The Actuated Workbench: Computer-Controlled Actuation in Tabletop Tangible Interfaces

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ABSTRACT
The Actuated Workbench is a device that uses magnetic forces to move objects on a table in two dimensions. It is intended for use with existing tabletop tangible interfaces, providing an additional feedback loop for computer output, and helping to resolve inconsistencies that otherwise arise from the computer's inability to move objects on the table. We describe the Actuated Workbench in detail as an enabling technology, and then propose several applications in which this technology could be useful.

KEYWORDS: Tangible user interfaces, physical interaction, actuation, synchronization, interactive surface, object tracking, computer supported cooperative work.

INTRODUCTION
Interactive tabletop surfaces are a promising avenue of research in Tangible User Interfaces. These systems, which we will refer to as "interactive workbenches," track the position and movement of objects on a flat surface and respond to users' physical input with graphical output. Systems such as the DigitalDesk [18], Bricks [7], Sensetable [13], and Urp [17] offer many advantages over purely graphical interfaces, including the ability for users to organize objects spatially to aid problem solving, the potential for two-handed interaction, and ease of collaboration between multiple collocated users.

Current interactive workbench systems share a common weakness. While input occurs through the physical manipulation of tangible objects, output is displayed only through sound or graphical projection on and around the objects. As a result, the objects can feel like loosely coupled handles to digital information rather than physical manifestations of the information itself.

SUBMITTED TO
UIST 2002

Figure 1. The Actuated Workbench uses a grid of electromagnets to move a magnetic puck across a table surface.

In addition, the user must sometimes compensate for inconsistencies when links between the digital data and the physical objects are broken. Such broken links can arise when a change occurs in the computer model that is not reflected in a physical change of its associated object. With the computer system unable to move the objects on the table surface, it cannot undo physical input, correct physical inconsistencies in the layouts of the objects, or guide the user in the physical manipulation of the objects. As long as this is so, the physical interaction between human and computer remains one-sided.

The Actuated Workbench provides a hardware and software infrastructure for a computer to smoothly move objects on a table surface in two dimensions. This paper describes the underlying technology of the Actuated Workbench, and discusses the variety of hardware and software design decisions involved in its construction. It also suggests a variety of preliminary applications of this actuation technology.

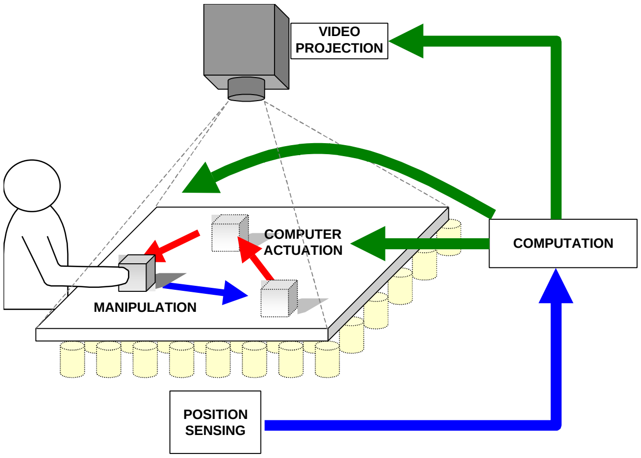

Figure 2: Traditional interactive workbench systems provide feedback through video projection alone. The Actuated Workbench adds an additional feedback loop using physical movement of the tracked objects.

DESIGN CONSIDERATIONS

The Actuated Workbench's design reflects several concerns of compatibility with current interactive workbench systems. First, the tagging and tracking technologies in these interfaces have begun to decrease in size, allowing the objects or "pucks" that hold them to be quite small. Zowie/LEGO demonstrated an example of such technology in a toy [8] which tracked objects with passive tags ~1.5cm diameter x 2mm height. While we considered designing motorized pucks that drive themselves around the tabletop on wheels, we felt these would tend to be relatively large compared to the tags. Motorized pucks would also require batteries that might need to be changed or recharged frequently due to the motors' power requirements. Since many tagging technologies used today are passive devices, we sought to keep the actuation technology passive as well.

A key interaction technique in most interactive workbench interfaces is the ability to manipulate multiple objects at the same time using both hands. Therefore, we wanted the computer actuation technology to be able to move multiple objects at the same time, preferably recreating users' gestures with the objects. We also wanted the actuation system to be scalable to accommodate a variety of sensing areas. Finally, our ideal system would be silent, so as not to unintentionally distract the user when an object is moved on the surface.

SYSTEM DESCRIPTION

Mechanical Details

The actuation platform consists of a 16.5cm (6.5") fixed array of 64 electromagnets arranged in an 8 x 8 grid under a layer of 0.63cm (¼") acrylic (Figures 1 and 3). Though this provides only a limited area for actuation, it is possible to tile these arrays together, the only limitations being the complexity of electronically addressing the arrays, and the power requirements of running such a large number of electromagnets. We built the system using custom made electromagnets, each measuring 1.9cm (0.75") diameter x 3.8cm (1.5") length. They are wound with 32 gauge copper wire with a total length resistance of 120-122 ohms.

Figure 3: Overhead view of electromagnet array.

