

# Ultra-Tangibles: Creating Movable Tangible Objects on Interactive Tables

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## ABSTRACT

Tangible objects placed on interactive surfaces allow users to employ a physical object to manipulate digital content. However, creating the reverse effect—having digital content manipulate a tangible object placed on the surface—is a more challenging task. We present a new approach to this problem, using ultrasound-based air pressure waves to move multiple tangible objects, independently, around an interactive surface. We describe the technical background, design, implementation, and test cases for such a system. We conclude by discussing practical uses of our system, Ultra-Tangibles, in the creation of new tangible user interfaces.

## Author Keywords

User interface device; tangible interface; feedback; ultrasound; actuated tabletops.

## ACM Classification Keywords

H.5.2. [Information Interfaces and presentation]: User Interfaces - Haptic I/O;

## General Terms

Design, Human Factors.

## INTRODUCTION

A stumbling block in the use of Tangible UIs on interactive tables is the lack of actuation mechanisms that can move physical objects to maintain their coupling with the digital content.

Actuating physical objects on interactive tables can be accomplished through the use of active or passive components. Active components contain actuators and control systems to allow the object to move around the tabletop. Typically such active components have involved semi-autonomous robots as in the Touch and Toys system [2]. However, such systems rely on custom made active objects that limit the flexibility of the systems use and can be expensive.

More recently, efforts have been made to support movement of passive objects around the tabletop system

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CHI '12, May 5–10, 2012, Austin, Texas, USA.

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through the use of external forces. This allows the use of a wider range of tangible objects and lower costs than active objects. An example of this is the ZeroN system which uses a movable electromagnet to levitate and manipulate a single magnetic object [4]. One issue with such a system is that it is difficult to scale it to manipulate multiple tangible objects simultaneously.

An alternative approach to manipulating passive tangible objects is the use of air pressure waves. Air pressure waves can be generated by a variety of methods, including ultrasound [3] or air jets [7]. These systems have been used to create haptic feedback [1, 3, 7], but the output waves can also be focused to create sufficient forces to move physical objects around a table.

The use of air pressure waves offers a number of useful features for moving tangible objects. The pressure waves can be accurately controlled and easily generated. Multiple waves can be created to allow manipulation of multiple tangible objects, independently. This allows us to create an actuated tangible interface that can control multiple objects without the complexity and expense of active objects.

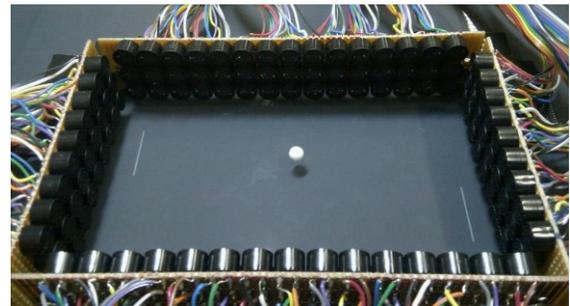


Figure 1: The Ultra-Tangibles System being used to play a game of Pong, with virtual bats and a tangible ball.

This paper presents Ultra-Tangibles (Figure 1) a system that uses ultrasonic transducers to create focused air pressure waves to actively control tangible objects on top of an interactive surface. We first describe the creation of pressure waves using ultrasonic transducers and show that an array of common transducers can be used to generate forces sufficient to move and control tangible objects. We then discuss our specific implementation of such an ultrasound-based system. Finally, we present new features for tangible user interfaces that are enabled by the Ultra-Tangibles system.

The main contribution of this note is the design and implementation of Ultra-Tangibles, a tangible tabletops system that supports actuation of multiple passive objects with the use of ultrasound air-pressure waves.

### ULTRA-TANGIBLES: DESIGN

There are a number of issues to be considered when designing an ultrasound-based tangible feedback system. These include generating enough force to move objects, the arrangement of the ultrasound transducers around the interactive surface and the ability to move multiple objects.

