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Relaxation in 4D state space – A competitive network approach to object-related velocity vector-field correction

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Abstract

A standard principle of (energy-)minimization is applied to the problem of visual motion analysis. In contrast to well-known mathematical optimization procedures and universal optimizing networks it is proposed to use a problem-adapted network architecture. Owing to the bilocal coincidence-type motion detector considered here the task of object-related motion analysis appears as a geometric correspondence problem. Hence, the correct spatio-temporal correspondences between elements in consecutive images must be selected from all possible ones. This is performed by neighbourhood operations that are repeatedly applied to the instantaneous signal representation in the space/velocity-domain until an estimate of the actual flow-field is reached.

1. INTRODUCTION

Per definition, any elementary measurement of velocity $\vec{v} = \mathrm{d}\vec{r}/\mathrm{d}t \approx \Delta\vec{r}/\Delta t$ means a local operation. Consequently, motion in 2D images, e.g. projections of 3D scenes, is often represented as dynamic velocity vector-fields $\vec{v}(\vec{r}, t)$. It is a basic fact that – without knowledge of (static) properties, such as shape (e.g. curvature), illumination and reflectance of the moving parts of an image – local velocity measurements do not suffice to characterize their motion [1, 2, 3, 4]. Although form analysis principally may precede the measurements of velocity the proposed concept deals with *a posteriori* corrections of the raw vector-field. Most problems associated with this concept are theoretically well-understood and various so-called computational approaches – essentially algorithmic minimization procedures applied to suitably constrained integral expressions – have been proposed [for a survey see 5]. However, object-related network approaches – other than the resistive network proposed by Wang et al. [6] – are lacking.

The concept introduced here is based on a constraint-defining type of network which turned out to be structurally related to the one Marr and Poggio [7] proposed for the computation of stereo disparity. It is object-related and thus there are no problems with the proper choice of integration areas as in [8] and it shows motion bias [9]. In spite of local operations which imply spatially confined network interconnections, it propagates velocity estimates into object regions where reliable measurements are not feasible. Unlike most approaches, the concept permits the computation of more than a single velocity vector at any location, a property which is requisite for the explanation of 'motion transparency' and the associated aftereffects [10, 11]. In contrast to cooperative resistive networks [6] it uses excitatory and inhibitory interactions and thus it must be termed spatially competitive.

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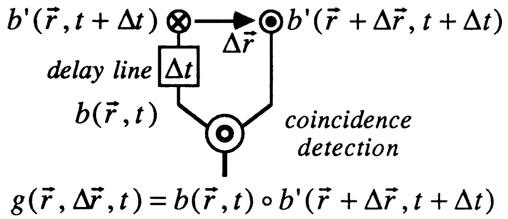
2. SIGNAL REPRESENTATION IN 4D STATE SPACE

Instead of using elementary velocity *measurements*, e.g. according to the so-called gradient scheme, spatio-temporal correspondence *detection* is applied at the frontend: According to psychophysical evidence [10, 12] ensembles of spatio-temporal coincidence detectors, i.e., velocity-tuned versions [13] of Hassenstein/Reichardt-subunits [14], with constant delay Δt but various spans Δr (see Figure 1) and direction angles, are assumed at every location of the pictorial representation. Though the latter in principle may contain form features, such as oriented edges, non-oriented contrast measures and thus minimal information are considered here. Such an arrangement of detector ensembles indicates all grey-value correspondences (velocity spectrum) at every element (pixel) of the 2D representation, as depicted for pixel 'D' of the rigidly displaced 2D object in the insert of Figure 2. Hence, pictorial correspondences are binary (coincidence/no coincidence) signals $g(\vec{r}, \vec{v}, t)$ in the 4D space/velocity-domain. Any *retinotopic* projection of this 4D state space onto a 2D surface will result in velocity-vector hypercolumns.

