Tangible Interfaces for Remote Communication and Collaboration

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Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Media Arts and Sciences at the
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Abstract

This thesis presents inTouch, a new device enabling long distance communication through touch. inTouch is based on a concept called Synchronized Distributed Physical Objects, which employs telemanipulation technology to create the illusion that distant users are interacting with a shared physical object. I discuss the design and prototype implementation of inTouch, along with control strategies for extending the physical link over an arbitrary distance. User reactions to the prototype system suggest many similarities to direct touch interactions while, at the same time, point to new possibilities for object-mediated touch communication. I also present two initial experiments that begin to explore more objective properties of the haptic communication channel provided by inTouch and develop analysis techniques for future investigations.

This thesis also considers the broader implications of Synchronized Distributed Physical Objects in the design of distributed multi-user systems. Current interfaces for long distance communication and collaboration are largely rooted in GUI-based groupware and voice/video conferencing methodologies. In these approaches, interactions are limited to visual and auditory media, and shared environments are confined to the digital world. Synchronized Distributed Physical Objects presents a new method for creating distributed multi-user systems that place greater emphasis on touch and physicality.

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Contents

1 Introduction

Touch is a fundamental aspect of interpersonal communication. Whether a greeting handshake, an encouraging pat on the back, or a comforting hug, physical contact is a basic means through which people achieve a sense of connection, indicate intention, and express emotion. Yet while many traditional technologies allow long-distance communication through sound or image, none are designed for expression through touch. Telephones, videoconferencing tools, and email systems stimulate the ears and the eyes, but not the hands. Current research in Computer Supported Cooperative Work (CSCW) has likewise been focused on the visual and auditory extension of space, while largely neglecting the tactile.

This thesis explores ways to bridge this gap and enable physical communication over distance. The core of the thesis is the inTouch system, a “tangible telephone” that provides distant users with a channel for expression through touch. inTouch is based on a concept called Synchronized Distributed Physical Objects, which employs telemanipulation technology to create the illusion that distant users are interacting with shared physical objects.

The remainder of this chapter describes the background and motivation of this thesis, as well as related work. Chapter 2 then describes the design and prototype implementation of the inTouch system. Chapter 3 continues with a more detailed description of the control algorithm used in the system and a discussion of the technical challenges in extending inTouch over arbitrary distance. Chapter 4 reflects on user reactions to inTouch. Initial experiments with inTouch are described in Chapter 5. In Chapter 6 I generalize the notion of Synchronized Distributed Physical Objects, pointing to applications for remote collaboration and shared workspace design. As an example, I present, PSyBench, a shared physical workspace across distance which enables distributed Tangible User Interfaces.

1.1 Background and Motivation

> As an adult human being, you can communicate with me in a variety of ways. I can read what you write, listen to the words you speak, hear your laughter and your cries, look at the expressions on your face, watch the actions you perform, smell the scent you wear and feel your embrace. In ordinary speech we might refer to these interactions as 'making contact' or 'keeping in touch', and yet only the last one on the list involves bodily contact. All the others operate at a distance. The use of words like 'contact' and 'touch' to cover such activities as writing, vocalization and visual signaling is, when considered objectively, strange and rather revealing. It is as if we are automatically accepting that bodily contact is the most basic form of communication. [Morris 1971]

The information age has long emphasized the development of audio-visual based technologies. As a result, we are now immersed in media technologies that allow us to disseminate and collect information in greater volumes, faster, and more efficiently than ever before. At the same time, this media structure has served as an extension of our eyes and ears, allowing us to communicate with distant friends and establish contact with strangers abroad. In this focus on information exchange, however, we have neglected what is often considered our most basic form of communication, physical contact ([Hardison 1980], [Katz 1989], [Montague 1978], [Morris 1971]).

Although the audio and visual channels are superb at transmitting information, they cannot compare to the intimacy and vitality of touch. One need only compare the impact of a handshake or hug to a verbal or visual greeting to appreciate the emotional power of physical contact. As Morris expresses, "The ability that physical feelings have to transmit emotional feelings is truly astonishing" [Morris 1971]. To understand why this is true, we will briefly consider a few related properties of touch.

