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Real-Time Simulation of Herds Moving Over Terrain

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Abstract

We present a method for animating herds of animals to follow terrain surfaces in real time. This method involves making modifications to Reynold's *boids* algorithm. The modifications use local properties of the terrain and thus have low complexity. They produce naturally behaving herds that follow the terrain, swerving around hills and attempting to reduce energy expenditure. The terrain-following rule has a parameter that can be adjusted to produce different behaviors. Empirical analysis shows how this parameter affects energy expenditure of the animals while traveling over the terrain. See demo: http://consystlab.unl.edu/our_work/herds.html

Introduction

Reynolds introduced the efficient *boids* algorithm for animating flocks of animals (1987; 1999), where each animal makes its own decisions on how to move. Reynolds suggested that further modifications could lead to a herd model by giving the animals the ability to follow three-dimensional terrain. This paper explores such modifications. The animals in Reynold's flocks move according to three simple rules, each resulting in an acceleration, which are combined to animate the animals:

1. *Separation*: accelerating away from nearby members of the flock that are closer than some threshold distance.
2. *Alignment*: adjusting an animal's velocity to match the average velocity of its neighbors. And
3. *Cohesion*: accelerating towards the center of the flock.

Additional rules can create new behaviors such as obstacle avoidance and goal seeking. We first discuss the mapping from 2D to 3D and the necessary correction for 3D. We then derive a new rule for traversing terrain.

Moving From Flocks to Herds

In order to traverse terrain, the animals must be constrained to the terrain's surface. One possibility is to use 3D flocking and add constraints or forces to keep the animals on the surface. However we chose to use 2D flocking, and apply a scaling correction to the movement for the third dimension.

We denote the 2D flocking space as $\mathcal{F}$. $\mathcal{F}$-vector refers to a vector in $\mathcal{F}$. Likewise $\mathcal{P}$ refers to 3D space. The terrain is a mapping $m : \mathcal{F} \mapsto \mathcal{P}$. We compute the flocking animation in $\mathcal{F}$, and render the animals at their corresponding location in $\mathcal{P}$. We assume there is an 'up' direction in $\mathcal{P}$ dictated by gravity, and $h(p \in \mathcal{F})$ gives the $\mathcal{P}$-coordinate along that axis.[1] The gradient $\vec{g}(p)$ of $h(p)$ is a vector whose components are partial derivatives of h evaluated at the point p (e.g., $\vec{g}(x, y) = [\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}]^T$). The gradient is a vector pointing in the direction of the greatest increase of h, and its magnitude is the slope $s(p) = ||\vec{g}(p)||$ of the terrain in that direction. The slope in the direction of a vector $\vec{v}$ is $s_{\vec{v}}(p) = \frac{\vec{v} \cdot \vec{g}(p)}{||\vec{v}||}$. The gradient at a point can be efficiently computed for most terrain models.

3D Correction

Note that distance in $\mathcal{F}$ and $\mathcal{P}$ may differ. The distance between a and b ($a, b \in \mathcal{F}$) is often less than the distance between $m(a)$ and $m(b)$. Since a constant velocity $\vec{v}$ in $\mathcal{F}$ may not yield a constant speed in $\mathcal{P}$, we must apply a correction to $\vec{v}$, rotating from $\mathcal{F}$ into $\mathcal{P}$ and projecting back onto $\mathcal{F}$. We apply this correction to $\vec{v}$ before using it to update the animal's $\mathcal{F}$-position each frame. For example, for height fields, Figure 1 illustrates how to rotate the velocity up (or down)

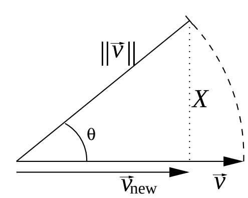

Figure 1: Rotating velocity by the slope.

the slope of the terrain. $\vec{v}_{new}$ is the corrected $\mathcal{F}$-velocity. Solving for $\vec{v}_{new}$ yields: $\vec{v}_{new} = \frac{\vec{v}}{\sqrt{{s_v}^2+1}}$,and we update the animal's $\mathcal{F}$-position using $\vec{v}_{new}$.[2] Note that the correction can be applied also to acceleration, but our experiments in this regard did not yield a noticeable effect.

[1]For example, for a height-field, $\mathcal{F}$ is the projection of $\mathcal{P}$ onto the horizontal plane, and $z = h(x, y)$ is the height of the terrain.

[2]We could approximate $\frac{1}{\sqrt{{s_v}^2+1}}$ by a piecewise linear function.