Figure 1. Detector for spatio-temporal coincidences tuned to the velocity $\vec{v} = \Delta\vec{r}/\Delta t$



3. NETWORK ARCHITECTURE FOR THE VECTOR-FIELD CORRECTION

For the 4D representation defined above, the correction of velocity vector-fields consists in the selection of appropriate vectors from every velocity spectrum. In order to change this ill-posed problem into a better defined one, it is usually assumed that the true velocity vectors at neighbouring pixels are identical (constraint 1) or at least similar (constraint 2). Hence, the idea is to discard all those vectors of every velocity spectrum that are not common or that are sufficiently dissimilar to spectra at the surrounding pixels, and to continue until a qualitatively or temporally defined criterion has been met. This relaxation process can be performed by networks in which summation/threshold-units stand for points in the 4D state space – each for a specific velocity vector at a certain pixel.

Constraint (1) applies perfectly to rigid objects that translate in isolation. The corresponding network is of the conjunctive type: A unit's threshold is surpassed, i.e., its velocity vector survives, only if the same vector is present at *all* its activated neighbouring pixels. This strict regime is of little value if arbitrary motion is to be locally approximated by translations. Thus, a more flexible network implementation (constraint 2) is considered: Every unit selectively excites its neighbours of the same or a similar vector specification and inhibits units of vectorially neighbouring velocities at the proper pixel. For a retinotopic representation, this scheme results in (velocity-)specific *inter*columnar excitation and in (patchy) *intra*columnar inhibition which are known from the cortical area 17 [15]. Figure 2 exemplifies this relaxation approach for the shifted object which is shown in the insert. The smallest isotropic excitatory $w_{exc}(\vec{r})$ and inhibitory $w_{inh}(\vec{v})$ correlation subkernels (receptive subfields) are applied. They are shown for one unit at pixel 'G' only. For all pixels, stable velocity estimates are reached after $n=4$ relaxation steps in this temporally discrete simulation. The two vectors at pixel 'F' nicely demonstrate the feasibility of (in this case incorrectly) coexisting correspondences – a property which is due to less strict constraint (2). In this example, the constant threshold θ of the computing units equals the coincidence value and all coupling strengths are the same $|w_{exc}| = |w_{inh}| = \varepsilon$. The choice of the latter is not critical as long as the condition $|\varepsilon| < 1/(m-1)$ is met, where m is the number of pixels of the excitatory subkernel.