1.1.1 Arousal

At perhaps the most basic level, physical contact is arousing. Being touched evokes a heightened state of awareness that can be taken advantage of as a way to communicate intensity and gain attention. As Reeves and Nass explain:

> Interpersonal distance dictates the intensity of responses. Standing close turns up the volume knob and heightens concerns about personal pleasure and pain. Close is arousing. When arousal increases, people are more focused on the cause of the excitement, they are more attentive and they remember more. There are also physiological preparations for possible action. [Reeves 1996]

As the closest that one person can be to another, it is not surprising that touch is often used to signal great importance when initiating as well as during conversation. For example, if it is critical that someone pays close attention to what we are saying, we may grab a hold of their hand or touch their shoulder.

1.1.2 Intimacy

More than our other senses, touch also evokes a basic and compelling sense of intimacy. Our eyes and ears allow us to sense at a distance, to sense the world as it exists apart from us. But touch defines our physical self and its connection to the world around us. Touch is immediate and personal. The intimacy of physical contact is intensified by the fact that, unlike seeing or hearing, touching is a shared experience. When you touch someone or something, you are necessarily allowing yourself to be touched and understood as well. Coupled with the fact that physical contact brings with it the potential to cause physical harm, touch can also be a very powerful signal of trust and camaraderie.

1.1.3 Comfort and Caring

The psychological literature additionally connects the feeling of comfort and emotional closeness evoked by touch to early childhood experiences ([Montague 1978], [Morris 1971]). In early childhood, touch is the most dominant sense given both its associations to sustenance, as well as its connection to earlier life in the womb. Partial recreation of physical sensations from prenatal life by holding and hugging is considered vital to an infant's survival. In fact, various studies have shown that an infant deprived of physical contact with another human will soon die (see [Montague 1978]). The feelings of comfort and caring evoked by touch in adulthood are then seen in terms of their connection with these early experiences. Many studies even suggest that physical contact is basic need of humans throughout their lifetime, which when absent has severe psychological consequences.

1.1.4 Proof of Existence

Another interesting perspective on touch considers its impact in terms of our sense of reality. Although we can acquire more information about the world more quickly with our other senses, touch seems to be of primary importance when determining the reality of the world around us and our own existence. It is interesting to note that we generally consider something seen but intangible as an illusion, while something tangible but unseen as merely invisible. Expressions such as, "pinch me so I know that I'm not dreaming", also point to the dominance of touch in our perception of reality. As Katz explains:

> Touch plays a far greater role than do the other senses in the development of belief in the reality of the external world. Nothing convinces us as much of the world's existence, as well as the reality of our own body, as the (often painful) collisions that occur between the body and its environment. What has been touched is the true *reality* that leads to *perception*.... [Katz 1989]

In this light, it is interesting to consider whether current telecommunication technology, which has given us the ability to see and hear people at a distance, has proven unsatisfactory in producing a compelling sense of presence, in part, because of the lack of physical interaction.

1.2 Related Work

The general importance of touch in understanding and affecting our environment has only recently been recognized in the field of Human-Computer Interaction (HCI). Traditional interfaces to the digital world have been based on the Graphical User Interface (GUI), which largely fails to address our sense of touch and offers only the generic keyboard and pointing device as tools for indirect manipulation of digital objects. Force-feedback devices and Tangible Interfaces pose two alternate approaches that begin to address this lack of physicality.

1.2.1 Force-Feedback

Force-feedback was originally developed in the field of teleoperation. In teleoperated systems, a user manipulates a control device that is linked to a distant slave robot. Research soon discovered that "feeding back" forces exerted on the slave to the controller could improve the performance of the operator (see [Hannaford 1991]).