#### Generating Sufficient Force to Move Objects

Ultrasound transmitters create moving air pressure waves which, when combined in a phased array manner allow us to create focal points [3]. The force generated by a phased array of ultrasonic transmitters is dependent on: the power of the individual transmitters, the number of transmitters in the array and the distance to the focal point. We can estimate the force generated by an array of transmitters based on these factors, using the following equation:

$$f = \alpha \frac{nP}{c}$$

Where  $f$  is the force generated,  $\alpha$  is the reflection coefficient of the object (for solid objects the value of  $\alpha$  is 2 as the pressure waves are totally reflected),  $n$  is the number of transmitters,  $P$  is the sound power radiated by one transmitter at the target distance and  $c$  is the speed of sound. For example, for a 25-element array of readily available ultrasound transmitters we can calculate the theoretical force generated at a distance of 3cm as 0.38gf (gram-force); this is more than sufficient to move small objects.

#### Arrangement of Ultrasound Transducers

There are two main options for the arrangement of the ultrasound transducers: in a grid under the active workspace, or in rectangle around the active workspace.

Arranging the transducers in a grid under the workspace results in two issues. First, to display digital information the workspace must be top-projected on to the transducers or a surface above them. This removes the possibility of using the system with portable tablets such as the iPad. Second, this only allows us to lift the tangible objects off of the surface (i.e. in the Z-axis). Pushing them around the surface is not possible.

By arranging the transducers in a rectangle around the display, such that they point into the display area we remove these two problems. We can now use the system with top projection, back projection or an LCD display. We can also move objects in the X-Y plane across the top of the surface.

#### Moving Tangible Objects

Moving tangible objects involves the use of a control loop. This monitors the current location of the objects, compares them with the target locations and estimates the pulses required to move the objects to the targets. As the pulses are

restricted to two directions, the two axes are dealt with separately. After the initial pulse, the velocity and direction of movement are tracked and small pulses are applied to correct the trajectory of the objects.

Finally, the control loop can detect when an object is going to overshoot the target. In this case, it initiates opposing pressure waves to slow and then stop the object at the desired location.

Moving multiple objects independently of each other requires us to create a number of independent pressure waves heading in different directions to each other. In order to ensure these waves do not interfere with each other we have to multiplex the pressure waves.

Firstly, we can use spatial multiplexing. This involves generating each pressure wave using a different set of transducers. So, for instance, we can generate two parallel pressure waves in one axis by using half of the transducers on one side of the array for each pressure wave. While this works well for many pressure wave combinations, there can be issues with waves interfering with each other when in close proximity. This can be addressed by adding temporal multiplexing of the pressure waves.

Temporal multiplexing creates multiple pressure waves that are apparently but not actually simultaneous. Instead, each pressure wave is created in sequence. Thus a pressure wave will be triggered for a set number of cycles of the ultrasound signal, before being turned off. The second pressure wave is then triggered for the same number of cycles. This continues for each pressure wave until all of the required waves are generated, before the series repeats.

By combining spatial and temporal multiplexing and alternating between the various pressure waves until each object has reached its intended target we can move multiple objects independently from each other and in an apparently simultaneous fashion.

### ULTRA-TANGIBLES IMPLEMENTATION

There are three main components to the implementation of Ultra-Tangibles: ultrasound transmitter array, pulse generation, and the control loop.

#### Ultrasound Transmitter Array

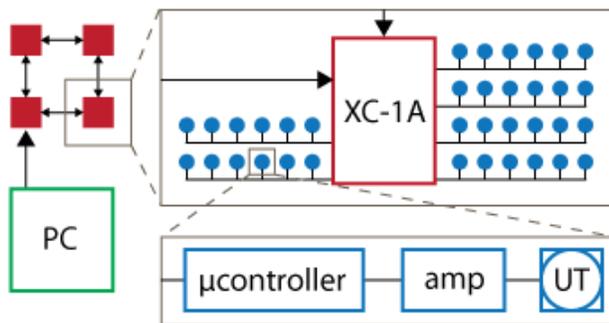
The Ultra-Tangibles system consists of a 7-inch display surrounded by 144 ultrasonic transducers arranged three high in a rectangle, as shown in Figure 1. Each side is a 15×3 array of transducers; the ends are each 9×3 arrays.