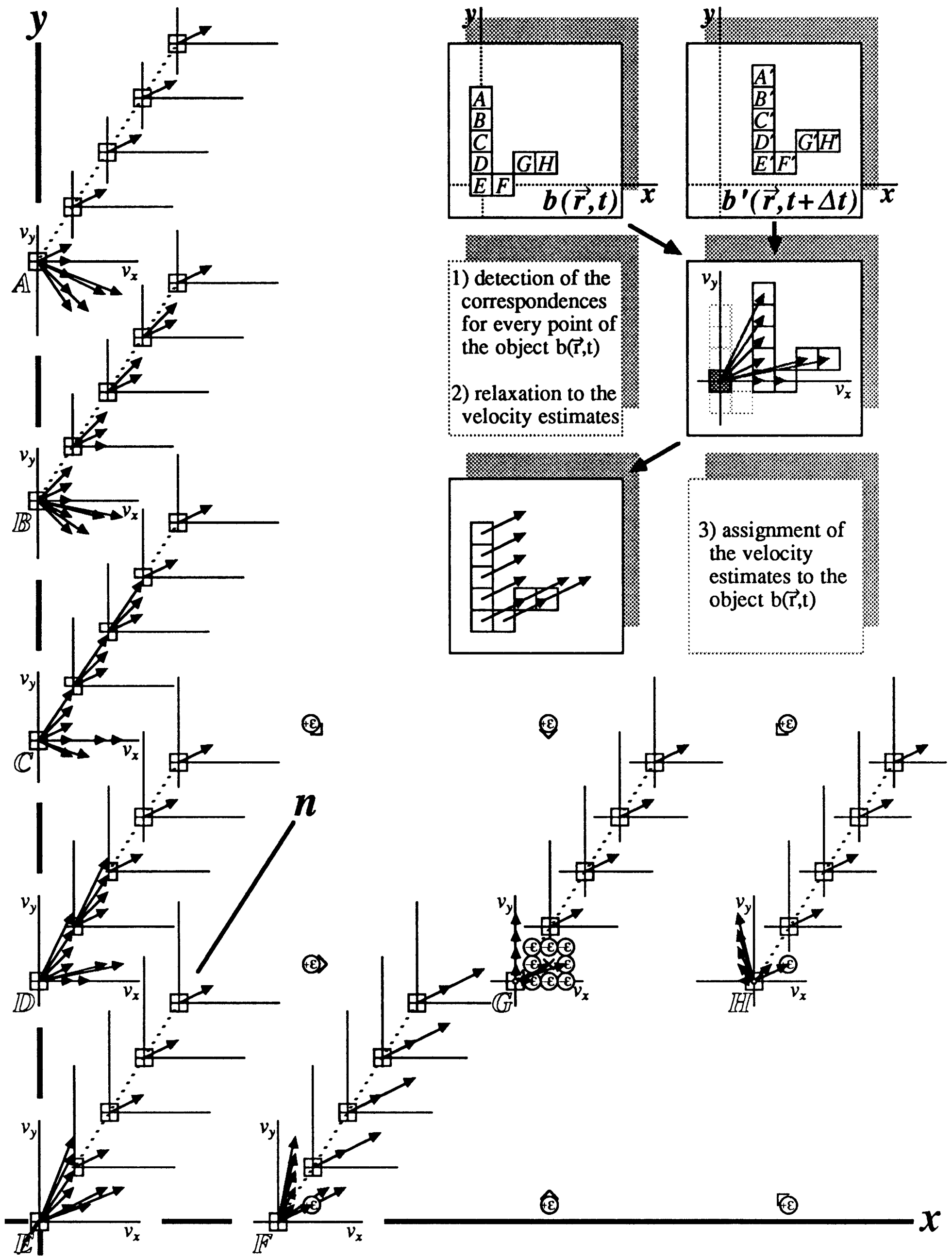


Figure 2. Relaxation in a planar 'hypercolumnar' representation of the 4D space/velocity-domain. The insert illustrates the idea of local velocity estimation. The 'receptive field' (4D correlation kernel) of the 'hypercolumnar' units is displayed for one unit at location 'G' only. After a fast increase in velocity vector-selectivity at points of high pattern curvature a stable result is reached after n=4 relaxation steps

4. DISCUSSION

It can be proven that in the case of rigid and planar objects which are separately translating the correct correspondences must survive if complementary subfields $w_{exc}(\vec{r}) = -w_{inh}(\vec{v})$ are used. However, and in contrast to constraint (1), additional and wrong correspondences may survive – especially with objects showing large unstructured regions. A higher degree of flexibility with respect to arbitrary motion can be obtained by interconnection schemes that either incorporate motion type-specific excitatory interconnections, or that comply better with deviations from the exact translatory correspondences by means of less specific excitation. While the former method leads to a combinatorial explosion of receptive-field types the latter results in an even higher percentage of wrong correspondences. Owing to constraint (2), which relies on smoothly varying vector fields, any discontinuity caused by directly neighbouring objects of different velocities, e.g. static background, disturbs the local velocity estimation, but – within limits – compliance can be traded in for a loss of correctness in cases of pure translations. For continuous motion, the excitation gives rise to motion bias [9], i.e., objects enter selectively sensitized regions thus accelerating and improving the relaxation.

More generally, the relaxation process can be formulated as a 4D correlation with a speed-variant kernel function $w(\vec{r}/cv, \vec{v}/cv)$ – e.g., a (not necessarily isotropic) Gaussian function – which is followed by a (sigmoidal) nonlinear transfer characteristic $\mathcal{S}$

$$g_{i+1}(\vec{r}, \vec{v}) = \mathcal{S}\{g_i(\vec{r}, \vec{v}) \ \underline{\text{corr}}\ w(\vec{r}/cv, \vec{v}/cv)\},$$ where c denotes a constant.

Finally, simulations suffer less from the restrictions due to constraint (2) if the relaxation process is restarted whenever the first units get near the saturation level of function $\mathcal{S}$. Such *temporally* competitive processing better copes with various kinds of motion discontinuities.

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