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Recovering 3D-Shape From Motion Stereo Under Non-Uniform Illumination-A vision system for mobile robot carrying an illumination source-

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Abstract

A reliable and precise estimation of optic flow is important for recovering 3D-shape in motion stereo[1),2)]. In actual scene analysis, however, the influence of non-ideal conditions[3),4)] should be taken into account. In this paper, we adopt an extended constraint equation for determining under non-uniform illumination. We try to recover 3D-shape from an image sequence under non-uniform illumination by introducing additional constraint equations of anisotropic constancies in optic flow and creation rate of brightness. We also propose a new concept of vision system for mobile robot carrying an illumination source in the night.

1 Introduction

Several approaches[5),6)] recovering 3D-shape from an image sequence have been proposed. One of these approaches is motion stereo. The approach is based on determining optic flow[7),8)] caused by relative motion between a TV camera and static scene. A reliable and precise estimation of optic flow is important for recovering 3D-shape. In the actual scene analysis, however, the influence of non-ideal conditions such as non-uniform illumination, occlusions and non-rigid motion of object should be taken into account. In this paper, we discuss several problems in the estimation of optic flow, and propose a vision system for mobile robot carrying an illumination source in the drak environment. A proposal to extend the gradient-based method is tested to estimate the optic flow. We also propose additional constraint equations to determine optic flow field under non-uniform illumination. The effectiveness of the proposed method is confirmed by (using) artificial and real image sequences.

2 Theory

2.1 Extended constraint equation

An extended constraint equation[9)] is derived from a conservation law of total brightness in a fixed small region δS as illustrated in Figure 1.

$$\frac{\partial}{\partial t}\int_{\delta S} f dS = -\oint_{\delta C} f\boldsymbol{v}\cdot\boldsymbol{n} dC + \int_{\delta S}\phi dS, \qquad (1)$$

where $f(x,y,t)$ is a spatio-temporal brightness distribution of a sequential image, δS is a fixed local observation area, δC is the contour surrounding of δS, $\boldsymbol{v} = (v_x, v_y)$ is optic flow (motion vector) to be determined, $\boldsymbol{n}$ is the unit normal vector to δC which pointing outwards, and ϕ is the rate of creation (or annihilation) of brightness at a pixel in δS. The creation term includes increasing or decreasing brightness on the image plane under non-uniform illumination. Since the integration along δC can be transformed into an integration over δS by Gauss's divergence theorem, the following equation can be obtained in two-dimension:

$$\frac{\partial}{\partial t}\int_{\delta S} f dS = -\int_{\delta S}\mathrm{div}(f\boldsymbol{v}) dS + \int_{\delta S}\phi dS. \qquad (2)$$

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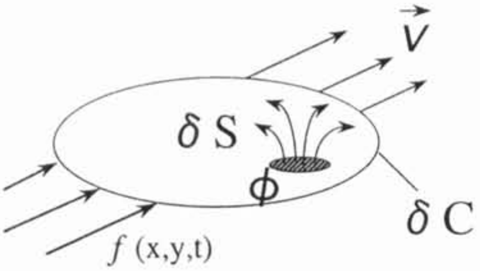

Figure 1: A schematic representation of parameters for the conservation equation.

The area δS for integral calculus is common for all terms and a differential formula of Eq.(2) is obtained as follows:

$$\frac{\partial f}{\partial t} = -f\mathrm{div}(\boldsymbol{v}) - \boldsymbol{v}\cdot\mathrm{grad}(f) + \phi. \qquad (3)$$

Under the assumption $\mathrm{div}(\boldsymbol{v})=0$ and $\phi=0$, Eq.(3) coincides with the basic constraint equation of the gradient-based method (e.g.Horn and Schunk,1981). In this study we adopt the following relationship for determining optic flow:

$$\frac{\partial f}{\partial t} = -\boldsymbol{v}\cdot\mathrm{grad}(f) + \phi. \qquad (4)$$

This relationship is deduced from Eq.(3) under the assumption of $\mathrm{div}(\boldsymbol{v})=0$. This assumption requires a rigid object motion perpendicular to camera optical-axis. Since the conservation equation contains the creation term of brightness, it is possible to manipulate the effect of non-uniform illumination. Namely, the conservation equation(Eq.(4)) can be applied to recover 3D-shape from a sequential image under these conditions.

