RESHAPE

Rapid forming and simulation system using unmanned aerial vehicles for architectural representation

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Abstract. As digital technology advances, multiple ways of representing objects interactively in space, architects and designers begin to use Virtual Reality (VR) and Immersive Digital Environments (IDE) to communicate their ideas. However, these technologies are bounded with their spatial limitations. In responding to this issue, our paper introduces ReShape, a digital-physical spatial representation system supported by Unmanned Aerial Vehicle (UAV) swarm technology that allows a user to project their unbuilt design and interact with them in real space, unattached by headset, fixed cameras or screen. ReShape can be controlled by user orientation and gesture as an input, where the real-time feedback is provided by UAV spatial arrangement in space, augmented by computational simulation. Spatial data is transmitted between the UAV agents for the user to experience the digital model, creating a versatile and computationally efficient platform to edit and enhance the design in real-space. This paper outlines four systems in ReShape, i.e., (1) detection system to identify and locate the user position and orientation; (2) task-arrangement system to provide spatial information to the UAV agents; (3) UAV’s communicating system to control the UAV position and task in space; and (4) Physical-Digital forming system, to project digital simulation by the UAV agents.

Keywords. UAV system; Spatial representation; a detecting system; human-computation interaction.

1. Introduction

Since CAD origination in 1963 by Ivan Sutherland, digital representation in architecture has been advancing through various mediums, from on-screen to off-screen simulation, and from virtual simulation to physical fabrication. These conversions have brought different consequences and opportunities. For example, Virtual Reality (VR) and Immersive Digital Environments (IDE) have brought new ways of experiencing virtual space, but attachment to the device remains unsolved (Jung et al., 2015). VR technology is limited by its headset and IDE are bounded by the projector location. Moreover, while 3D printing allows for quick
prototyping, the flow between designing and physical validation mostly occurs linearly, the physical prototype does not provide feedback to the digital model. The next reasonable step is to then reconsider ways to liberate spatial attachment and one-way simulation, by reconfiguring the relationship between virtual and physical representation in architecture.

This paper introduces ReShape: a rapid formation system with a physical user interface, an intelligent UAV system, and real-time feedback of multiple spatial simulations. Our preliminary experiments and case studies indicate a promising avenue by using ReShape to reduce the digital barriers by projecting virtual design and relevant information into a real environment. With ReShape, design information is no longer attached to a pair of eyes behind the headset or exclusive to people, who have access to fixed screen and projectors but instead offers ultra-mobility and openness to the surrounding observer. While programmable swarm drones have been widely applied to portray object in space, the main difference with ReShape is that each drone has a unique role in forming an object rather than following a uniform flight path program. This system allows users to manipulate the way in which each UAV system collaborates with each other as a bi-directional Tangible User Interface (TUI) (Ishii et al., 2012).

1.1. BACKGROUND

Inspiration for ReShape was drawn upon speculation about the evolution of User Interface (Ishii et al., 2012). Ishii outlines his research areas (e.g., shape displays, swarm robotics and self-levitating user interfaces) in three main evaluation phases: [1. GUI - Graphic User Interface] where the user data is displayed fully on the screen, [2. TUI - Tangible User Interface] when the user accesses the data via a hybrid of a screen and mechatronic systems and [3. Radical Atom], where digital data is fully embodied in a physical object. ReShape responds to the latest challenge in Radical Atom.