In recent years, this force-feedback technology has matured and been applied to augment digital objects (be they virtual 3D objects or icons in a traditional GUI) with physical properties. Through the use of a device like Immersion Corporation's *Impulse Engine* [Jackson 1995] or SensAble Technologies' *PHANToM* [Massie 1994], for example, users can simultaneously manipulate and feel point forces from onscreen objects (Figure 1.1). (For a detailed overview of research in force-feedback interfaces, see [Burdea 1996]).

a) **b)**

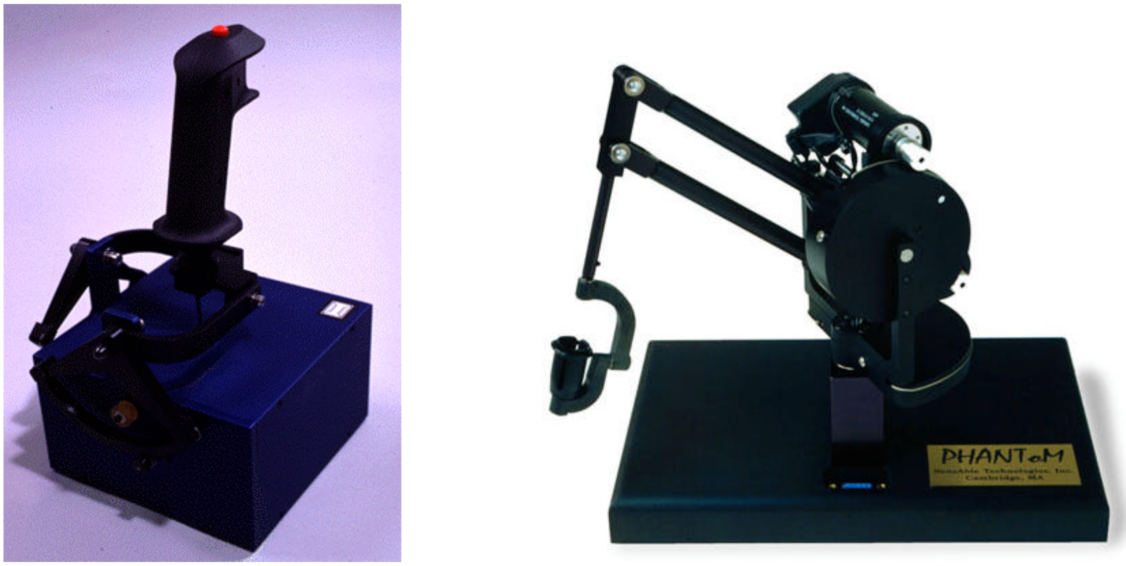

Figure 1.1 Force-Feedback Devices for augmenting on-screen objects. a) Immersion's Impulse Engine b) SensAble's PHANToM

1.2.2 Tangible Interfaces

Tangible Interfaces [Ishii 1997] present an alternate approach to addressing the lack of physicality in traditional human-computer interfaces that instead makes greater use of real physical objects as interface tools. Illuminating Light [Underkoffler 1998] is one example of a Tangible Interface for optical design and layout (Figure 1.2). In this system, users directly arrange and manipulate physical objects representing lasers, mirrors, lenses, and other optical components on an augmented tabletop. The positions of these objects are recognized by the system and the behavior of the laser light is projected onto the table in the same physical space as the optical components. Users are thus able to make full use their hands and bodies in affecting the simulation, as well as use their spatial and kinesthetic senses in understanding the arrangements. Other examples of Tangible Interfaces include the metaDESK [Ullmer 1997], Triangles [Gorbet 1998], and mediaBlocks [Ullmer 1998].

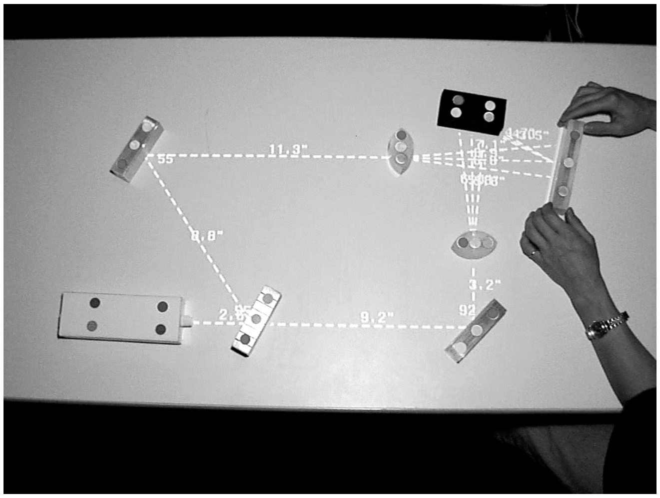

Figure 1.2 Illuminating Light, a Luminous-Tangible Interface for holography simulation.