Using these custom-wound magnets proves an advantage over most commercially available electromagnets, which are often designed with metal housings intended to focus the magnetic field within a small area around the electromagnet. The uncontained fields of our electromagnets make it easier to create combinational flux patterns between individual electromagnets, the importance of which will be discussed later. Each electromagnet is driven with 27 DC volts and draws about 250mA. In our current applications, each electromagnet is only active for a few milliseconds at a time, and significant heating of the electromagnets does not occur. However, if many electromagnets were activated for a long period of time, cooling of the array might be necessary.

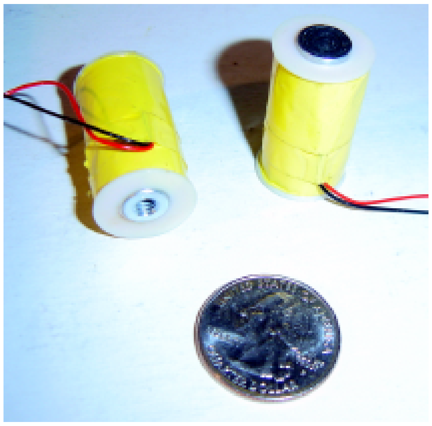

Figure 4: Custom-wound electromagnets produce broad, uncontained magnetic fields.

Electronics Details

We designed custom electronics to drive each electromagnet in the array bi-directionally, making it possible to set the polarity of each magnet's field, as well as turn individual magnets on and off. Our electronics are designed to set the state of each electromagnet in the array at the same time. This makes moving multiple objects simultaneously a simple matter of setting up separate magnetic fields in different areas of the array. Of course we must take care that these magnetic fields do not overlap, and this consideration limits the number of objects that can be moved simultaneously.

An Ethernet-equipped microcontroller board, the Systronix SaJe board, natively runs a Java program that receives UDP packets sent via Ethernet from a control computer. It processes these packets and converts the data for output on two parallel 8-bit data buses. Every 15 microseconds, the microcontroller board clocks each magnet's polarity and enable status (off or on) into a set of octal flip-flops that connect to motor driver chips (containing the H-bridge transistor configuration frequently used for driving electric motors), which then connect to the electromagnets via ribbon cable.

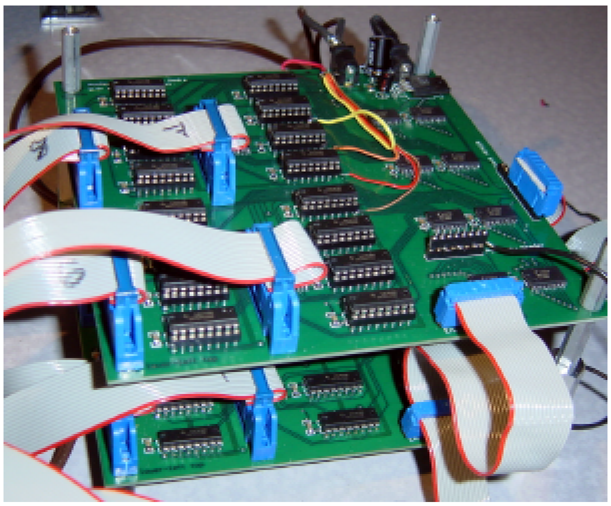

Figure 5: Custom-fabricated circuit board containing flip-flops and H-bridge transistor arrays.

The 15 microsecond refresh rate allows us to vary the strength of each electromagnet's field through pulse-width-modulation (PWM), a common technique for driving electric motors at different speeds by sending them pulses of various duty cycles depending on the speed at which one wants the motor to turn. We can move objects between individual electromagnets by combining the magnetic fields of several adjacent electromagnets, each set to a different strength through PWM, so that the object is attracted to a point somewhere in between the electromagnets.

Movable Objects

Though all of the pucks that we use with the system contain permanent magnets, the system is capable of moving any lightweight ferromagnetic object, such as a paperclip or steel bolt. Our acrylic pucks are built to hold powerful (1.1 Tesla) neodymium magnets, each 1.26cm x 1.26cm x 0.63cm (½" x ½" x ¼"), in order to provide the strong attractive forces needed to drag the 14g (0.5oz) pucks around on the Active Workbench's acrylic surface. The pucks themselves measure 2.54cm (1") diameter x 2.54cm (1") length, and also contain a battery, an IR led for vision tracking and a switch (to save the battery when not in use). Though the inclusion of a battery violates one of our design goals, we hope to switch to a passive radio frequency tag for object tracking in our future work. A felt pad is attached to the bottom of each puck, providing the necessary kinetic friction to keep the object from sliding around uncontrollably on the table's surface -- bare acrylic-on-acrylic is too slippery, resulting in oscillations as the puck slides past its goal and is then attracted back to it.

The 0.63cm (¼") thickness of the felt pad, combined with the 0.63cm (¼") bottommost acrylic layer of the puck, results in the permanent magnet being about 1.26cm (½") from the surface of the table, which is itself a piece of 0.63cm (¼") acrylic. This positions the permanent magnet about 1.89cm (¾") above the tops of the electromagnets. The height of the permanent magnet in the puck has significant effects on the performance of the system, since the neodymium magnet is strong enough to be attracted to the ferrous cores of the underlying electromagnets even when they are not activated. This attraction increases friction on the object, which affects the puck's ability to slide on the surface. We found the amount of friction between the pucks and the table to be a critical element in the system's ability to create smooth 2D motion. In general, we observed that static friction (the friction between the object and the surface when the object is at rest) inhibited smooth motion of the pucks, while kinetic friction facilitated smooth motion by controlling oscillations. After trying a variety of materials, we found that felt on acrylic gave adequate frictional characteristics, but other materials may yield better results in the future.