There are growing interests aimed at developing interactive application for Radical Atom in the last few decades. Particularly, for controlling physical matter as a digital embodiment to produce interactive simulation in spaces. Some systems support discretized shapes to perform 2.5D surfaces i.e., a surface made of two-dimensional array of linear actuators, while others use continuous shapes with advanced materials, such as servo, pneumatic actuation (Yao et al., 2013) or shape-memory alloys (Poupyrev et al., 2004). For instance, Lumen explored individual control of shape and graphics by varying the height of a 5x5 array of light guides using shape-memory alloys. Relief (Leithinger and Ishii, 2010) investigated a set of common interactions for viewing and manipulating content on a 12x12 shape display. Recompose (Leithinger et al., 2011) implemented a framework that allowed for gestural and direct manipulation of an actuated surface. More Recently, InForm (Follmer et al., 2013) showcased a 30x30 shape display aimed at exploring the design space of dynamic physical affordances and constraints with shape-changing user interfaces. Nevertheless, boundary issues, as addressed in the introduction, remain in these projects. Lumen, Relief, Recompose and InForm are constrained by the surface area where the actuators are fixated.

Experiments in swarm robotics in the past ten years offer more flexibility
than 2.5D surfaces. Recently, roboticists have started to develop methods for interacting with large collectives of robots that support either direct or gestural user interactions. Formation of tiny robots to mimic an object collectively was demonstrated with Kilobot by Rubenstein et al. (Rubenstein et al., 2012) with a dynamic programmable display method (Rubenstein et al., 2014). While Rubenstein robots did not respond to user input, hence, a one-way system, Zooids (Le Goc et al., 2016) extended this approach further, focusing on direct manipulation of tangible robots. In another case, Alonso-Mora et al. (Alonso-Mora et al., 2012) proposed a swarm display in which each pixel is a robot of controllable color. Their system was recently extended to support interaction through sketching and mid-air gesture (Alonso-Mora et al., 2011) (Alonso-Mora et al., 2015). A common drawback with such system, however, is that they are inherently limited to two-dimensional configurations.

A natural extension to swarm user interfaces is that of self-levitating tangible user interfaces, self-propelled robots that can arrange spatially to assemble a complex three-dimensional structure on the fly. Such systems were exemplified with Flight Assembled Architecture (D’Andrea, 2013) and Termite Inspire construction (Justin et al., 2014). While these examples provide exciting technical innovations, there has been little focus on interaction among those systems. Researchers have explored the concept of levitating displays via flying robots equipped with projectors and high-resolution displays (Nozaki, 2014) (Scheible et al., 2013) (Schneegass et al., 2014) (Gomes et al., 2016). While these explorations have enabled user interaction, they were limited to a single drone that primarily acted as a visual information display. An exception to the above work is Drone 100 (“spaxels® research initiative - Swarms of the Future,” 2017), a platform comprising of 100 quadcopters that act synchronously to display images. Another example of quadcopters working together to represent 3D structures can be found in BitDrones (Gomes et al., 2016) and GridDrones (Braley et al., 2018). Nevertheless, the scale of this large operation prevents user from directly interact with them, and only few of these applications were related to form and space creation.

It is for such constraints and opportunities, i.e., fixation on 2.5D actuators, 2D swarm robots, and 3D drone formation, that this research aims to extend the swarm logic with self-levitating agents. ReShape system took advantage of tangible interfaces and UAV systems to expand the limitations of traditional architectural representations (restricted by 2D surface and only visual effect.) into space simulations. To investigate ReShape’s capacity, the scope of this study is limited to architectural representation in the real world for one user.

2. Methodology

2.1. DESIGN OF RESHAPE

The ReShape system has User Inputs, Connections and Outputs to simulate space and to display spatial information (we refer to the drone as UAV system from this page onward). To let the UAV agents perform a correct formation based on the users’ or clients’ perspective view, ReShape tracks users’ location and orientation.
The user’s data is then analyzed and aligned with the UAV position which carrying a set of apparatus (e.g., projector, panel) to simulate the digital design in physical space. The spatial information would be transferred into the physical apparatus, for example, rendering information or heat map of the space.

