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Walking on Tiles

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Abstract. It is shown that a tiled floor provides continuous stabilizing visual information against stumbling and falling while walking. A steady walk, eyes at a nearly constant height, maintains a certain level of net optical flow in a tile's image. A stumble generates a disturbance in the net flow, which is fed back as a corrective signal to the limbs. This may explain why people with certain motoric disorders, such as those associated with Parkinson's disease, appear to be more comfortable walking on tiled floors than on untiled ones.

Key words: Parkinson's disease, visual feedback, optical flow

Certain neurological disorders, such as those associated with Parkinson's disease, are known to cause both motoric and visual impairments [1–8]. It has been noted that while people with such disorders have distorted visual feedback effects [3, 4], they are more dependent on such feedback than healthy people [2]. It has been observed that Parkinson patients show an improvement in their walking abilities when put on a floor with highly visible tiles. A famous book [9] and its motion picture version "Awakenings" tell the story of a doctor who discovers this phenomenon.

The detection of an imminent collision is obviously crucial to safe autonomous motion. Range, direction and time to contact can be extracted from the optical flow generated on the eye retina of a moving observer by the relative motion of rigid bodies [10–12]. Such visual information may be used as a feedback signal to the motoric system for generating desired motion trajectories [13]. A textured surface induces local divergence in the optical flow, which is inversely proportional to the time to contact [14]. Local divergence patterns can be learned by neural networks, trained for obstacle detection [15, 16]. For untextured objects, the average divergence over the projected image may be calculated by integrating local flow measurements along the contour of the projected image, which may be approximated by the state of a locally connected diffusion network [17, 18]. Similar networks have been proposed for filling-in of brightness, color and depth in vision [19–21]. The resulting average divergence of an object is equivalent to the expansion rate of its projection on the image plane. This paper shows that the optical expansion of a

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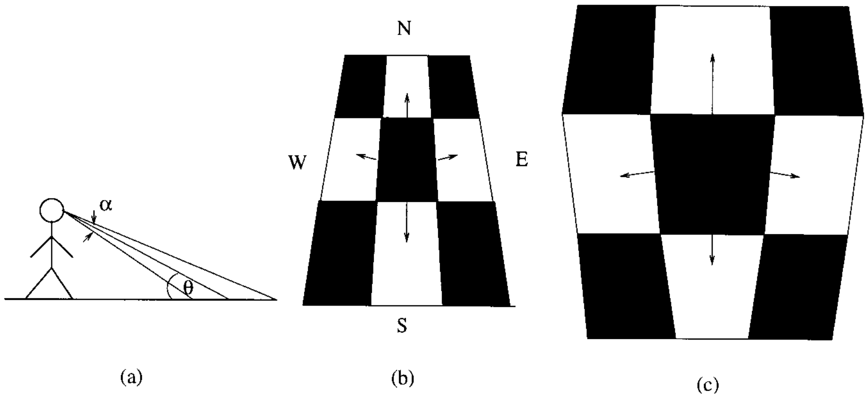

Figure 1. (a) Observation geometry (b) Tile arrangement and steady optical flow (c) Expansion pattern created by a stumble.

tile's image can create a useful correction signal for the feedback control system of a walker with otherwise uncontrollable motion disruptions.

Consider the observation geometry depicted in Figure 1 (a). The observer's eyes are first assumed to be placed at a constant distance from the floor, and his field of view is assumed to be centered about a line intersecting the floor at an angle θ. The size of the field of view is represented by the viewing angle α. The tile arrangement is shown in Figure 1 (b). The observer's motion in the "N" direction creates a motion, called "optical flow," of projected tile edges on the observer's eye retina. Each of the tile images expands. The motion of the projected edges of the center tile is represented by the arrows attached to the tile's edges. If the walker stumbles, his eye level reduces suddenly, while he continues his forward motion. This results in a sudden change in the optical flow, as illustrated by Figure 1 (c). The actual flow will depend on the actual motion of the eye, but, in general, the tile's image expansion rate will increase drastically.