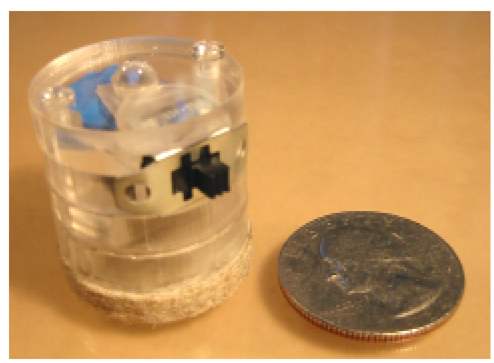

Figure 6: Our puck design includes a permanent magnet and an infrared LED for vision tracking.

The current design of our pucks is somewhat limited in that we cannot control their rotation on the surface. Our experiments show that the electromagnetic mechanism of the Actuated Workbench could be used to control the pucks' orientation if we design larger pucks containing multiple magnets. This is discussed in further detail in the "Future Work" section.

Vision Tracking

Electromagnetic radio frequency sensing technology is evolving rapidly to provide robust, low-latency object tracking on table surfaces [13][5]. Though this technology is used often in interactive workbench systems, we encountered preliminary difficulties using electromagnetic sensing in conjunction with our magnetic actuation system, because of distortions created by the strong magnetic fields of our electromagnets. We believe that this problem can be overcome in the future through careful calibration of the tracking system, but to avoid these difficulties in the short term, we chose vision tracking for our system prototype.

We embed each puck with a small battery and an infrared LED, and suspend a camera directly above the Actuated Workbench. Adding an infrared filter to the camera blocks out ambient fluorescent light, making the video signal easy to process (Figure 7). We used an inexpensive *Intel PC Camera Pro* USB CCD camera and were able to achieve a tracking rate of 30 updates per second. This frame rate, though high from a human interaction standpoint, is somewhat slow from a control systems perspective. However, since this is a limitation of the capture rate of the device, we could improve tracking speed by replacing the USB webcam with a high-end framegrabber.

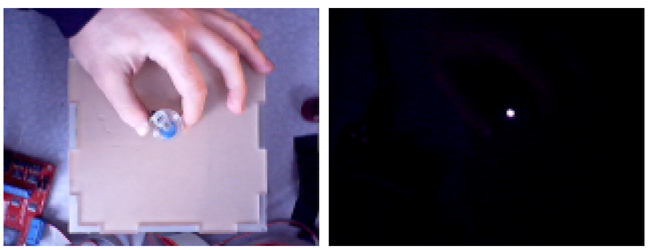

Figure 7: Overhead view of the Actuated Workbench from vision camera without IR filter (left) and with IR filter (right).

Puck tracking is accomplished by detecting bright regions within the image. We use the image histogram to compute a threshold value on startup, and the threshold is used to divide the grayscale image into zeros and ones. We then employ standard blob-analysis techniques [9] to determine the longest horizontal segments. We can track multiple pucks simultaneously in real-time using an association method [1] to distinguish the pucks between frames. In every frame, we associate each observed location with the closest puck location in the previous frame. This association method is not wholly reliable, since puck paths that cross each other can interchange identities, but since the permanent magnets inside of the pucks tend to repel each other, the pucks rarely get close enough for this method to break down.

MOTION CONTROL AND INTERPOLATION

Manhattan Motion

Moving the puck across the table in a linear "Manhattan" fashion (in straight lines at right angles to each other) is a straightforward process. The puck can be moved to any grid cell on the table by consecutively activating the electromagnets in neighboring cells at full strength, as shown in Figure 8. Using Manhattan motion, objects can be moved across the table at rates on the order of 25cm/sec (10in/sec).

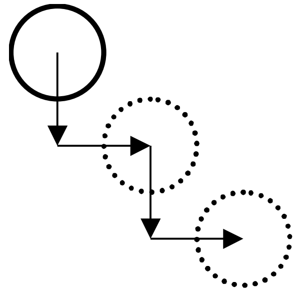

Figure 8: "Manhattan" motion between points.

If the board is operating in an "open loop" mode, in which we do not know the current position of the puck, we can still move it to any point on the table using a sweeping algorithm (Figure 9). To move the puck to the point (x,y) we begin by activating the outermost rows (0 and 7) and then sweeping inward until the target row y is reached. Next, we begin with the outermost columns, and sweep inward in a similar fashion until we reach column x. This method was useful for moving the puck to the far corners of the table to calibrate the vision tracking system.

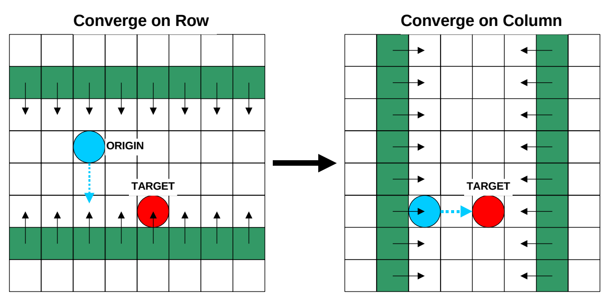

Figure 9: Sweeping to a desired point from an unknown origin.