The UAV that is used in this project is Tello, which installed with one normal camera and two infrared cameras. Using this UAV, the ReShape system is divided into four sub-systems: [1] a task arrangement system, [2] a detecting system, [3] a communication system and [4] a physical-digital system. (Figure 1). The relationship between the input-connection-output system with the four subsystems outlined as follows:

1) **Users Input**: Any information or data that is sent to a computer for processing is considered user input. For example, in the ReShape system, the first input is the pre-designed model that is required to be imported into the Task Arrangement System before operating the rest of the system. The second input uses the users’ spatial values that are perceived by detecting system, for example, the users’ orientation in connection to the users’ visual field and position values. After obtaining those two kinds of data, the next step requires sending it into the next process, connection.

2) **Connection**: The connection process acquires data from the User Input and exports data to the Output. In the ReShape system, the users’ value (input) is provided to the Task Arrangement System, where the task of the UAV system would be calculated based on the users’ imported value. After generating the spatial organization data of UAV, ReShape system then transfers the data into the UAV system (output) in the physical world to simulate space.

3) **Output**: The expected output in the ReShape system requires UAV spatial simulation to correspond to the spatial analysis information. Thus, in the following procedure, the UAV system attached with pre-installed boards will begin to perform the designed space based on the data from the communication system. Also, due to one of the UAV systems carrying projectors, the spatial analysis information simulated in computers would be projected into boards carried by the UAV system.

![Figure 1. System structure of ReShape System.](image-url)
2.2. TASK ARRANGEMENT SYSTEM

To control UAV system to perform particular spatial simulation, there are several UAV system’s tasks need to be considered, firstly, the flying path of UAV system based on imported model with users’ visual field need to be calculated before simulating in physical world (Figure 2-top). Secondly, the collision problems of UAV system need to be avoided. Thirdly, the safety of users’ needs to be taken into account. Thus, these flying paths of UAV system need to be arranged before exporting those spatial data into Output part.

While the UAV agent is commonly regarded as a single point in the physical world (e.g., in displaying shape as a point could), in ReShape, we augmented the UAV agent’s point-based representation into higher dimensional shapes by having them carry certain apparatus (e.g., string, panels or boards). With this apparatus, a surface, for example, does not have to be simulated with an array of many UAV systems as point cloud, but rather by carrying a 2D surface apparatus itself. Different UAVs have unique roles, and hence, carrying different apparatus.

Firstly, the digital model information is imported to simulate those tasks of the detecting system and physical-digital forming system, before the Task Arrangement System starts to divide the UAV into three parts: [1] carrying the UAV system, [2] detecting the UAV system and [3] projecting the UAV system based on the digital model’s outline (Figure 3). Carrying UAV systems focuses on spatial organization, which is carrying portable material to perform designed space. For detecting-UAV system, the main task is to detect the users’ spatial information. Lastly, projecting - UAV system needs to follow carrying the UAV system to project simulated data into a specific area (Figure 3). To simulate the space correctly, the task arrangement system needs to maintain the spatial relationship between these three types of UAV systems precisely. For example,
during an experiment, we can see how the left drone would change its orientation to follow the right one to maintain the relative position (Figure 4-top). Also, in Figure 4-bottom, those tow drones are designed to fly as a rectangle together. Thus, task arrangement system could be regarded as one of the bridges between designed space and the physical world.

![Figure 3. Task Arrangement: the process of designing flying path based on shortest walk.](image)

![Figure 4. Demonstration: Two Carrying UAVs perform a certain task (flying as rectangle).](image)

2.3. DETECTION SYSTEM

![Figure 5. Task Arrangement System: (left) maintaining the relationship between Carrier, Projector, and Detector; (far right) Figure 12. Demonstration (top) tag recognizing platform (extracting video from detecting drone with Arduino and Processing) in Grasshopper with AprilTag.](image)

The detecting-orientation system serves one of the key roles in ReShape system: to simulate what the user would see in a real space based on their location in physical space. Therefore, the user’s position and orientation will determine the UAV position in the spatial simulation task (Figure 5). ReShape detects the user position and orientation based on camera sensor devices, which is used to connect the physical and digital world. A tag called AprilTag needs to be attached to users so that camera would be able to recognize users’ orientation and location value.
While the accuracy of the detection system would be higher via a fixed camera, the camera position will limit the user’s movement and spatial orientation. To anticipate this, ReShape’s liberates their users to spatial experience by capturing their movement with a camera attached to the UAV agent. The detecting UAV system can follow users’ position to provide relatively flexible detecting range (Figure 5-far right). Video’s from the camera is then streamed to another UAV agent that project the digital design aligned to the user visual field in real time.