1.2.2 Telehaptic Communication

Although sparse, there have been a few projects that explore haptic interpersonal communication (or telehaptic communication). *Telephonic Arm Wrestling* (Figure 1.3) provides a basic mechanism to simulate the feeling of arm wresting over a telephone line [White 1986].

Figure 1.3 Telephonic Arm Wrestling

Denta-Dentata (Figure 1.4) is an elementary "hand holding" device that communicates one bit of information over the phone line to activate a mechanism that can squeeze a user's hand [Goldberg 1993].

Figure 1.4 Denta-Dentata

Feather, Scent, and Shaker consists of a pair of linked "shaker" objects [Strong 1996]. Shaking one object causes the other to vibrate, and vice-versa. *HandJive* (Figure 1.5) is a pair of linked hand-held objects for playing haptic games [Fogg 1998]. Each object has a joystick-like controller that can be moved vertically or horizontally. A horizontal displacement of the local object causes a vertical displacement in the remote object, and vice-versa. *Kinesthetic Constructions* (Figure 1.6) explores the application of bilateral force-feedback to interpersonal communication [Schena 1995]. Schena describes a network of large modern sculptures distributed around the world where parts of each sculpture are hapticly connected to sculptures at other locations.

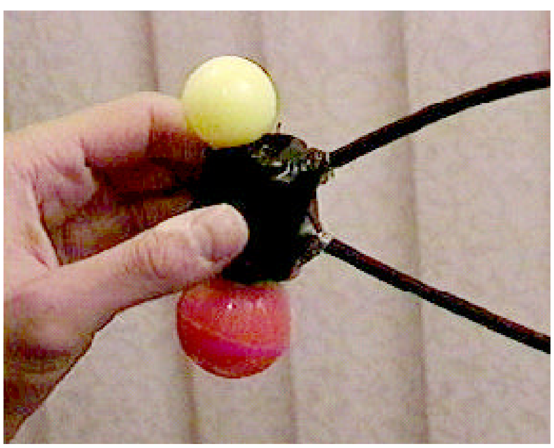

Figure 1.5 HandJive

Figure 1.6 Kinesthetic Constructions

2 inTouch Concept and Prototypes

Our aim with inTouch was to allow two distant users to sense each other's physical presence. In approaching this one might attempt to simulate direct physical contact across distance, transmitting *all* of the tactile information associated with such an interaction. However, this task is far beyond the current state of the art.

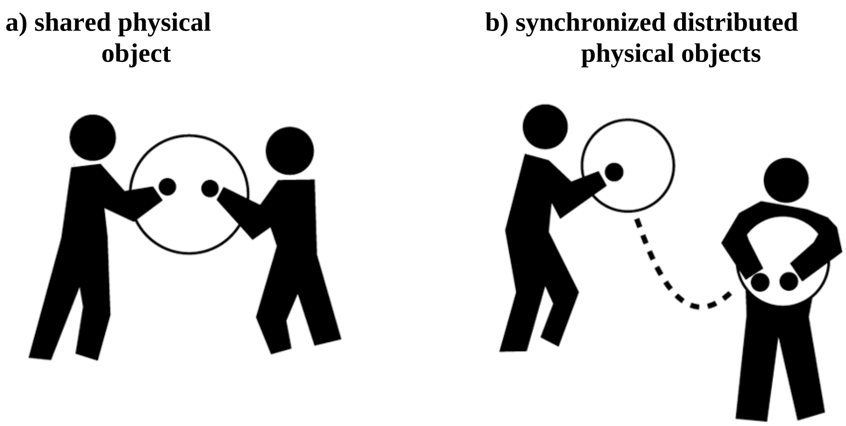

Figure 2.1 Object-mediated communication

Instead, we employ the concept of a "shared physical object." When in close proximity, two people can also communicate hapticly through simultaneous manipulation of a common object—a book, a picture frame, or a toy, for example (Figure 2.1a). Such an object serves to mediate the exchange of haptic information. Simulating object-mediated communication across distance is technologically feasible, as the object's dimensions and its degrees of freedom can be constrained.

