GridDrones: A Self-Levitating Physical Voxel Lattice for 3D Surface Deformations

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Abstract
We present GridDrones, a self-levitating programmable matter platform that can be used for representing 2.5D 15 voxel grid relief maps with capabilities of rendering overhangs and 3D spatial transformations. GridDrones consists of 15 cube-shaped nanocopters that can be placed in a volumetric 1x*n*x*n* mid-air grid. Grid deformations can be applied interactively to this voxel lattice by first selecting a set of voxels using a 3D wand, then assigning a continuous topological relationship between voxel sets that determines how voxels move in relation to each other, then drawing out selected voxels from the lattice structure. Using this simple technique, it is possible to create overhanging structures that can be translated and oriented freely in 3D. Shape transformations can also be recorded to allow for simple physical shape morphing animations. This work extends previous work on selection and editing techniques for 3D user interfaces.

Author Keywords
Real Reality Interface; Programmable Matter; Drones

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

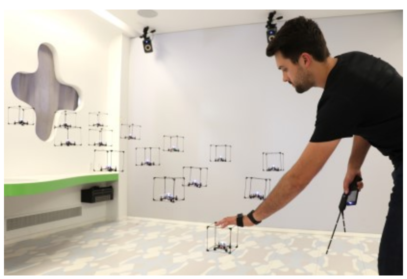

Figure 1. GridDrones system with an array of self-levitating physical voxels represented by small quadcopters.

Introduction

The creation of bi-directional tangible interfaces has been an enduring research goal. Sutherland [9] envisioned early on that the ultimate form of Virtual Reality (VR) would entail the rendering of physical matter in lieu of virtual pixels. There are two main reasons for this: 1) Physical matter provides haptic feedback that is difficult to simulate in VR; and 2) to achieve symmetry between the ability for physical objects to control software, and software to control physical representations [5]. Toffoli and Margolus [10] coined the term "programmable matter", refining the concept to pertain to massively parallel arrays of physical cellular automata capable of rendering 3D geometric shapes that, someday, would be of sufficient resolution to be indistinguishable from actual physical objects. The effort towards interactive programmable matter is continuing today, within user interface paradigms such as *Claytronics* [3], *Organic User Interfaces* [6], and *Radical Atoms* [5] and studied in related fields such as modular [7] and swarm robotics [8]. These interfaces are capable of representing physical 3D objects via synchronous movement of large quantities of miniature robots dubbed *Catoms* (Claytronic Atoms) [4]. However, one of the problems with existing programmable matter prototypes is that it is challenging to position Catoms in 3D, especially in the vertical (*z*) dimension [4]. This is because Catoms need to overcome gravity in order to move in the vertical dimension, and because structures need to always remain structurally stable under gravity during deformation. Indeed, when we examine prior work in programmable matter prototypes, such as Kilobots [8], or Zooids [2], we note that these robot swarms, while relatively high resolution, are only capable of rendering 2D structures.

In recent years, there have been significant advances in the research space of Shape-Changing Displays as well. A notable prototype is inFORM [11], a system that relies on a motorized pin relief map to create a Shape-Changing Display using 2.5D surface normal deformations, again at relatively high resolutions. Structural integrity is not an issue with inFORM, because all surface normals are supported physically along the *z* axis. However, approaches relying on motorized pins are limited in that they can *only* render transformations of the actual *surface* of the device: i.e., they cannot render overhangs, as holes along the *z* axis are not possible, and cannot apply 3D spatial transformations such as rotation to the resulting shapes as this would involve rotating the entire display mechanism.

Contribution

We present GridDrones (Figure 1), a self-levitating programmable matter platform that can be used for representing 2.5D 15 voxel grid relief maps capable of rendering overhangs and 3D spatial transformations. GridDrones consists of 15 cube-shaped nanocopters that can be placed in a room-scale volumetric 1x*n*x*n* mid-air grid and a custom 3D wand input device enabling complex control routines and interactive deformations.

INTERACTION TECHNIQUES

Our interaction techniques were aimed at the efficient selection, translation and orientation of sets of voxels from the grid, (bi)manually, or using the custom designed wand depicted in Figure 2 for large selections, or voxels that are out of reach.

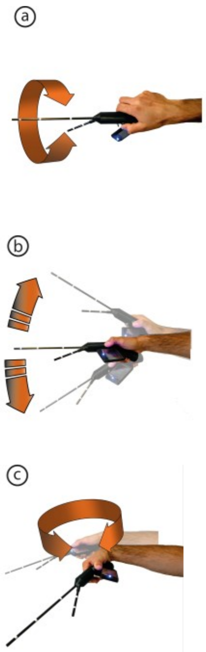

Figure 2. Rotating the entire grid with a wand is accomplished by pressing the secondary button after which, a) rotating the wrist rotates the grid about the wand's axis, b) rotating the wand up/down tilts the grid relative to the wand, c) rotating left/right rotates the grid clockwise/ counterclockwise.