Note that the distance between user and detecting UAV in our project is limited by four meters. To get the relative location value of user, we use two key algorithms. The first one is for ‘following.’ Based on the April Tag attached to user, a detecting UAV would detect the tag and send their coordinate value to the computer. The computer will then calculate the value between the last and the latest value of user, to get the user’s movement. Based on this information, the detecting UAV will execute command to follow user (e.g., by rotating, translating, etc.). Secondly, in order to get the absolute coordinate of user based on the relative coordinate read by detecting UAV, the location value of the detecting UAV when taking off need to be recorded to get the location value of user during experiment process.

2.4. UAV COMMUNICATION SYSTEM

The communication system connects the task arrangement system with UAV simulation in the physical world. Firstly, the data generated from the task arrangement system is based on the Cartesian coordinates system. This value is then transferred into a series of command lines to propel the UAV agent, e.g., ‘forward 1’, ‘back 1’, ‘left 1’, ‘right 1’, ‘up 1’, ‘down 1’ and so on. Secondly, these command lines are transmitted through WIFI signals to the UAV agent that would allow them to perform what has been simulated in digital work in real-time (Figure 6).
2.5. PHYSICAL AND DIGITAL FORMING SYSTEM

2.5.1. Physical simulation

After receiving data through a communication system, UAV system would start to carry pre-attached material to perform the designed space. The formation of UAV’s system is updated in real time based on the users’ orientation and visual field in real space. Due to the budget and amount of time, the materials in this study were limited to flat panels, and fabric yet could still simulate a certain amount of various shapes and space. For example, two portable boards could be carried by UAV system to form a corner space (Figure 7). Fabric could also be used to simulate space bounded with flexible form.

The simulated data are transferred into a projector attached to one of the UAV systems, which is called a projecting-drone. This system would provide users with a different spatial experience compared with traditional sample space via overlaying various information. The physical-digital forming system allows users to experience the designed space in multiple layers of information, such as photorealistic rendering or environmental, structural and spatial analysis (Figure 8).

![Figure 7. Demonstration: carrying different objects to perform different tasks (e.g., frame, layer, and holders).](image)

2.5.2. Digital Simulation

While experiencing space formed by ReShape, designers can adjust the spatial organization by gesture controlling mechanism. For example, to quickly test certain ideas for shape modification (Figure 8) or testing different material (Figure 9). The user controlling gesture can be detected and sent into computers to simulate through task arrangement system. The adjusted design will be then recorded for further steps in the design process.
3. Conclusion

This paper has outlined a method to integrate a user’s input into the UAV system with multiple drones, each with their own task. The system creates new opportunities on the way in which a designer interacts with their design rapidly. There are three contributions of this prototype system design:

1) Evidence-Based Decision Making: The ReShape System equipped with database to accommodate evidence-based decision-making process between architects and clients.

2) Rapid Physical Simulation Tools: Using ReShape, information from designers can be mapped onto the physical world rapidly to the users and allow them to participate in the design process.

3) UAV Human-Oriented Control System: Compared to regular drone applications, such as surveying or aerial photographing, ReShape focuses on how users interact with UAV systems directly to accomplish complex design tasks in real time.

With ReShape, design iterations and refinements happen in real time, allowing for live mockups that do not require manual assembly and dis-assembly. Due to the flexible boundaries offered by the UAV system, ReShape has the potential to expand the architectural field by providing a more realistic approximation of volume form that can be easily adjusted in life size rather than constrained by specific area, for example, fixed camera or fixed motion tracking system.

References

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