#### Pulse Generation

Activating and deactivating the ultrasonic transducers, as well as calculating the phase differences between them is carried out by four XMOS XS1-G4 processors. They are mounted on XC-1A development kits to provide easy access to their outputs. Each processor controls 36 transducers and they are all connected via XMOS links to provide communication between them.

The first processor is connected to a PC via USB, through which it receives requests to create a pulse at a particular location. Upon receiving such a request, the first processor works out which transducers need to be activated and calculates the phase differences between them. This is then transmitted to the other processors, causing them to trigger the required transducers and thus generating the desired pressure waves.

Each ultrasonic transducer is driven by an 8-bit microcontroller (an ATMELE ATTiny26), which generates a 40 kHz 5V square wave signal when triggered by an XMOS XC-1A board. This signal is amplified to a 36Vp-p square wave using a MOSFET driver amplifier and then output as an ultrasonic sound wave by the transducer. An overview of the system is illustrated in Figure 2.



**Figure 2: A schematic overview of the hardware used in our system. The PC is connected to the first of four linked XMOS processors. Each processor is connected to 36 ultrasonic transducers (UT), via a microcontroller and amplifier.**

### Control Loop

A Playstation Eye camera operating at 100FPS is mounted above the ultrasound hardware assembly. This is used to track the tangible objects. The video stream is fed into Community Core Vision, which extracts the positions and velocities of the objects and sends them to control software on the PC.

This control software calculates the direction and location of pulses that are required to move the objects to their designated target, or slow them down if they are going to overshoot. Requests for these pulses are then sent via USB to the XMOS processors.

### TESTING THE IMPLEMENTATION

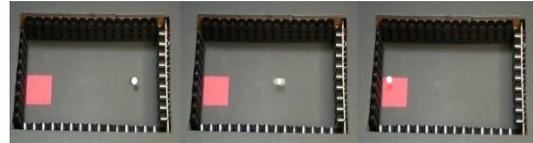
To test and demonstrate our implementation we developed a number of test cases in which the system moved single or multiple objects simultaneously. Each test involves the user placing the object(s) on the surface and setting the target positions by touching the appropriate place on screen. All tests were successfully completed by our system (see accompanying video figure for examples)

#### Moving Single Objects

The most basic test of the Ultra-Tangibles system is to move a single tangible object along one axis. Our first test case implements this by pushing a tangible object across the

surface from one side to another (Figure 3). The second case moves a single object on two axes, resulting in a diagonal movement from one corner of the surface to another.

The third scenario tests the system's ability to correct the path of an object. The initial pulse was intentionally made too strong and a target was selected in a more central location on the surface. In this case, a strong corrective pulse was required to prevent the object from overshooting its target.

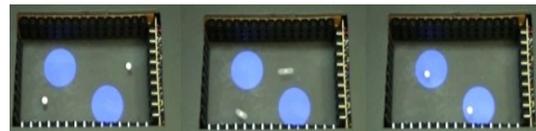


**Figure 3: System test: moving a single object in 1 axis.**

#### Moving Multiple Objects

We implemented three test cases for movements of multiple objects. The first moves two identical tangible objects in opposite directions to each other. They come to rest at targets on the opposite end of the surface. The second test case implements the same test, but uses objects of different sizes. These objects have different masses and so require different forces to move them.

Finally, we implemented a test case in which two objects are moved in opposite directions, to separate targets and both need corrective pulses (Figure 4). As the objects move at slightly different speeds, they must be treated individually when calculating and applying the corrective force to bring them to rest within their respective targets.