Smooth Motion

Though Manhattan motion can move the pucks rapidly across the table, it is not so useful for recreating the smooth motions with which a user moves objects on an interactive workbench's surface. Since we can control the strength of individual electromagnets through pulse-width-modulation, we can perform a sort of physical anti-aliasing to create smooth travel paths along the table between the discrete positions of the electromagnets. In this section we describe our mathematical model of the Actuated Workbench and present the equations we used in our software to produce smooth motion along arbitrary paths. For a detailed derivation of these equations, refer to the appendix.

Figure 10 is a vector diagram showing our force model. A single puck on the surface of the Actuated Workbench is subject to gravitational force, frictional force, the magnetic forces of attraction between the puck and the activated electromagnets, and the force of attraction between the permanent magnet in the puck and the iron cores of the electromagnets beneath.

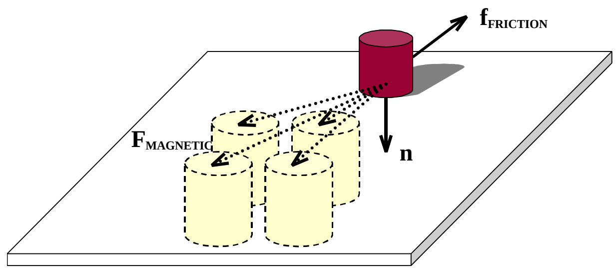

Figure 10: The electromagnets (lower left) exert forces on the puck (upper right).

We add these forces to arrive at an equation for the total force on the puck in terms of $\mathbf{f}_{\text{MAG-NET}}$, the total force of magnetic attraction, and $\mathbf{f}_{\text{FRICTION-NET}}$, the net friction:

$$\mathbf{f}_{\text{TOTAL}} = \mathbf{f}_{\text{MAG-NET}} \cdot \hat{\mathbf{x}} + \mathbf{f}_{\text{MAG-NET}} \cdot \hat{\mathbf{y}} + \mathbf{f}_{\text{FRICTION-NET}}$$

$$\mathbf{f}_{\text{MAG-NET}} = \sum_i \frac{a_i \mathbf{f}_{\text{E}}}{(x - x_i)^2 + (y - y_i)^2 + z_{\text{S}}^2}$$

$$\left\|\mathbf{f}_{\text{FRICTION-NET}}\right\| = m(mg + \left\|\mathbf{f}_{\text{P}}\right\| / z_{\text{S}}^2 + \left\|\mathbf{f}_{\text{MAG-NET}} \cdot \hat{\mathbf{z}}\right\|)$$

Here the puck is positioned at (x, y) and each electromagnet i is positioned at (x_i, y_i) with duty cycle a_i. $\mathbf{f}_{\text{E}}$ and $\mathbf{f}_{\text{P}}$ are constant-magnitude forces of attraction proportional to the strengths of the electromagnet and the permanent magnet in the puck, z_{S} is the vertical separation between the puck and the electromagnets, m is the mass of the puck, g is the acceleration due to gravity, m is a dimensionless coefficient of friction, and $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$ are the standard unit vectors.

In reality, the magnetic fields of the activated electromagnets interact in a somewhat more complex manner (Figure 11). Nonetheless, the force-summing model just described, in which electromagnets are treated independently of one another, is a reasonable method of approximating the more complicated underlying physics, since the summation of multiple forces due to individual magnets parallels the summation of multiple magnetic fields to produce a single force.

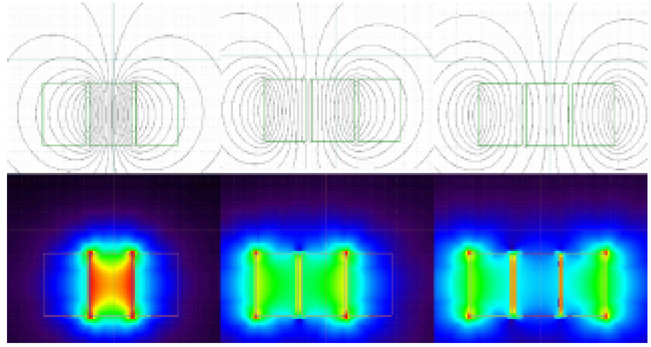

Figure 11: Magnetic field interactions between electromagnets. The top images show magnetic flux lines and the bottom images map flux density to brightness. The three image pairs show the fields resulting from a single center magnet turned on (left), the left and center magnets turned on (center), and all three magnets turned on (right). The effect of this field-shifting behavior can be modeled approximately using force summation. These images were generated with the *VisiMag* software package [2].

To produce a puck displacement $\Delta\mathbf{x}$ during a loop interval Δt, we activate the electromagnets with duty cycles a_i such that

$$\mathbf{f}_{\text{TOTAL}} = 2m(\Delta\mathbf{x} - \mathbf{v}_0 \Delta t) / \Delta t^2$$

This equation assumes we are keeping track of the puck's instantaneous velocity $\mathbf{v}_0$. If we are using the Actuated Workbench in an "open-loop" mode in which we do not track the instantaneous position or velocity of the puck, we can still compute a reasonable estimate of $\mathbf{f}_{\text{TOTAL}}$ using a dead reckoning approach based on assumptions about how the previous electromagnet settings have affected the position and velocity of our puck according to our force model.

There are many ways in which we could activate the electromagnets so that the resulting forces summed to the desired value of $\mathbf{f}_{\text{TOTAL}}$. In the next section, we describe several different methods for choosing the magnet values.

