JOSA COMMUNICATIONS

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Extracting object motion during observer motion: combining constraints from optic flow and binocular disparity

Phillip J. Kellman

Department of Psychology, University of California, Los Angeles, Los Angeles, California 90024

Mary K. Kaiser

NASA Ames Research Center, MS 262-2, Moffett Field, California 94035

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Detection of object motion by moving observers and perception of velocity by stationary or moving observers ordinarily require information about object distance. It might be expected that object motion could be obtained without distance by use of a combination of optic flow and binocular disparity information. We describe how object motion could, in principle, be derived this way. The analysis also permits recovery of target distance. Finally, information about the observer's motion may be obtained in a similar fashion, assuming the existence of two stationary environmental points at an unknown distance. Although studies of human observers have not been completed, it appears that these informational variables are available under conditions in which observers perform well at detecting motion and stability. In particular, the information may help to explain why a visible surface in near space facilitates accurate perception.

1. INTRODUCTION

When a moving observer views a scene, the motion or stability of an object in the environment may be indeterminate. The indeterminacy involves the component of the object's motion parallel to the observer's motion. The optical change registered at the observer's retina is a vector sum of the optical changes produced by the object's motion and the observer's motion. A given optical change may be due to a stationary object at a particular distance, to a closer object moving in the same direction as the observer, or to a farther object moving in the direction opposite the observer (see Fig. 1). Gogel independently[1,2] and with Tietz,[3] described the geometry of this situation and studied perceptual performance in it. In their experiments absolute distance information determines motion perception, with misperceptions of distance (or experimentally altered distance information) giving rise to illusions of motion or stability.[1,3] The dependence, geometric and perceptual, of motion on distance led Gogel to conclude that "all motion perception involves distance perception."[1]

Besides motion detection by moving observers, velocity perception involves a similar constancy problem for both moving and stationary observers. In the absence of distance information the optical changes given to the observer may be consistent with the rapid movement of a faraway target or the slower movement of a nearer one.

There are exceptions to the requirement that moving observers must utilize absolute distance information. Absence of motion may be detectable when an object rests on a stationary ground surface that is continuously visible between the observer and the object. Also, there are cases in which object motion may be detectable from a combination of occlusion relations and optical velocities among visible points.[4] Such conditions are not always present in ordinary viewing, and these sources of information offer little information about velocity.

It might be expected that target motion could be extracted from some combination of optic flow and binocular disparity information. In this Communication we show how this extraction could occur, permitting detection of both target motion and absolute distance.

2. OPTIC FLOW AND BINOCULAR DISPARITY

Both optical change during observer motion and binocular (horizontal) disparity involve constancy problems. Depending on distance, a given optical change could arise from either a stationary or a moving target. Likewise, the disparity signaled by a given depth interval depends on its distance from the observer.[5] Disparity information thus cannot directly supply absolute target distance to resolve the ambiguity of motion and stability during observer motion. By combining disparity and optical change information, however, we can determine target motion.

Consider an observer viewing two points of a target object, p1 and p2, at different distances from the ob-

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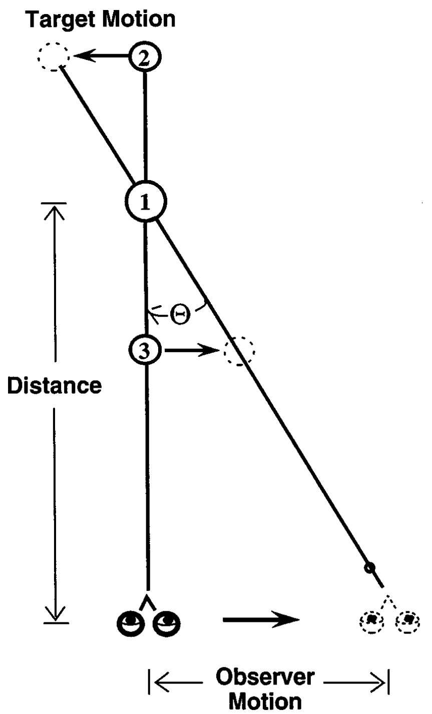

Fig. 1. Geometry of optical change during observer motion. A given optical change (Θ) may arise from a stationary target at position 1 or from moving targets at other distances, including positions 2 and 3. See text.

server. Assume that the observer does not have information about target distance. From a single viewing position the depth difference (d) between p1 and p2 gives rise to a binocular disparity (γ).[6] Assume that the observer translates laterally, as in Fig. 2. This provides an angular change Θ for the nearer point and α for the farther point. Let M be the observer motion; D, the distance to the nearer point; and I, the interocular distance. For the initial analysis we assume that the observer has information about the extent of his or her motion and about the interocular distance. (Below we suggest a way of recovering the observer's motion in cases in which it is not directly available.) The observer's problem is to determine T, the extent of target motion parallel to the observer.

As shown in Fig. 2, the relation among observer motion, target motion, and distance for the nearer point p1 is given by

$$1/D = 2\tan(\Theta/2)/(M - T). \tag{1}$$

Subtracting the similar equation for the farther target point p2 in Fig. 2 gives

$$1/D - 1/(D + d) = 2[\tan(\Theta/2) - \tan(\alpha/2)]/(M - T). \tag{2}$$

The geometry for determining binocular disparity (γ) is similar. Using the small-angle approximation, we obtain

$$1/D - 1/(D + d) = \gamma/I. \tag{3}$$

Combining Eqs. (2) and (3) yields an expression for the extent of target motion T:

$$T = M - \{2[\tan(\Theta/2) - \tan(\alpha/2)]I/\gamma\}. \tag{4}$$

Target motion parallel to the observer can thus be derived from three optical variables available to the observer (Θ, α, and γ), from the interocular distance (assumed to be available to the subject), and from information about the extent of observer motion.[7] In the case of a knowledgable stationary observer (M is known to be 0), the velocity of the target depends only on the disparity, the angular change of the two points, and the interocular distance, all plausibly available to the observer.

