has two components: (i) a coupled graphical representation that consists of a depth map and a color image and (ii) an automatic way using the *ant colony optimization* (ACO) technique to propagate the known depth values in input low-resolution depth map to estimate the unknown depth values of the neighboring pixels, which have similar color values and small distances. ACO is a nature-inspired optimization algorithm [17] motivated by the natural collective foraging behavior of real-world ant colonies. It is suitable to solve the optimization problem in graph representation; it has been widely used in many image processing areas [18–25]. In the proposed approach, a coupled graph representation is first formulated, where the nodes represent the image pixels, the links among nodes are determined by the neighborhood structure used in images. Then, a number of artificial ants are dispatched to move on the graph to propagate the known depth information from the observed low-resolution depth map to its up-sampled high-resolution depth map.

The rest of this paper is organized as follows. The proposed depth map up-sampling approach is presented in Section 2. Experimental results are presented in Section 3 to compare the proposed approach with conventional approaches. Finally, Section 4 concludes this paper.

2. Proposed depth map up-sampling approach

The proposed approach consists of a coupled graph representation to model the depth map and its registered color image, and an ACO algorithm to automatically propagate the known depth information from the observed low-resolution depth map to its up-sampled counterpart. These two components are presented in next two sections, respectively.

2.1. Coupled graph representation

Since the known depth values in input depth map can be propagated to estimate the unknown depth values of their neighboring pixels, the propagation is determined by the color image in the proposed approach. In view of this, we define a coupled graph using both color and depth pixel values.

The proposed graph, as illustrated in Fig. 1, is defined as $G(V_d, V_i, E)$, where V_d and V_i are sets of vertices or nodes and E is the set of edges. The vertices (nodes), $v_d \in V_d$, are pixels in depth map (black/white pixels in Fig. 1), and the vertices (nodes), $v_i \in V_i$, are pixels in color image (gray pixels in Fig. 1), while the edges, $e \in E$ represent the connection between the nodes. The links among nodes are determined by the 4-neighborhood structure used in images. In addition, each pixel of the depth map is linked to the corresponding pixel in the color image. Based on this formulation, the ACO technique will be exploited in next section to automatically propagate the known depth information (black pixels in Fig. 1) on this coupled graph to estimate those unknown depth values (white pixels in Fig. 1).

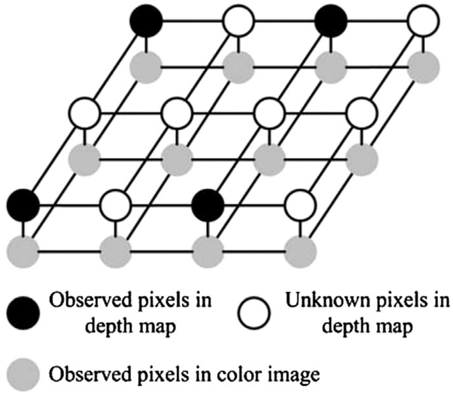

Fig. 1. The proposed coupled graph representation.

2.2. Depth map up-sampling using ACO

The idea of the proposed approach is to dispatch a number of artificial ants on the pixels (black pixels in Fig. 1), where depth values are available. Then, these artificial ants carry the depth values, move on the grid of the enlarged depth map, and deposit these color values on the pixel positions (white pixels in Fig. 1) where no depth value is available. The movements of these artificial ants are steered by local statistics of the color image; they tend to move towards neighboring pixels that have similar color values and small distances. For each pixel position with unknown depth value, it can be visited by a few artificial ants. We record the frequency that this position is visited by other artificial ants. Finally, its depth value is copied from that of the artificial ant, which visits this pixel most frequently.

More conceptually, given a function to maximize (propagation of observed depth values on a coupled graph), different solutions are examined (artificial ants exploration in the proposed graph), each of which is memorized (the frequency of visit is recorded, described in more details below) depending on its quality, and then guide the search (driven by the local statistics of color image) of the next solutions until convergence.

The procedure of the proposed approach is described in details as follows. It utilizes a number (say, K) of artificial ants to move on a graph for constructing a *pheromone* matrix, each entry of which represents the frequency of artificial ants visiting each pixel. The proposed approach starts from assigning one artificial ant on each node of the observed depth map (i.e., black nodes in Fig. 1). Furthermore, the initial value of each component of the pheromone matrix $\boldsymbol{f}^{(0)}$ is set to be a constant 1. Then the proposed algorithm runs for N iterations, in each iteration, each ant moves to neighboring nodes and the pheromone on the ant's path is updated. Finally, for each pixel that has unknown depth value, its depth value is copied from that of the artificial ant, which visits this pixel most frequently.

More specifically, at the n-th iteration, one artificial ant is randomly selected. Then, this artificial ant moves from