**Figure 4: System test: moving two objects that both require correctional pulses.**

### USING ULTRA-TANGIBLES IN TANGIBLE INTERFACES

#### Interaction between Tangible Objects

The ability to control the position of tangible objects allows for complex relationships between multiple objects and their parameters. An example of this would be if the movements of one object changed parameters of another object. For instance, in a tangible application to teach simple physics concepts such as balance, the tangible objects could represent weights. When one weight is moved the system could then move the other weight to illustrate the change in equilibrium.

#### Linking Physical and Digital Representations

In most tangible interfaces moving the physical object can change the underlying digital representation. However, they can rarely change the physical position of the object when the digital representation changes. Ultra-tangibles allows

the link between the physical and digital objects to work in both directions. In our system when a parameter of the digital representation is modified (e.g. volume-slider of a media player) that change can be reflected in the system by performing a corresponding movement of the physical object.

### Recalling Tangible Configurations

The Ultra-Tangibles system allows tangible interfaces to directly move physical objects. This can be used to allow tangible interfaces to remember and recall configurations. The computer vision portion of the system can identify objects and their location on the display. This data can then be saved for later recall. Should the arrangement of object be disturbed, the system could move each object until it reaches its previous recorded position.

### Recording and Replaying Tangible Interactions

As with recalling configurations, the Ultra-Tangibles system allows a tangible interface to record and replay interactions. The vision system can track each object as the move over the display and record these movements. It can then replay the movements by generating the necessary pressure waves to move the objects over the same paths.

## DISCUSSION

### Scalability

Our Ultra-Tangibles implementation made use of a 7-inch display surrounded by 144 ultrasound transducers. The size of an ultrasound-based actuated tangible object system is not limited to this size. There are however a number of issues with designing a larger interface. Increasing the size of the interactive surface increases the distance the ultrasound pressure waves must travel and so results in a greater loss of force. This can be counteracted by adding more transducers or increasing the power of the existing transducers so that a greater force can be generated.

### Size and Weight of the Tangible Objects

The force that we can generate with the ultrasound transducers also affects the size and weight of the tangible objects that we can manipulate. The objects possess inertia that must be overcome in order to move them. As with the issue of scalability, this can be overcome to some extent by using more, or more powerful, transducers. Along with increasing the power, it is also possible to reduce the force required by decreasing the level of friction between the objects and the surface. This could be achieved by placing transducers under the surface so that can be used to vary surface friction [5].

### Dealing with the Ultrasound Transducer Lip

Our implementation of the Ultra-Tangibles system has a raised lip around the interactive surface caused by the placement of the ultrasound transducers. It is possible that this lip could obstruct access to the surface, by not allowing the user to rest their hands on the edge of the surface while making long interaction gestures. However, for many people, interacting with multi-touch surfaces is based on

tapping rather than complex movements [6]. This means that for most interactions there is no real need to rest the hands and arms on the surface itself.

### Resolving Conflicts between Moving Objects

One possible issue with the use of ultrasound pressure waves to move objects is that it requires a line-of-sight to the object to be moved. This means that it is possible for objects to block the line-of-sight to other objects. This may mean that the system works better with sparsely populated tabletops. Due to the fact that our system generates small focal points in order to move objects, it requires just a 1cm gap to reach the object. It is also possible for the system to move blocking objects out of the way temporarily so that space is available to reach the target object. They can then be moved back once the movement of the target object is complete.

## CONCLUSION

This paper presents Ultra-Tangibles, a novel system to address the issue of digital content manipulating tangible objects. Ultra-Tangibles use an ultrasound-based system for independently moving multiple tangible objects on top of an interactive surface. We described the design and implementation of such a system and provided a series of test cases that validated its operation. Future work will include the development of Tangible UI applications to take advantage of the unique features of Ultra-Tangibles.

## ACKNOWLEDGEMENTS

This work was funded jointly by EPSRC (EP/G058334/1) and MobileVCE (www.mobilevce.com) as part of the User Interactions for Breakthrough Services research program.

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