ANTI-ALIASING TECHNIQUES

In computer graphics, the mathematical model of an image is a continuous analog signal that is sampled at discrete points called pixels. Aliasing occurs when the sampling frequency is too low for the signal frequency, resulting in a coarse image in which smooth curves are converted to steps and jagged outcrops. The anti-aliasing technique of prefiltering combats this problem by treating each pixel as an area, and computing pixel color based on the overlap of the scene's objects with a pixel's area.

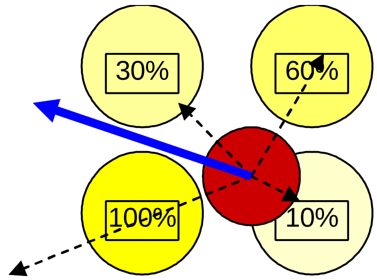

Figure 12: Four electromagnets with different duty cycles combine to produce a force with a new direction and magnitude.

With the Actuated Workbench, we are faced with a similar problem: we wish to render an analog signal (in this case, a force of a particular direction and magnitude) using a discrete array of cells (variable-duty electromagnets). To do so, we can employ a similar technique: the strength of each electromagnet is determined by the "overlap" of its magnetic flux lines with the location of the point force. Figure 12 shows a configuration in which the forces of four neighboring electromagnets of different duty cycles combine to create a single force of a new magnitude and direction.

"Dot"-based Anti-aliasing

The simplest algorithm for anti-aliasing draws the computer graphics equivalent of a smoothed dot centered at the location of desired travel. Given a desired force vector with head at point (x,y), we compute the distance from each electromagnet to (x,y), and set its duty cycle in inverse proportion to this distance. As in computer graphics, we can choose any number of falloff metrics. We experimented with Gaussian falloff, but found that in practice it was no better than a simple linear falloff metric.

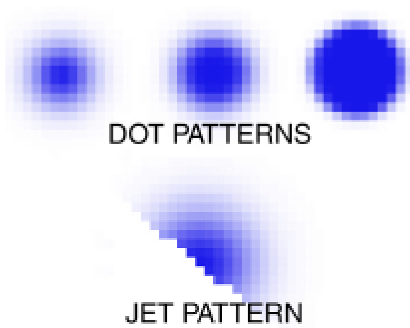

Figure 14: "Dot" and "Jet" equivalents in computer graphics (using a higher resolution grid than is present in our system). The three dots use different falloff metrics.

"Jet"-based Anti-aliasing

A drawback of the dot-based method is that it limits the puck's top speed of travel to about 15cm/sec (6in/sec). In order to produce enough force to move the puck, the center of the dot must be positioned close to the puck, and the forces produced by some of the activated electromagnets will pull the puck backwards against the desired direction of travel (Figure 13).

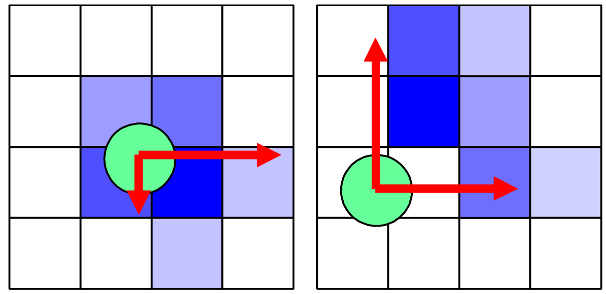

Figure 13: Anti-aliasing methods. The squares represent magnet cells, and intensity of each shaded square corresponds to the duty cycle of the magnet. The "dot" technique (left) results in slower travel than the "jet" technique (right).

If we know the position of the puck and the direction of travel that we hope to produce, we can pull the puck using only the electromagnets located in this direction relative to the puck. To do so, we first compute the vector from each electromagnet to the target (*x*,*y*), and then compute the scalar projection of this vector onto the direction-of-travel vector. Taking the set of vectors of positive magnitude produces a collection of forces resembling a "jet" in fluid mechanics (Figure 15). Jet-based movement can move pucks across the table almost as fast as Manhattan motion.

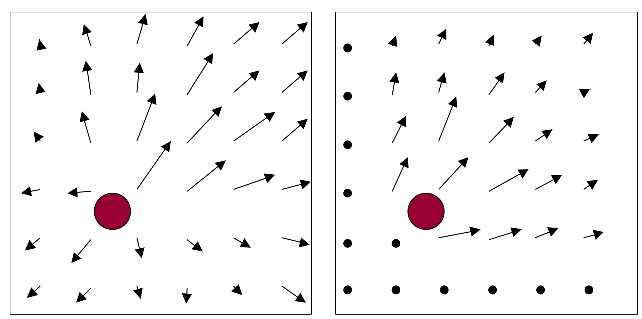

Figure 15: "Dot" force field (left) versus "Jet" force field (right).

APPLICATION IDEAS

Having developed a system meeting our design criteria for an interactive workbench actuation system, we can begin to imagine new interaction techniques and applications that our system can support. This section begins by extending some basic GUI functions into the physical domain, and then goes on to describe some higher level applications, including some solutions to old problems in interactive workbench interfaces. Many of these applications would require further development of the Actuated Workbench to address its limitations in speed, magnetic strength, scale, and resolution.

Basic GUI Functions

Search and retrieve. As the number of pucks increases in an interactive workbench system, it becomes more difficult for a user to keep track of every data item on the table, just as it is difficult to keep track of many graphical icons on a computer desktop. A search and retrieve function could respond to a user query by finding matching data items and either moving them to another place on the tabletop or wiggling them to get the user's attention.