2.2 Vision model for a robot carrying an illumination source

The parameter ϕ represents the effect of the non-uniform illumination. However, it seems difficult to determine spatio-temporal characteristics of $\phi(x,y,t)$ directly. Nomura[10] et al.(1995) introduced an assumption of separability of non-uniform illumination. According to their method we assume that the actual brightness distribution $f(x,y,t)$ is

$$f(x,y,t) = r(x,y,t)\cdot g(x,y,t), \qquad (5)$$

where $g(x,y,t)$ is a virtual brightness distribution under uniform illumination (or a normalized reflectance map). The $r(x,y,t)$ is the effect of non-uniform illumination(spatially and temporally). The relationship is substituted in Eq.(4). We obtain

$$\frac{\partial(rg)}{\partial t} = -\boldsymbol{v}\cdot\mathrm{grad}(rg) + \phi. \qquad (6)$$

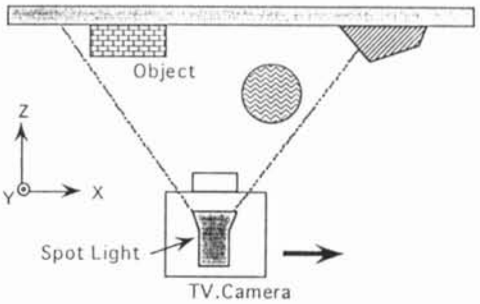

Figure 2: A model of mobile robot carrying an illumination source in the dark environment

Expansion of the left side of Eq.(6) for rg yields

$$g\left\{\frac{\partial r}{\partial t} + \boldsymbol{v}\cdot\mathrm{grad}(r)\right\} + r\left\{\frac{\partial g}{\partial t} + \boldsymbol{v}\cdot\mathrm{grad}(g)\right\} = \phi. \quad (7)$$

We can assume that $g(x,y,t)$ obeys the equation

$$\frac{\partial g}{\partial t} + \boldsymbol{v}\cdot\mathrm{grad}(g) = 0. \qquad (8)$$

Then we obtain the relationship

$$g\left\{\frac{\partial r}{\partial t} + \boldsymbol{v}\cdot\mathrm{grad}(r)\right\} = \phi. \qquad (9)$$

For, only spatially non-uniform illumination (constant with respect to time), ϕ is expressed as

$$\phi(x,y) = g\{\boldsymbol{v}\cdot\mathrm{grad}(r)\} = f\boldsymbol{v}\cdot\mathrm{grad}(r)/r. \qquad (10)$$

Here, they introduced a vector $\boldsymbol{p}=\mathrm{grad}(r)/r$. The Eq.(10) is written by

$$\phi = f\boldsymbol{v}\cdot\boldsymbol{p} = f|\boldsymbol{v}||\boldsymbol{p}|\cos\alpha = f\sqrt{{v_x}^2 + {v_y}^2}|\boldsymbol{p}|\cos\alpha, \qquad (11)$$

where α is the angle between $\boldsymbol{v}$ and $\boldsymbol{p}$. The term $\boldsymbol{v} = (v_x, v_y)$, $\boldsymbol{p}$ and α in Eq.(11) are also constant with respect to time. If the symbol is used as an unknown constant, Eq.(11) is rewritten as

$$\phi(x,y) = fq\sqrt{{v_x}^2 + {v_y}^2} \qquad (\text{where} \quad q = |\boldsymbol{v}|\cos\alpha). \qquad (12)$$

Finally, we obtain the constraint equation

$$\frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\mathrm{grad}(f) = fq\sqrt{{v_x}^2 + {v_y}^2} \qquad (13)$$

Here, we adopt Eq.(13) and try to recover 3D-shape under non-uniform illumination as shown in Figure 2. In the model a mobile robot, carrying an illumination source, has a translational motion with constant velocity. This system can be expected to recover 3D-shape of object in the dark place and in the night. The usefulness of the proposed method is demonstrated by applying the method to real image sequence in the following section.

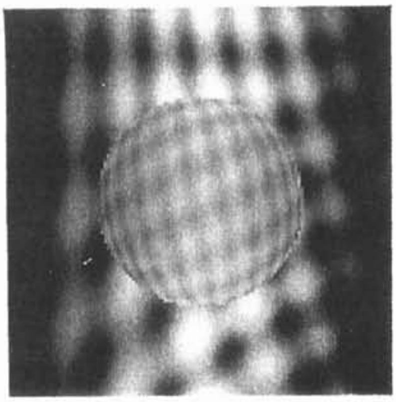

Figure 3: Simulation image sequence of a spherical ball under non-uniform illumination.

2.3 Additional constraint equations

While Eq.(13) contains three unknown variables, $\boldsymbol{v} = (v_x, v_y)$ and q, we have only one constraint equation at a point in sequential images. More than two additional constraint equations[11),12)] for $\boldsymbol{v}$ and q are necessary to obtain a full solution. We propose an assumption that optic flow is constant with respect to time and space in a local volume of $\delta S \times \delta t$ as the following relationship:

$$\left\{ \begin{array}{l} q = \text{const} \\ v_x = \text{const} \\ v_y = \text{const.} \end{array} \right. \tag{14}$$

As described in Eq.(12), we assume that illumination is spatially non-uniform and constant with respect to time. Considering this assumption a longitudinal local volume of 3×3 pixels area and 8 frames are adopted as an anisotropic neighbor. Then, optic flow $\boldsymbol{v}$ and the unknown constant q are determined by minimizing the following error function with the non-liner least squares method(for example the $Newton - Raphson\ method$):

$$E = \sum_{\delta x}\sum_{\delta y}\sum_{\delta t}\left(\frac{\partial f}{\partial t} + v_x\frac{\partial f}{\partial x} + v_y\frac{\partial f}{\partial y} - fq\sqrt{{v_x}^2 + {v_y}^2}\right)^2. \tag{15}$$