As will be shown mathematically, when the observer's velocity and eye level are constant, the net optical flow (NOF) of the center tile, representing the integral of the normal velocity along the projected tile boundary, grows approximately as the reciprocal of the forward velocity. As the observer moves forward, one center tile leaves the field of view and another enters. The walker fixates at the tile and visually tracks it, allowing the angle θ to grow with time. When θ reaches a certain threshold value, the observer's eyes make a fast movement to the next center tile, which lies farther away ("saccade", see, e.g., [6]) and the process repeats itself. The resulting NOF signal is a steady "spike train", as depicted in Figure 2 (a). It serves as a reference signal, Φ_r, which may be learned by the observer in a few steps of steady walk, or from a standing position by eye motion, increasing the angle θ at a certain rate. A stumble will create an abrupt change in the actual spike train, Φ_a, as shown in Figure 2 (b), where the last spike is considerably greater than the previous ones. The difference, $\Delta\Phi$, between Φ_r and Φ_a is a single relatively large spike, as

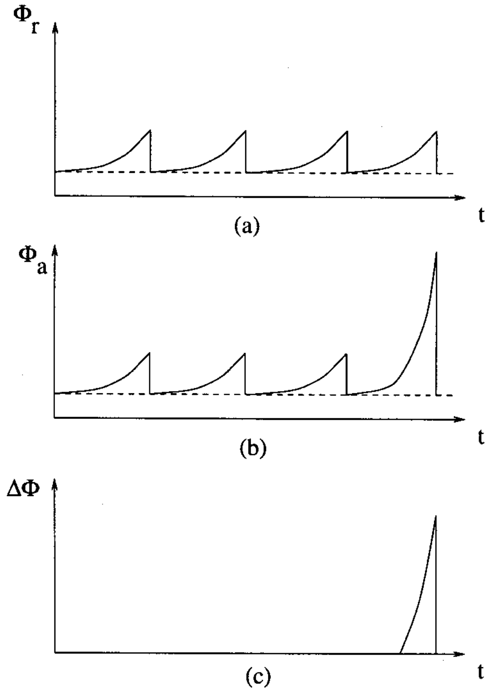

Figure 2. Spike trains of net optical flow generated by a steady walk (a) and by a stumble (b), and the difference signal (c).

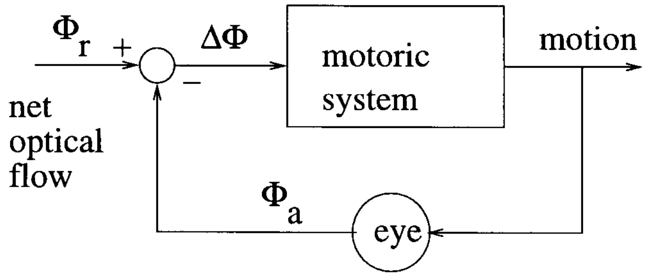

Figure 3. Feedback control system that counter-acts stumbling on tiles.

shown in Figure 2 (c). It constitutes a correction signal to the limbs, causing them to counteract a fall. The feedback control system is depicted in Figure 3.

Clearly, even in healthy people, neither is the eye level constant nor are the visual tracking of tiles and the catch-up saccades so smooth as to create a uniform spike train as the one displayed in Figure 2. Yet, the proposed idealization seems to represent the essence of the stabilizing visual effect provided by the tiles. In Parkinson patients, the idealization seems even less realistic [1–8], although certain eye-tracking functions, such as prediction in smooth-pursuit, have been reported to remain intact [8]. While the motoric impairment may cause severely irregular motion, the visual feedback signal, unsteady as it might be, provides, in essence, the same, and far more needed, stabilizing effect. It is like a cane which, held by a healthy walker can provide some unnecessary comfort, and, when held by a motorically impaired person, will provide, unsteady as it might be, essential support. The psychological effect is particularly interesting. It has been observed [9] that the mere appearance of tiles in the field of view would cause a Parkinson patient to start walking. This observation on the comforting effect of tiles seems to be supported by findings that more severely impaired patients display a higher anticipatory saccades activity than less severely impaired ones [7]. Relative tile motion generates such seemingly needed saccade activity. It has been suggested that pathological tremor present in Parkinson patients interferes with their visual feedback [4]. Expanding and contracting visual tile images may be generated by tremor and may serve in creating a feedback signal that activates the muscles, which, in turn, counteract these disruptions.