Sort. A more powerful function would be one in which the computer could physically sort and arrange pucks on the table according to user-specified parameters. This could help the user organize a large number of data items before manually interacting with them.

History and Undo. As a user makes changes to data through physical input, she may wish to undo some changes. A physical undo in this system could move the pucks back to their positions before the last change. It could also show the user the exact sequence of movements she had performed. In this sense, both "undo" and "rewind" commands are possible.

Teaching and Guiding. Because the Actuated Workbench gives the computer the ability to recreate users' gestures with the pucks, it becomes possible for the computer to teach the user something about interacting with the system through physical gestures. If certain gestures are used in the interface to trigger certain commands (such as a shaking gesture to unbind a puck from a data item), then the computer can show a novice or a forgetful user how to make that gesture with the puck. This way, many of an application designer's commands can be taught to users without the need for intensive human coaching. In addition, if a user is uncertain how to proceed while using a problem-solving or simulation system, the computer could suggest a physical configuration of the pucks.

High Level Applications

Remote Collaboration. One advantage that interactive workbench interfaces offer is the ease with which multiple users can make simultaneous changes to the system. Users can observe each other's changes, and any user can reach out and physically change the shared layout without having to grab a mouse or other pointing device. This is not the case, however, when users are collaborating remotely. In this scenario, a mechanism for physical actuation of the pucks becomes valuable for synchronizing multiple physically separated workbench stations. Without such a mechanism, real-time physical synchronization of the two tables would not be possible, and inconsistencies could arise between the graphical projection and the physical state of the pucks on the table.

One example of a system that could benefit from physical synchronization is Urp [17]. In the Urp system, users manipulate physical models of buildings on a table and the computer displays simulation information in the form of projected "digital shadows" around the buildings. "Distributed Urp" (Durp) later attempted to create distributed workspaces between multiple remote users. Identical Urp systems were set up in two separate locations, and the two systems were synchronized through identical graphical projections onto the workbench. However, if a user in one location moved a building, only the "digital shadow" of the building, and not the physical model, would move in the remote location. In addition to facilitating the simple synchronization of these models, the Actuated workbench could recreate remote users' actual gestures with objects on the table, adding greatly to the "ghostly presence" [4] sought in remote collaboration interfaces.

Simulation and Display for Interacting Objects. The Actuated Workbench could be helpful in the scientific visualization of complex mechanical systems. For example, a solar system model in the manner of an orrery could be created on an interactive interface with full actuation of the planetary orbits. The user could change the physical properties of the planets or teach the computer new orbit paths, and then watch the resulting motions of the planets.

Similarly, the Actuated Workbench could be used to teach students about physics by demonstrating the attraction and repulsion of charged particles represented by pucks on the table. As a student moved the pucks around on the table, the system could make them rush together or fly apart to illustrate forces between the objects.

Entertainment. In addition to these more practical applications, the Actuated Workbench could be used to add a physical dimension to computer entertainment. Though motorized chess sets have existed for many years, they operate using a single electromagnet mounted on an *x-y* plotter mechanism, which are limited to moving one object at a time. The Actuated Workbench could provide a significant improvement to these devices, making them more flexible for a variety of games. Classic computer games like Pong could now be played using a physical puck and two physical paddles manipulated by the users. Distributed Pong could be played with a local user moving one paddle and the computer moving a remote user's paddle on the table. As we will discuss in the section on future work, the Actuated Workbench can be used to flip over thin, polarized magnetic pucks by rapidly reversing the polarity of the electromagnets. This could be used to play a physical game of *Reversi* with the computer. Finally, one could create painting or drawing programs in which a pen or brush was attached to the puck. The computer's movement of the puck could then be used to teach the user certain artistic gestures, or even handwriting movements.

RELATED WORK

The computer-controlled configuration of objects on a flat surface has been studied in both the HCI domain and in the realm of industrial mechanics. Some early systems such as

Seek [12] used robotic arms to arrange parts or objects on a table. Though an effective and dexterous method for computer control, the use of robotic arms would likely be distracting for interactive workbench systems. Moreover, it would be complicated and expensive to implement the multiple arms required to move multiple objects simultaneously. Recently, researchers in HCI and robotics have developed systems attempting to move objects without the use of robotic arms. We examine some of these for their applicability to interactive workbench systems.

In response to the problem encountered in the experiments with Distributed Urp, the PsyBench [4] system was prototyped using parts from a computerized chess set that moved magnetic pieces using an electromagnet mounted on an *x-y* plotter under the table. This allowed the position of objects in the two workspaces to be synchronized. Though similar to the Actuated Workbench in its use of magnetism to grab objects, the PsyBench prototype suffered a variety of implementation limitations. It was only capable of inaccurate, teetering movements of the objects, and it was limited to straight-line "Manhattan" motion. Furthermore, it was unable to control the orientation of the moving objects, and it could only move one object at a time.

