BitDrones: Towards Self-Levitating Programmable Matter Via Interactive 3D Quadcopter Displays

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ABSTRACT
In this paper, we present BitDrones, a platform for the construction of interactive 3D displays that utilize nano quadcopters as self-levitating tangible building blocks. Our prototype is a first step towards supporting interactive mid-air, tangible experiences with physical interaction techniques through multiple building blocks capable of physically representing interactive 3D data.

Author Keywords
Organic User Interfaces; Claytronics; Radical Atoms; Tangible User Interfaces.

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

INTRODUCTION
The thought that computer interfaces might some day *physically* embody user interactions with digital data has been around for a long time. In 1965, Sutherland envisioned the "Ultimate Display" as a room in which the computer controlled the existence of matter [8]. According to Toffoli and Margolus [9], such programmable matter would consist of small, parallel, cellular automata nodes capable of geometrically shaping themselves in 3D space to create any kind of material structure. Since then, there has been a significant amount of research conducted towards this goal under various monikers, such as Claytronics [3], Organic User Interfaces [10], and Radical Atoms [4]. All of these seek, at least in part, to utilize programmable matter for user interface purposes to allow for a full two-way synchronization of bits with atoms — something the first generation of Tangible User Interfaces was not capable of [4]. While there has been progress in building hardware modules capable of various forms of self-actuation (known as *Catoms*) [3, 7], much of the work on programmable matter has been theoretical in nature [2]. How to create a massively parallel system of Catoms capable of creating two-way immersive physical user experiences very much remains a research goal of the future. However, this lofty goal would promise virtual reality systems that would be fully physically integrated with real reality. The problem we address in this paper is that Catoms need to overcome gravity, typically via structural support by other Catoms, when building larger structures. While there has been some prior work in this area, most notably using ultrasound levitation [6], the movement of individual Catoms in threespace is typically limited. Other solutions use magnetic levitation to overcome gravity [5], again with distinct limitations on the independent motion of multiple Catoms. We propose to address the levitation problem through the use of nano quadcopter drones. While there have been explorations of swarms of quadcopters for visualization applications [1], there has been little work on fully interactive, real-time user interface applications of 3D drone displays. In this paper, we present BitDrones, an interactive 3D display that uses nano quadcopters as self-levitating voxels. Our prototype is a first step towards interactive mid-air tangible user interfaces with multiple building blocks that are capable of physically representing 3D data on the fly.

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IMPLEMENTATION
In BitDrones, each drone represents a Catom that can hover anywhere inside a volume of 4m *x* 4m *x* 3m in size. Drones are safe for users, who can walk around the interaction volume and interact with each drone by touch. A drone can be used for input, for output, or for both at the same time. Simple atomic information can be displayed by a single drone, while more complex 3D data displays can be constructed using several drones, providing the rudiments for a voxel-based 3D modeling system capable of representing sparse 3D graphics in real reality.

Hardware
Figure 1 shows the 3D-printed body of a nano quadcopter of our own design. Each 8.9 cm diameter drone is equipped with quad-rotors, coreless motors, a Micro MultiWii flight controller board, a wireless Xbee point-to-point radio, and an RGB LED to provide visual feedback to the user. Each

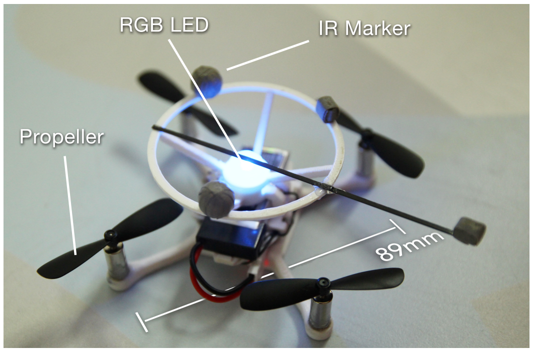

Figure 1. BitDrone with colour LED and Vicon markers.

drone also has a set of reflective markers in a unique configuration, so it can be individually tracked by a Vicon Motion Capture System [11]. An iMac provides location-based flight control information to the drones over the Xbee network.

Software

The drones run MultiWii 2.3.3 as a flight control platform. A custom C# application running on the iMac in Windows 8.1 receives drone locations from the Vicon and wirelessly sends flight and navigation control signals to the MultiWii software of each drone. A set of PID loops directs each drone's movements towards end positions based on user input and interface actions. The Vicon also tracks markers on the user's hands, allowing for gestural input. By estimating the relative positions between markers on the user's hands and on the drones, the system detects interaction primitives such as touching or dragging of individual drones across 3D space. These primitives can be combined for more complex interactions with 3D compound objects.

APPLICATION EXAMPLES

Our current implementation is limited to 3 drones, with the main limiting factor being drift due to turbulence. Drones are sufficiently stable to stay within a cube 25 cm in diameter, with some limitations on the ability to fly above one another, again due to turbulence. This means our current implementation can only be used to implement sparse 3D interfaces at present. However, we expect to be able to scale up our architecture to include at least a dozen drones in the near future. Within the limitations we designed the following application scenarios:

Interactive Representation of Real 3D Structures

Molecular modeling software allows the exploration of bonds between pairings of atoms in 3D. Our BitDrone system can represent molecular structures in 3D in mid-air, allowing users to interact with these structures in real reality. To simulate induced chemical reactions (such as electrolysis), a user can manipulate individual atoms by dragging drones in or out of a bond. LEDs on the drones represent the type of atom by colour coding.

Interactive Real-Reality InfoViz

Drones can also represent points in interactive data visualizations. For instance, the position of the drones can be determined by a mathematical expression, creating a physical representation of that expression. Manipulating one of the drones modifies some parameters of the expression, such as the curvature of a parabolic function. Other drones adjust their position accordingly, preserving the spatial relations as defined by the mathematical expression.

CONCLUSION

We presented BitDrones, an interactive, tangible 3D display that uses nano quadcopters with RGB LEDs as levitating building blocks. Our prototype is a first step towards supporting interactive mid-air tangible experiences with physical representations of 3D data.

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