Lasso Select

The lasso gesture is similar to that found in paint programs. It is performed by clicking the primary physical button on the wand while pointing outside of a voxel, then drawing an enclosed figure that ends at the original location. Voxels inside this enclosed figure are selected, with their LEDs highlighted, after releasing the button.

Ray Cast Select

Individual selection of voxels is performed by pointing at a (number of) voxel(s), and pressing the primary physical button on the wand. Any voxels that intersect the line are selected, producing a simple raycasting technique. This selection area around each voxel has a radius of 15 cm from the voxel centroid.

Topological Program

The topological relationship between sets of voxels is programmed by setting a touch slider on the wand display. Voxels are programmed such that the vertical distance of a voxel follows the movement of a connected voxel by a factor (0-100%) that determines the ratio of distance to travel in the *z* dimension. From 0-50%, this ratio is exponentially related, at 50% it is linearly related, and between 50% and 100% it is inversely exponentially related, with 100% representing a direct connection between voxels.

Drag

Pressing the primary button while pointing at a selection allows dragging a set of voxels, translating the entire group in the *z* dimension of the grid.

Rotate and Translate

The grid is rotated by pressing the secondary button on the wand, then tilting the wand, which results in rotations of the entire grid with relative mapping. Rotating the wrist rotates the grid about the wand's axis (Figure 2a); rotating the wand up/down tilts the grid relative to the wand (Figure 2b); and rotating left/right rotates the grid clockwise/counterclockwise (Figure 2c). The entire grid can also be dragged (translated) by pressing both wand buttons and moving the wand.

BitDrones Hardware

Each BitDrone is a stabilized, standalone quadcopter flight platform with external flight control and two-way telemetry. The propulsion system of a single BitDrone consists of four propellers, each driven by a coreless DC motor. These propellers have been laser cut to maximize the active surface area within the propeller radius to increase overall lift in a smaller area, at the expense of efficiency. A flight control board with integrated motor controllers running MultiWii 2.4.2 stabilizes the drone and enacts movement commands through the proportional variation of thrust between all four motors. This variation is determined through orientation PID (proportional, integral, derivative) control loops using feedback from an onboard MPU-6050 inertial measurement unit. Each BitDrone is powered by a 3.7V, 300mAh lithium-polymer battery.

GridDrones Software

The flight controller takes in the position of the tracking markers on the hand or a wand, and presents it to the UI system as a transformation matrix, based on the marker closest to the grip, a rotation matrix that represents the wand's 3-space rotation, and a list of BitDrones that the wand is pointed at. Pointing is detected by checking the distance from the drones to an infinite vector along the wand's main axis. The system also reports when a user's hand is nearing a

BitDrone, and when it has made contact, by tracking markers on the hand.

Topological Programs

The grid is a 1x*n*x*n* array of BitDrones. When created, it will dynamically add drones until there are none available. In the current system, 15 voxels are typically arranged in a 1x3x5 grid, however, other variations of rectangular grids are supported. The grid can be completely represented by a position in 3-space, which represents its anchor point, a transformation matrix, and a 2D array of vertical offsets for each voxel. Using this data, any grid state can be recorded and played back. The grid allows for arbitrary groupings within itself. These groups are non-exclusive and can support an arbitrary number of voxels. Groups have a topological relation value, between 100% and 0%, which determines how much they will move up or down in relation to movement by a neighbor. When a voxel is moved, changes in its position are communicated to neighbours in the group, which follow this behavior according to their topological program (see Fig. 3).

Grid Transformation

Translation and rotation of the entire grid is achieved by applying the wand's relative transformation matrix to the grid. A transformation is calculated from the wand's rotation and translation matrices. To rotate, the user presses and holds the secondary wand button.

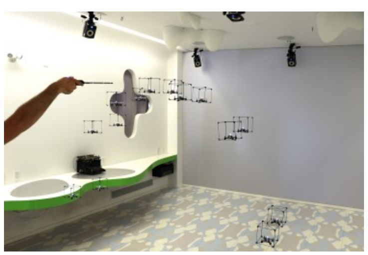

Figure 3. Creating a catenary archway with GridDrones by raycast selecting a backbone, then lifting. Secondary drones follow the actions.

Conclusion

We presented GridDrones, a self-levitating programmable matter platform that can be used for representing 2.5D 15 voxel grid relief maps capable of rendering overhangs and 3D spatial transformations. GridDrones consists of 15 cube-shaped nanocopters that can be placed in a volumetric 1x3x5 mid-air grid.

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