Aleš Leonardis
Horst Bischof
Axel Pinz (Eds.)

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9th European Conference on Computer Vision
Graz, Austria, May 2006
Proceedings, Part II

2 Part II

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Preface

These are the proceedings of the 9th European Conference on Computer Vision (ECCV 2006), the premium European conference on computer vision, held in Graz, Austria, in May 2006.

In response to our conference call, we received 811 papers, the largest number of submissions so far. Finally, 41 papers were selected for podium presentation and 151 for presentation in poster sessions (a 23.67% acceptance rate).

The double-blind reviewing process started by assigning each paper to one of the 22 area chairs, who then selected 3 reviewers for each paper. After the reviews were received, the authors were offered the possibility to provide feedback on the reviews. On the basis of the reviews and the rebuttal of the authors, the area chairs wrote the initial consolidation report for each paper. Finally, all the area chairs attended a two-day meeting in Graz, where all decisions on acceptance/rejection were made. At that meeting, the area chairs responsible for similar sub-fields thoroughly evaluated the assigned papers and discussed them in great depth. Again, all decisions were reached without the knowledge of the authors' identity. We are fully aware of the fact that reviewing is always also subjective, and that some good papers might have been overlooked; however, we tried our best to apply a fair selection process.

The conference preparation went smoothly thanks to several people. We first wish to thank the ECCV Steering Committee for entrusting us with the organization of the conference. We are grateful to the area chairs, who did a tremendous job in selecting the papers, and to more than 340 Program Committee members and 220 additional reviewers for all their professional efforts. To the organizers of the previous ECCV 2004 in Prague, Vaclav Hlaváč, Jirí Matas and Tomáš Pajdla for providing many insights, additional information, and the superb conference software. Finally, we would also like to thank the authors for contributing a large number of excellent papers to support the high standards of the ECCV conference.

Many people showed dedication and enthusiasm in the preparation of the conference. We would like to express our deepest gratitude to all the members of the involved institutes, that is, the Institute of Electrical Measurement and Measurement Signal Processing and the Institute for Computer Graphics and Vision, both at Graz University of Technology, and the Visual Cognitive Systems Laboratory at the University of Ljubljana. In particular, we would like to express our warmest thanks to Friedrich Fraundorfer for all his help (and patience) with the conference software and many other issues concerning the event, as well as Johanna Pfeifer for her great help with the organizational matters.

February 2006

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Comparison of Energy Minimization Algorithms for Highly Connected Graphs

Vladimir Kolmogorov[1] and Carsten Rother[2]

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Abstract. Algorithms for discrete energy minimization play a fundamental role for low-level vision. Known techniques include graph cuts, belief propagation (BP) and recently introduced tree-reweighted message passing (TRW). So far, the standard benchmark for their comparison has been a 4-connected grid-graph arising in pixel-labelling stereo. This minimization problem, however, has been largely solved: recent work shows that for many scenes TRW finds the global optimum. Furthermore, it is known that a 4-connected grid-graph is a poor stereo model since it does not take occlusions into account.

We propose the problem of stereo with occlusions as a new test bed for minimization algorithms. This is a more challenging graph since it has much larger connectivity, and it also serves as a better stereo model. An attractive feature of this problem is that increased connectivity does not result in increased complexity of message passing algorithms. Indeed, one contribution of this paper is to show that sophisticated implementations of BP and TRW have the same time and memory complexity as that of 4-connected grid-graph stereo.

The main conclusion of our experimental study is that for our problem graph cut outperforms both TRW and BP considerably. TRW achieves consistently a lower energy than BP. However, as connectivity increases the speed of convergence of TRW becomes slower. Unlike 4-connected grids, the difference between the energy of the best optimization method and the lower bound of TRW appears significant. This shows the hardness of the problem and motivates future research.

1 Introduction

Many early vision problems can be naturally formulated in terms of energy minimization where the energy function has the following form:

$$E(\mathbf{x}) = \sum_{p\in\mathcal{V}} D_p(x_p) + \sum_{(p,q)\in\mathcal{E}} V_{pq}(x_p, x_q) \ . \tag{1}$$

Set $\mathcal{V}$ usually corresponds to pixels; x_p denotes the label of pixel p which must belong to some finite set. For motion or stereo, the labels are disparities, while for image restoration they represent intensities. This energy is often derived in the context of Markov Random Fields [1]: unary terms D_p represent data likelihoods, and pairwise terms V_{pq} encode a prior over labellings. Energy minimization framework has been applied with great success to many vision applications such as stereo [2, 3, 4, 5, 6, 7],

A. Leonardis, H. Bischof, and A. Pinz (Eds.): ECCV 2006, Part II, LNCS 3952, pp. 1–15, 2006.

image restoration [2], image segmentation [8], texture synthesis [9]. Algorithms for minimizing energy E are therefore of fundamental importance in vision. In this paper we consider three different algorithms: Graph Cut, belief propagation (BP) and tree-reweighted message passing (TRW). For the problem of stereo matching these methods are among the best performing optimization techniques [10]. A comparison of their advantages and disadvantages is at the end of this section.

So far, comparison studies of these optimization methods have been rather limited in the sense that they only consider energy functions with a particular graph structure [11, 12, 13, 14]. The algorithms have been tested on the energy function arising in stereo matching problem [2]. This energy is defined on a graph with a 4-neighborhood system, where nodes correspond to pixels in the left image. Occlusion are not modeled since this gives a more complex and highly connected graph structure. The comparison studies consistently concluded that the lowest energy is obtained by TRW, graph cuts come second and BP comes third [11, 12, 13, 14]. Very recently, it has been shown [13] that TRW even achieves the global optimum for standard benchmark stereo pairs [10]. Consequently, this problem, which was considered to be very challenging a decade ago, has now largely been solved. The comparison studies also showed that the proposed energy gives large error statistics compared with state-of-the art methods, and consequently progress in this field can only be achieved by improving the energy formulation itself, as stated in [11, 13].

The main goal of this paper is to test how different optimization methods perform on graphs with larger connectivity. Our study has two motivations. First, such energy functions are becoming increasingly important in vision [3, 4, 5, 6, 7, 15]. They typically arise when we need to match two images while imposing regularization on the deformation field. Pixels (or features) in one image can potentially match to many pixels (features) in the other image, which yields a highly connected graph structure.

Our second motivation is to understand better intrinsic properties of different algorithms. One way to achieve this is to consider a very difficult problem: Algorithm's weaknesses then become more apparent, which may suggest ways of improving the method. It is known that the presence of short cycles in the graph makes the problem harder for message passing techniques. From this point of view, the problem that we are considering is much more challenging than 4-connected grid graphs. Another indicator of the difficulty of our problem will be shown by our experiments.

We choose the energy function arising in the problem of stereo with occlusions [4]. In this case there are nodes corresponding to pixels in the left and right image, and each node has $K + 4$ neighbors where K is the number of disparities. We propose this problem as a new challenging test bed for minimization algorithms. Our experiments also show that modeling occlusions gives a significantly better stereo model, since the energy of the ground truth is close to the energy of the best optimization method, and the value of the energy correlates with the error statistics derived from ground truth.

When applying BP or TRW to this energy, we immediately run into efficiency problems. There are K labels and $O(NK)$ edges, so a straightforward implementation would take $O(NK^2)$ memory and time for one iteration, even with the distance transform technique in [16]. By exploiting a special structure of the energy we show that