A mathematical analysis of the visual information generated by motion with respect to a single tile and the processing of this information can be based on the obstacle detection mechanism proposed in [17, 18]. The sequential appearance of different tiles in the field of view is handled by "saccades", as described above. Consequently, the corrective feedback signal is a sequence of "spikes", as depicted by Figure 2 (a), each representing the signal generated by a single tile. The tile projection geometry is shown in Figure 4. A focal point O, representing the observer's location, is connected to a point P on a tile. An image plane, representing the retina, is placed at a certain distance from the focal point, perpendicularly to the line (OP), which intersects the image plane at point p. The points of the tile's boundary are connected to the focal point by straight lines and the projected image of the tile is defined by the intersection of these lines with the image plane. Let (X,Y,Z) be a Cartesian coordinate system with origin at the focal point O and let (x,y) be a coordinate system in the image plane, with origin at point p. Let the relative velocity of the observer, located at O, with respect to the tile be given by $V = (V_X, V_Y, V_Z)$. Normalizing the velocities, $(\tilde{V}_X, \tilde{V}_Y, \tilde{V}_Z) = (V_X, V_Y, V_Z)/D$, where D is the distance between O and P, the optical divergence at a point p on the contour of the tile's projection on the image plane is given by [17, 18]

$$\psi(p) \equiv \nabla \cdot \mathrm{v}(p) = u_x + v_y = 2\tilde{V}_Z + (\tilde{V}_X, \tilde{V}_Y) \cdot (F_x, F_y), \tag{1}$$

where $\mathrm{v}(p) = (u, v)$ is the velocity of p and u_x and v_y are the respective partial derivatives in the x and y directions and where F_X and F_Y are the slopes of the tile with respect to the X and Y directions. It can be seen that in a steady walk forward at a constant velocity V_Z with $V_X = V_Y = 0$, the local divergence is inversely proportional to the time to contact with the tile ($t = D/V_Z = 1/\psi(p)$). It can also be seen that when the tile is perpendicular to the line OP, (i.e., when $F_X = F_Y = 0$), the normalized velocity $\tilde{V}_Z$ is the reciprocal of the time to collision between the observer and the tile. In steady walk, a tile is perpendicular to the line OP only if the observer looks straight down. But then both $V_Z = 0$ and $\nabla F = 0$, which means that there is no prospect of colliding with the tile directly underneath

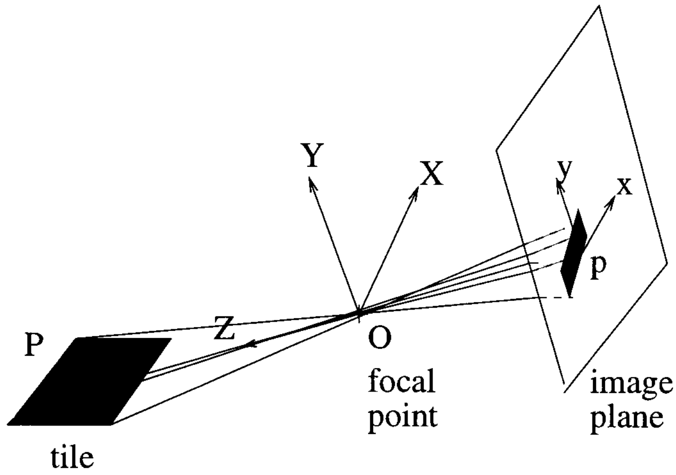

Figure 4. Projection geometry.

the observer. When the observer looks at a point on the floor well ahead of him and walks steadily, both V_Z and ∇F are non-zero. A stumble will cause abrupt changes in V_Z and F_Y, increasing both.