Some recent robotics research targets actuation problems such as part feeding in factories, parcel sorting in distribution warehouses, and luggage sorting in airports. The Universal Planar Manipulator (UPM) [15] uses the horizontal vibration of a flat surface to move multiple objects at a time. Complex movements of specific objects on the surface are achieved using interference patterns of the vibration waves as they propagate across the surface. This system presents an effective way to manipulate many small parts without the need for motors or magnets, and its designers successfully use it in a closed-loop vision-tracking system. However, several aspects of the UPM's design detract from its usefulness in interactive workbench interfaces. First, in its present state, it is only capable of slow object translations and rotations (feed rates are on the order of millimeters per second, while our system's feed rates are on the order of centimeters or tens of centimeters per second). Second, the mechanism for vibrating the surface occupies space around the edges, preventing the easy tiling of multiple surfaces. Third, the system is noisy due to the mechanism needed to vibrate the flat surface and the sound of the vibrating objects. While not a problem in a factory assembly-line setting, this noise might be distracting for HCI.

Another system, the Modular Distributed Manipulator System (MDMS) [11] consists of an array of orthogonally oriented wheels that support and move objects through combined vector forces created by the rotating wheels. This actuation method presents a clever solution to the problem of friction by doing away with the friction between two flat surfaces. Instead of dragging or sliding objects, they are rolled along the tops of the wheels. Like the Actuated Workbench, the MDMS is scalable to larger areas, requiring only that more actuators be set up next to the existing array. The MDMS differs from our work in that it is intended for manipulating large parcels, factory materials, or pieces of luggage in a conveyor belt type situation. Moreover, the surface upon which the objects rest is neither flat nor continuous (because it is made up of many small wheels), making it unsuitable for the projection often used in interactive workbench interfaces.

CONCLUSIONS AND FUTURE WORK

With one exception, the Actuated Workbench satisfies the design considerations we established at the beginning of this paper. The system does not necessitate the building of larger pucks; it can move multiple pucks at the same time; it can recreate a range of user gestures with the pucks; and it is silent because its actuation mechanism has no moving parts. Unfortunately, we could not build our pucks as entirely passive devices because of the IR LED and battery needed for vision tracking. This and other limitations of the current system can be overcome in future work.

Tiling of Actuation Surfaces and Scale

Since the current actuation area is only 6.5" square, we plan to tile four to six of these arrays to form an actuation surface 13" to 19", which should be large enough for use with most interactive workbench interface systems. We also hope to explore using different sizes of electromagnets. Smaller electromagnets may yield higher resolution of object movement on the table, while larger or more powerful electromagnets may provide more force for moving objects, making it possible to provide stronger force feedback in interactive workbench interfaces.

Puck Modifications

We intend to make shorter, larger diameter pucks that fit better in the hand. These will probably require multiple magnets to provide enough force to move the additional mass. An advantage arises from the use of multiple magnets in the same puck: if the permanent magnets are placed in the puck with opposite polarities facing downward, it becomes possible to control the rotation of the puck by attracting each side of the puck with opposite magnetic fields. This solves a critical problem in interactive workbench systems like Urp, in which the orientation of the objects is significant. This technique again requires careful design, as the reverse-polarized magnets must be placed far enough apart in the puck that their forces do not interfere.

Use with Electromagnetic Tracking Technologies

Preliminary experiments suggest that it will be possible to use the Actuated Workbench's electromagnetic mechanism with some current electromagnetic tracking platforms. The integration of these two technologies will require careful placement of the magnets in relation to the tracking surface. It will also be necessary to dynamically recalibrate the tracking system to accommodate the constantly changing magnetic field of the actuation mechanism. Otherwise, different tracking technologies may need to be developed or integrated, such as a capacitive tracking platform similar to the technology used in DiamondTouch[5]. Another tracking possibility might use Hall-effect sensors under the table's surface to detect the permanent magnet in the puck. This would require careful timing in order to avoid spurious readings from activated electromagnets in the array.

New Types of Motion

In addition to controlling orientation, the Actuated Workbench is also capable of flipping over magnetic objects or launching them into the air by reversing the polarity of the electromagnet underneath the object. If the polarities of the electromagnet and the permanent magnet are the same, a strong repulsion results. This repulsion could be used to flip over a double-sided object, so that the opposite side is attracted downward.

Since the strength of the magnetic field can be quickly controlled in any part of the table, the Actuated Workbench is theoretically capable of levitating magnetic objects above the table. This would require constant object monitoring and rapid adjustments in field configuration, since a stable configuration of static magnetic forces is incapable of maintaining levitation, as stated by Earnshaw's Theorem [6]. Even if full levitation is not possible (or useful) in the future, small repulsive forces could be used to provide greater control over the friction between the pucks and the table surface. Giving the pucks a small "kick" to help them overcome static friction, or using repulsion as well as attraction to create a push-pull actuation system could result in new motion possibilities.

Coordinating Multiple Objects

Though our current system can manipulate and track multiple objects on the table, our software contains no mechanisms for preventing collisions between pucks. In the future, we hope to design path-planning algorithms to coordinate the simultaneous motion of multiple pucks. This would enable us to set the positions of multiple pucks to any configuration without the danger of destabilizing the system due to magnetic interactions between pucks.

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APPENDIX: Derivation of Control Equations

The magnitude of the frictional force on the moving puck is given by the equation

$$\|\mathbf{f}_{\text{FRICTION}}\| = m_{\text{k}}\|\mathbf{n}\|$$

where m_{k} is the dimensionless coefficient of kinetic friction and $\mathbf{n}$ is the normal force on the puck. The value of m_{k} can range from 0.05 to 1.5, depending on the choice of materials for the puck bottom and the table surface. When the puck is stationary, we replace m_{k} with the coefficient of static friction m_{s}. In general, $m_{\text{s}} > m_{\text{k}}$, but we simplifiy matters by trying to choose materials for which m_{s} and m_{k} were nearly identical.