We can create the illusion of a shared physical object across distance, by employing computer-controlled sensors and motors to synchronize the physical states of two separate identical objects. This virtual connection allows manipulation of one object to affect the state of the other distant object, and vice-versa. We call such coupled objects, "Synchronized Distributed Physical Objects" (Figure 2.1b).

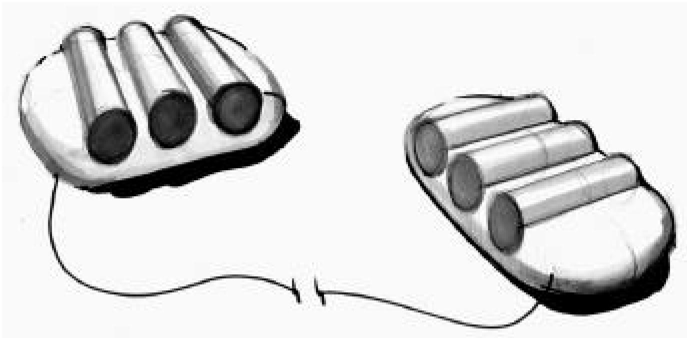

Figure 2.2 inTouch concept sketch.

InTouch is one example of Synchronized Distributed Physical Objects. In our design, the objects each consist of three cylindrical rollers embedded within a base (Figure 2.2). The rollers on each base are hapticly coupled, such that each one feels like it is physically linked to its counterpart on the other base. Two people separated by distance can then passively feel the other person's manipulation of the rollers, cooperatively move the "shared" rollers, or fight over the state of the rollers.

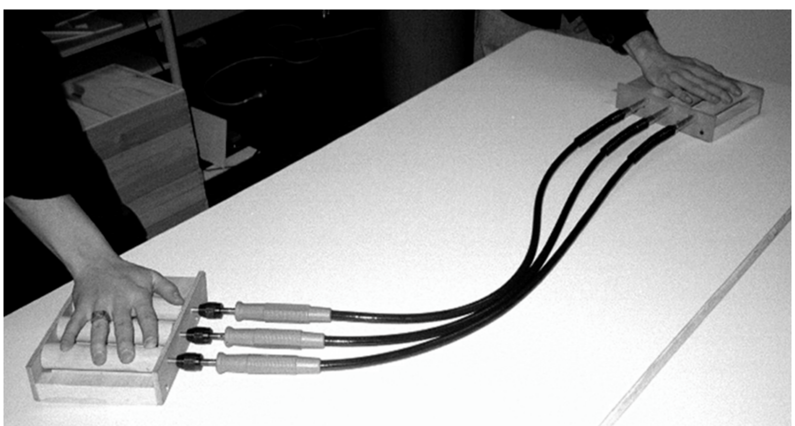

Figure 2.3 Mechanical mockup of inTouch (inTouch-0). Corresponding rollers are connected using flexible drive shafts.

2.1 Mechanical Mockup: inTouch-0

Figure 2.3 shows an early mockup of inTouch where corresponding rollers were actually mechanically connected using flexible drive shafts. This model was implemented in a graduate course on interface design, in October 1996, and was presented in class (see [Brave 1997a]). Users often described the interaction as fun or playful, with one student relating the experience to when he and his sister would use a broom to play tug-of-war as children. Some remarked that the lack of ability to pass concrete information made the medium uninteresting, while others applauded the subtle and abstract nature of the interaction. This mechanical mockup can been seen as a benchmark for creating the distributed version, since it is this feeling of direct connection that we are aiming to simulate across distance.

Figure 2.4 Prototype of inTouch where corresponding rollers are connected virtually, using force-feedback technology.

2.2 Standalone Prototype: inTouch-1

InTouch-1 was created next to implement the connection between rollers, virtually, using force-feedback technology (Figure 2.4). Ideally, the goal is to have virtually connected rollers that behave identically to the mechanically connected rollers in inTouch-0.