3 Simulation image analysis

Figure 3 shows a snap shot of simulation image sequence under non-uniform illumination. The image sequence corresponds to the proposed model, Fig.2, of a mobile robot carring an illumination source. Consequently, a sphere ball and a wall are moving with different velocity in the scene. In Figure 4 and Figure 5, the results of analysis are presented. Result of 3D-shape recovery obtained by the conventional method(ϕ=div($\boldsymbol{v}$)=0) is shown in Figure 4. There are serious errors especially at the both end of high illumination-gradient place. On the other hand, using the proposed method($\phi = \phi(x, y)$), 3D-shape is well recovered as shown in Figure 5.

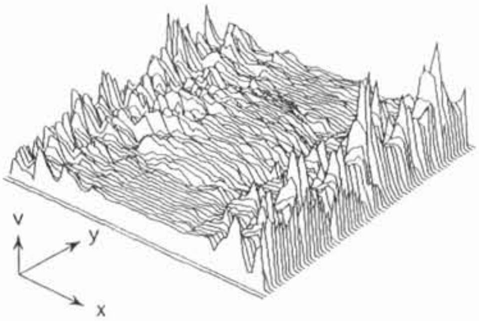

Figure 4: 3D-shape recovered by the conventional method.

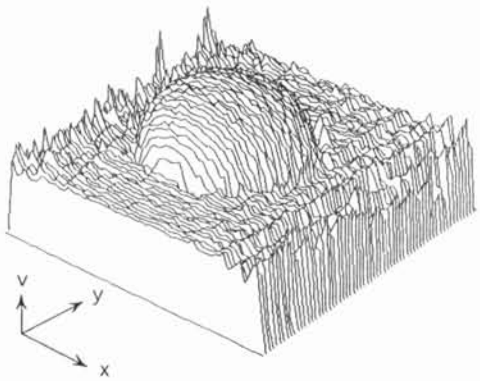

Figure 5: 3D-shape recovered by the proposed model (see Eq.(15)).

Figure 6: Actual image sequence of under non-uniform illumination.

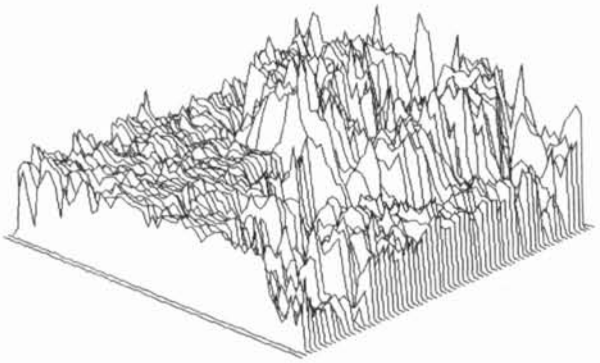

Figure 7: 3D-shape in actual scene recovered by the conventional method.

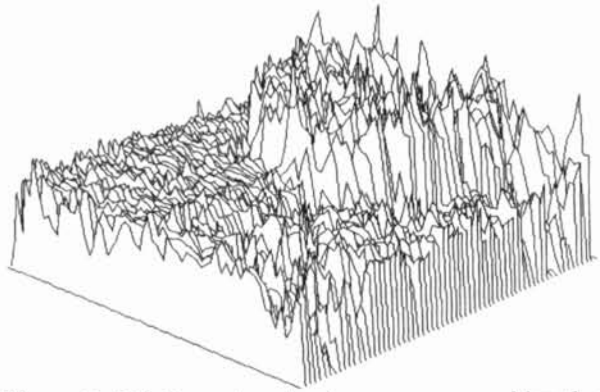

Figure 8: 3D-shape in actual scene recovered by the proposed model (see Eq.(15)).

4 Actual scene analysis

In this section, the usefulness of the proposed method is tested for a real image sequence. Figure 6 shows a snap shot of actual image sequence acquired by our system, originally developed. A sphere ball and a wall are moving with different velocity and lighted by illumination source on a TV camera. Apparently, spatially non-uniform illumination is observed nearby center of the scene. A dynamic scene is acquired by a computer system having TV camera with sampling frequency of 30 Hz. The brightness is digitized into 256 steps (gray levels). Figure 7 shows the result of analysis by the conventional method. Edge and shape of the ball are not clear. On the other hand, using the proposed method, the result is improved as shown in Figure 8.

5 Conclusion

In this paper, a model for determining optic-flow from image sequence under spatially non-uniform illumination is tested to recover 3D-shape. We propose a new concept of vision system for a mobile robot carrying an illumination source. For this purpose, constancies of optic flow and creation rate of brightness are assumed in an anisotropic volume of local spatio-temporal neighbor. The usefulness of the proposed methods is confirmed by applying the model to an artifical and real image sequence.

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