When none of the electromagnets are activated, the normal force on the puck is the sum of the gravitational force on the puck and the attractive force between the permanent magnet in the puck and the iron cores of the electromagnets below. Since the iron cores are spaced at intervals, this attractive force varies with the position of the puck on the table, but our simplified model assumes that this variation is slight enough to be negligible. Substituting these values, the equation for friction becomes

$$\|\mathbf{f}_{\text{FRICTION}}\| = m(mg + \|\mathbf{f}_{\text{P}}\| / z_{\text{S}}^2)$$

where m is the mass of the puck, g is the acceleration due to gravity, $\mathbf{f}_{\text{P}}$ is a constant force of attraction proportional to the strength of the permanent magnet in the puck, and z_{S} is the vertical separation between the puck and the electromagnets. The z_{S} term is squared because the magnetic force between two objects attenuates in proportion to the square of the distance between the objects. In practice, we chose a value for z_{S} large enough to make the contribution of f_{P} negligible, but small enough that the attractive forces of the activated electromagnets are able to move the puck. With our current materials, we empirically found a z_{S} of 1.89cm (¾”) gave the best results.

We modeled the magnetic force between the puck and an activated electromagnet using the equation

$$\mathbf{f}_{\text{MAG}} = \frac{a\mathbf{f}_{\text{E}}}{x_{\text{S}}^2 + y_{\text{S}}^2 + z_{\text{S}}^2}$$

where a is the duty cycle of the pulse-width-modulated electromagnet (0-100%), $\mathbf{f}_{\text{E}}$ is a constant-magnitude force of attraction proportional to the strengths of the electromagnet and the permanent magnet in the puck, and x_{S} and y_{S} are the separation distances between the puck and the activated electromagnet along the horizontal axes. The direction of $\mathbf{f}_{\text{E}}$ is from the center of the puck to the center of the upper end of the electromagnet. Note that the *z* component of $\mathbf{f}_{\text{MAG}}$ will contribute to the normal force, increasing the magnitude of $\mathbf{f}_{\text{FRICTION}}$. This can actually be desirable: as the puck approaches its target, the *z*-component of $\mathbf{f}_{\text{MAG}}$ increases, increasing the friction and preventing the puck from overshooting its goal.

We can sum the contributions of each activated electromagnet to compute the net force on the puck due to the electromagnets:

$$\mathbf{f}_{\text{MAG-NET}} = \sum_i \frac{a_i \mathbf{f}_{\text{E}}}{(x - x_i)^2 + (y - y_i)^2 + z_{\text{S}}^2}$$

In this equation, the puck is positioned at (x, y) and each electromagnet i is positioned at (x_i, y_i) with duty cycle a_i.

Adding the *z* component of $\mathbf{f}_{\text{MAG-NET}}$ to the normal force in our friction equation, we reach the final equation for net friction:

$$\|\mathbf{f}_{\text{FRICTION-NET}}\| = m(mg + \|\mathbf{f}_{\text{P}}\| / z_{\text{S}}^2 + \|\mathbf{f}_{\text{MAG-NET}} \cdot \hat{\mathbf{z}}\|)$$

where $\hat{\mathbf{z}}$ is the unit vector in the direction of the positive *z*-axis. The direction of the friction vector $\mathbf{f}_{\text{FRICTION-NET}}$ is opposite the direction of the applied force, in this case the horizontal components of $\mathbf{f}_{\text{MAG-NET}}$. We are now ready to write an equation for the total horizontal force on the puck:

$$\mathbf{f}_{\text{TOTAL}} = \mathbf{f}_{\text{MAG-NET}} \cdot \hat{\mathbf{x}} + \mathbf{f}_{\text{MAG-NET}} \cdot \hat{\mathbf{y}} + \mathbf{f}_{\text{FRICTION-NET}}$$

where $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ are the positive unit vectors along the horizontal axes. The acceleration of the puck of the puck is proportional to this total force:

$$\mathbf{a}_{\text{PUCK}} = \mathbf{f}_{\text{TOTAL}} / m$$

The resulting velocity of the puck is given by the standard differential equation

$$\frac{\partial \mathbf{x}}{\partial t} = \mathbf{a}_{\text{PUCK}} t + \mathbf{v}_0$$

which can be reduced to the position equation

$$\mathbf{x}(t) = \frac{1}{2}\mathbf{a}_{\text{PUCK}} t^2 + \mathbf{v}_0 t + \mathbf{x}_0$$

where $\mathbf{v}_0$ and $\mathbf{x}_0$ are the instantaneous velocity and position of the puck, respectively. This means that if we keep track of the puck’s velocity and position, we can produce any desired displacement $\Delta\mathbf{x}$ of the puck during loop interval Δt by solving this equation for $\mathbf{a}_{\text{PUCK}}$ and in turn for $\mathbf{f}_{\text{TOTAL}}$:

$$\mathbf{f}_{\text{TOTAL}} = 2m(\Delta\mathbf{x} - \mathbf{v}_0 \Delta t) / \Delta t^2$$

We then find a combination of electromagnet settings a_i that produce this net force $\mathbf{f}_{\text{TOTAL}}$, as described in the section on anti-aliasing methods.