As has been observed by many researchers, the local divergence represented by $\psi(p)$ is a rather noisy signal, when derived from real images and must be averaged over the projected image of an object [10, 11, 14–16]. For an untextured object, such as a tile, $\psi(p)$ may be integrated along the contour of the tile's image [17, 18]. Let R denote the projection of the tile on the image plane, let $A(R)$ denote the area of the projected image and let ∂R denote the projected boundary of the tile. Further let ds and dl denote infinitesimal elements of R and ∂R, respectively. Then the average divergence of the points of R is

$$\Phi(R) \equiv \frac{1}{A(R)} \int_{R \backslash \partial R} \psi(p)\, ds = \frac{1}{A(R)} \int_{\partial R} \mathrm{v}_n(p)\, dl = \frac{1}{A(R)} \frac{dA(R)}{dt}\,, \quad (2)$$

where $\mathrm{v}_n(p)$ is the velocity normal to the edge at p. We see that $\Phi(R)$ can be calculated from the component of the velocity normal to the boundary and that it represents the relative rate of expansion of the tile's image. The averaging action in (2) suggests that the noise in $\psi(p)$ will be largely eliminated and that $\Phi(R)$ will be a more accurate measure of the reciprocal time to contact with the tile. As before, it should be noted that, in a steady walk, $\Phi(R)$ represents a certain rate of net optical flow through the tile's image, used as a reference signal in the feedback control system. Between saccades, the observer, moving forward at a constant velocity, follows each of the center tiles with his eyes. Consequently, the time to contact with the tile, as measured by the inverse of the average divergence, reduces approximately at a linear rate, equal to the forward velocity. This implies that the average divergence, or the net optical flow signal, increases between saccades at a rate which is inversely proportional to the forward velocity, which explains the

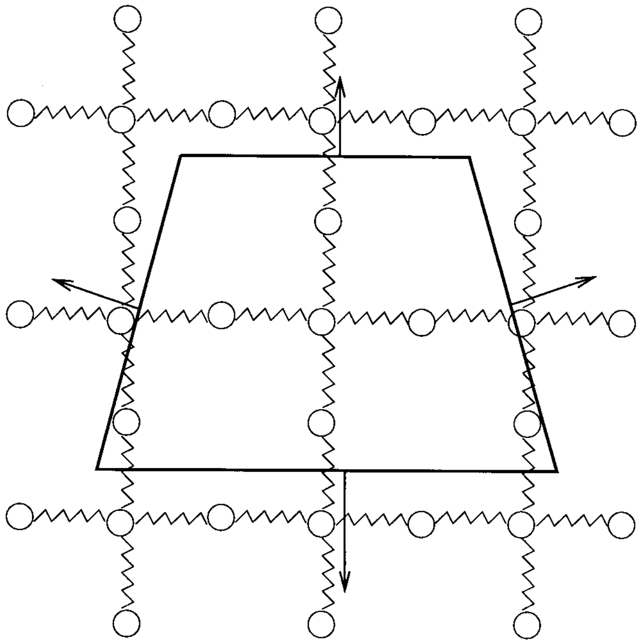

Figure 5. A locally connected network for calculating size change by diffusion.

spike train depicted in Figure 2. A stumble will generate an abrupt increase in $\psi(p)$ and, consequently, in $\Phi(R)$.

It has been shown [17, 18] that the calculation of $\Phi(R)$ is approximated by the final state of a network of locally connected array of cells, implementing a discrete diffusion process. Similar processes were previously proposed for performing other vision functions [19–21]. Assuming a two dimensional grid arrangement of cells, as the one depicted in Figure 5, the cell in position i at time $(k+1)\Delta t$, where Δt is some time interval, performs the calculation

$$u(i, k+1) = \frac{1}{\mid C(i) \mid} \sum_{p \in C(i)} u(p, k) \qquad k = 0, 1, \ldots \tag{3}$$

where $C(i)$ is the group of neighboring cells connected to the i'th cell and $\mid C(i) \mid$ is the number of cells in this group. This discrete diffusion process is initialized by zero everywhere but at the cells on the boundary of the image, which take the values

$$\mathrm{v}_n(i) = \frac{I_t(i)}{\sqrt{I_x^2(i) + I_y^2(i)}}$$

where I_t, I_x and I_y are the partial derivatives of the image light intensity with respect to t, x and y, respectively. It has been shown that, for a large number of nodes, the network is resistant to a high rate (nearly 50%) of connectivity failures [22].

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