The system architecture for inTouch-1 is shown in Figure 2.5. Hewlett Packard optical position encoders were used to monitor the physical states of the rollers (positions were read directly, other values were interpolated) and high performance Maxon DC motors were used to synchronize those states. A 200MHz Pentium PC controlled all motor/encoder units (one unit for each roller) using Immersion Corporation's Impulse Drive Board 1.0 boards and 2-Axis Card 1.0 ISA cards.

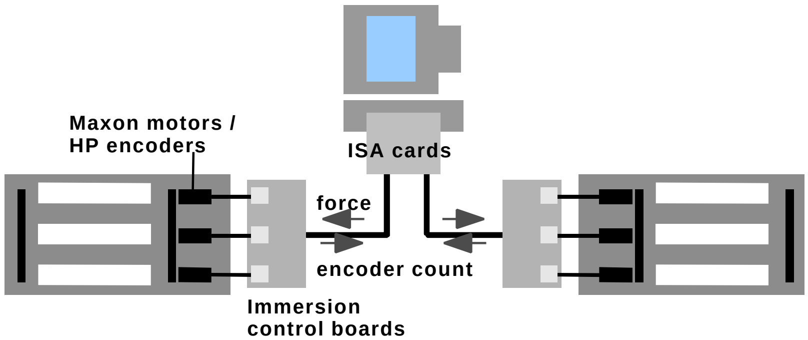

Figure 2.5 inTouch-1 system architecture (standalone prototype)

The control algorithm that ran on the host PC simulates a highly damped, stiff rotary spring between corresponding rollers. In other words, the algorithm looks at the difference in position of each pair of "connected" rollers and applies a restoring force, proportional to that difference, to bring the rollers together (see Chapter 3 for an in depth discussion of the control algorithm and optimization).

The first prototype of inTouch-1 was completed in March 1997, and has been demonstrated at sponsor meetings and at the 1997 Ars Electronica Festival [Brave 1997b], as well as tested internally. People who knew the previous version, inTouch-0, were surprised at how closely the interaction matched the mechanical mockup. In total, more than 500 people have tried inTouch, several of whom have made enthusiastic requests for the system to truly "keep in touch" with distant family and loved ones. We will discuss user reactions to this prototype in more detail in Chapter 4.

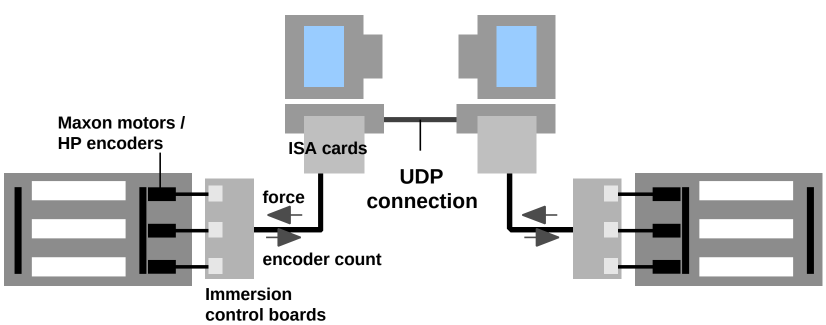

Figure 2.6 inTouch-2 system architecture

2.3 Networked Prototype: inTouch-2

Our current prototype, inTouch-2, allows the virtual connection of inTouch-1 to be extended over arbitrary distance, using the Internet.

The system architecture for inTouch-2 is shown in Figure 2.6. The architecture is identical to that of inTouch-1 except that the two sets of three rollers run on separate host computers, distributed over a standard network. Positions and velocities of the local rollers are passed to the remote computer using User Datagram Protocol (UDP).

The basic control algorithm for the networked design is also the same as that for inTouch-1. Each computer simply calculates the forces to impart to its three rollers given the state of each local roller (received from the local control hardware) and the most recently received position and velocity of the corresponding remote roller (passed over the network by the other PC).

We have so far distributed inTouch-2 over the local area network in our building. At this distance, with a little modification to the control algorithm (see Chapter 3), inTouch-2 behaves identically to inTouch-1. Simulations of longer distances, and consequently longer network delays, have shown promise in extending inTouch over arbitrary distances (see Chapter 3).