Distance can be derived from the optical variables and from I by use of

$$D = [(1 - \tan(\alpha/2)/\tan(\Theta/2)]I/\gamma. \tag{5}$$

Detection of the absolute distance to some point in the field potentially permits the calibration of all the disparities as absolute-depth intervals.[6]

3. RECOVERING OBSERVER MOTION DURING VEHICULAR MOTION

A limitation of this information for a moving observer is that it requires an estimate of M, the observer's motion. Under conditions of active motion it is often realistic to assume that such information is available,[1,8] but passive (e.g., vehicular) motion is more problematic. As a practical matter, there are important contexts in which direct information about vehicular velocity is negligible, including aircraft landings during the day or at night, nighttime taxiing, and night driving.

It may be possible to compute observer motion in such cases by means of one, often plausible, assumption. Assume that, besides the two target points (which may or

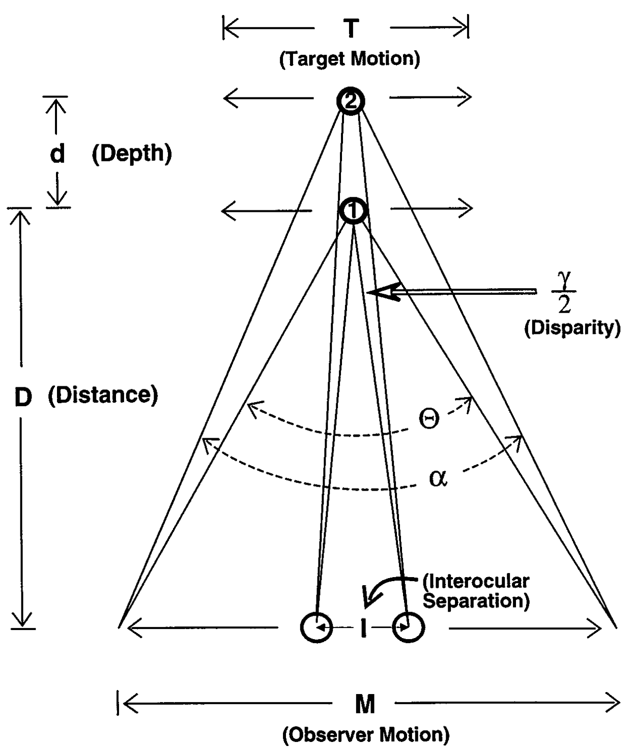

Fig. 2. Optical change and binocular disparity during observer motion. See text.

may not be moving), there are two points visible on a portion of the ground surface, of another surface, and that they are fixed in space. It is not necessary for the observer to know how far away this surface patch is; it is only necessary that it be stationary. Using the disparity for the two points on the stationary patch and their optical change during the observer's motion, one can derive the extent of observer motion from the relationship in Eq. (4) by solving for M with $T = 0$. M can then be used to solve for the target motion of the original two points.

This kind of bootstrapping provides a possible way of using information from a stable ground surface in perception. Assigning the ground surface as stationary might itself be based on certain optical variables, such as the absence of relative shear of its texture elements and its relatively large extent. Finding a stationary ground patch (or other stationary reference) thus itself requires information (or an assumption), but the information may be different from and more readily available than other information that would otherwise be needed to solve the target motion problem.

Informal observation suggests that a visible ground surface does reduce illusions of motion during passive observer motion. For example, isolated taxiway lights often produce illusory motions during nighttime taxiing in an aircraft, but not during daylight operations. More formal empirical studies on the role of a visible ground surface, as well as on the sources of information about target motion, stability, and distance described above, are needed to determine the degree to which human observers utilize these relationships.

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Requests for reprints should be addressed to P. Kellman, Department of Psychology, University of California, Los Angeles, Franz Hall, 405 Hilgard Avenue, Los Angeles California 90024–1563.

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6. For simplicity we ignore both the information and the noise given by changes in disparity that are due to the subject's lateral motion. The disparity value used in this analysis is given at the observer's position when the line of sight connects the two points and is perpendicular to the subject's motion. This value will be the maximum disparity of any position in the observer's motion.
7. For ease of exposition we have described the case in which the target lies along the perpendicular to the observer's movement that intersects the midpoint of the movement path. For the more general case in which the target lies at some angle β away from this perpendicular, both the optical change given by $M - T$ and the disparity (γ) are reduced. The exact equations are cumbersome but are well approximated by multiplication of the expressions for γ, $\tan(\Theta/2)$, and $\tan(\alpha/2)$ by $\cos^2 \beta$. Equation (1) becomes

$$1/D = 2 \tan(\Theta/2)/[(M - T)\cos^2 \beta], \tag{6}$$

where D remains the perpendicular distance from the observer's motion path (or its linear extension) to the point p1. (The actual distance to the point becomes $D/\cos B$.) The $\cos^2 \beta$ term then appears in the denominators of the right-hand sides of both Eqs. (2) and (3) and in the numerator of Eq. (5). It drops out when Eqs. (2) and (3) are combined, leaving Eq. (4) as given in the text.
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