Natural Behavior Over 3D Terrain

Now we have a framework for mapping $\mathcal{F}$ to $\mathcal{P}$, but the herd still travels straight over terrain features in its way, as in Path 1 in Figure 2. However, we may prefer a more natural-looking route such as Path 2 or 3.

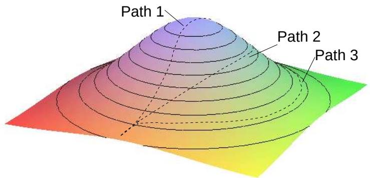

Figure 2: Possible paths to get past a hill.

Natural Routes One possibility is to pre-compute a route. For example, Kapoor describes a method for computing the geodesic shortest path across the surface of a polygonal mesh (1999). The shortest path is not necessarily what we would like. Animals and humans naturally choose behaviors that minimize energy expenditure. Further, pre-computing shortest paths violates the essence of the boids algorithm. Consequently we consider how the terrain affects energy expenditure. (Minetti 1993; Minetti & Alexander 1997) lead us to form an energy function like Figure 3. Generally, to conserve energy, the herd should try to follow contour lines. But following a contour line around a wide, short hill might be less economical than a more direct route.

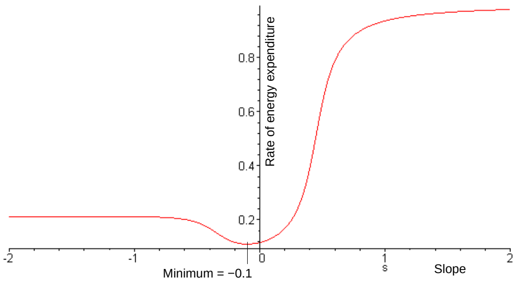

Figure 3: Energy expenditure as a function of slope.

Terrain Force Our solution is to apply a force that resists motion orthogonal to the contour lines. We obtain nice results when the force is proportional to the gradient. If the animals are already following a contour line, then we need to avoid pushing them up or downhill. Thus, the force should also be proportional to the negative of the component of velocity along the gradient, thus for some constant K:

$$\vec{F} = -Ks\frac{\vec{v}\cdot\vec{g}}{||\vec{g}||^2}\vec{g} = -K\frac{(\vec{v}\cdot\vec{g})}{||\vec{g}||}\vec{g}. \qquad (1)$$

We define $\vec{F} = 0$ when $||\vec{g}|| = 0$. To determine a value for K we performed experiments with herds of 50 animals traveling over smooth, randomly-generated terrain from one location to a goal point. We varied the constant K and calculated an estimate for the average energy expended over 300 trips. We estimated energy expenditure at each time step using the energy function of Figure 3. The results are shown in Figure 4. We can now choose K to minimize energy expenditure. Setting $K = 0$ eliminates the effect. Increasing K decreases the energy expenditure, up to a point, after which the animals take longer routes. At some higher value, the animals can no longer accelerate enough to climb hills, and may never reach their goal. We can choose K to obtain various behaviors, e.g. cattle may choose to stick close to the contour lines, while mountain goats may prefer to hop over the top of a steep hill. These modifications to the flocking algorithm produce pleasing results. The herd curves naturally along terrain, and can divide into two groups to go opposite directions around a hill, regrouping on the other side.

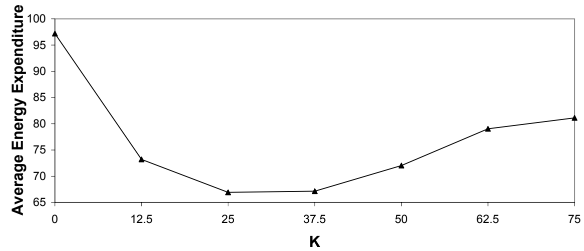

Figure 4: Mean energy expenditure as a function of K.

Summary

In order to create the behavior of herds moving over terrain we have made modifications to the basic flocking algorithm:

1. We use a 2D algorithm, mapped into 3D space.
2. At each time step, we update the position of an each animal not by its velocity $\vec{v}$ but by $\vec{v}$ mapped from $\mathcal{F}$ to $\mathcal{P}$.
3. We add an additional rule: an acceleration equal to $-K\frac{(\vec{v}\cdot\vec{g})\vec{g}}{||\vec{g}||}$.

The constant K controls how tightly the herd will follow the contour lines of the terrain. K can be adjusted for low energy expenditure or other terrain-following behaviors. In the future we would like to develop higher-level behaviors such as migrating, finding food, and avoiding predators.

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