2.4 inTouch Design Rationale

2.4.1 Seamless Transition from Active to Passive Interaction

One reason that rollers were chosen as the manipulable part of the shared object was because they allow both passive and active interaction between users. A user can actively "grab" and manipulate the rollers by applying enough contact force to minimize slippage under the hand. In this way, the motion of the hand is directly translated to the rollers and the interaction is a kinesthetic one. If both users manipulate the rollers in this way, the interaction is fairly equal and mutual, like a handshake or a hug. Alternatively, one user could allow the rollers to slide comfortably beneath the hand, interacting in a more tactile and passive way, feeling but not affecting the motion of the rollers—like getting a pat on the back.

Interactions falling between these two extremes, reflecting various levels of engagement with the rollers, are also clearly possible. To compare, an object like a joystick is most likely to be used only in an active way, since it requires the user to grab the device. The roller can be engaged more passively than a joystick shape because of its symmetry along the axis of rotation (degree of freedom). When the roller's state changes, it moves, but the general shape is unchanged. This allows a users hand (or other body part) to remain at a constant position relative to the device and simply feel the movement. As you can imagine, passively feeling a joystick would be quite difficult.

2.4.2 Type of Motion (bounded/unbounded, size of motion)

The type of motion capable with the device can have a large effect on the expression and interpretation of emotions. It may, for example, be difficult to express anger in a device with a half-inch linear range of motion. The boundaries of the motion can also be very important. The choice of rollers as the manipulable part of the object was, in part, for this reason. The rollers can be rotated in either a clockwise or counterclockwise direction forever. Unlike a joystick or throttle, for example, where the motion of the device is bounded, the roller affords more fluid and continuous strokes (see Figure 2.7). Although the roller has the potential to be manipulated aggressively, thrashing between bounds is not possible.

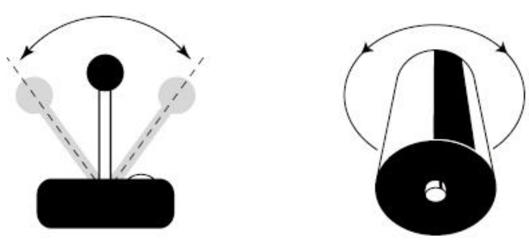

Figure 2.7 Bounded motion of joystick vs. unbounded motion of roller

For this reason, we felt that the motion of the roller was more appropriate for the expression of subtle emotion states than a bounded motion. The bounds on the motion could also be more complicated that this affording different types of interactions. One could imagine a joystick-like device with a circular instead of square boundary that affords both more aggressive thrashing from one side of the circle to the other and more fluid strokes around the perimeter.

2.4.3 Mechanical Complexity (degrees of freedom, spatial complexity, resolution)

We made the decision to use *three* rollers for a combination of functional and aesthetic reasons. Because we wanted the user to be able to feel or activate all of the rollers simultaneously, with one hand, the more rollers within the object, the smaller each roller had to be. Three was chosen as a compromise between the higher spatial resolution provided by more rollers and a greater surface area to "grab" and interact with possible with fewer rollers. The three rollers also gave a visual balance to the design, suggesting its rotational movement and drawing people to touch the rollers.

There are three main aspects of movement that a user may want to express through a device: position, motion, and expression. Each of these different aspects is afforded differently by the mechanical complexity of the design.

The higher the number of degrees of freedom in an object, the more complex the motion that can be translated. InTouch is composed of three one-degree of freedom objects, each object allowing only simple linear motion. A joystick, a two-degree of freedom device (e.g. *Impulse Engine* [Jackson 1995]), allows for more complex planar motions. If two three-degree of freedom devices (e.g. *PHANToM* [Massie 1994]) were connected you could translate 3D motions. You could imagine up to six degrees of freedom allowing for x, y, z, roll, pitch, and yaw. The more degrees of freedom, the more complex the motions can be.

The complexity of the motion, however, is secondary in importance to the expression of the motion. With only one degree of freedom, it is possible to have an infinite number of intricate motions (imagine all of the different ways you can interact with a roller). The resolution of the device is a reflection on how intricate the motions can be. If the device is capable of producing only two magnitudes of force, the ability to translate an expressive motion is diminished. Another aspect of the resolution is the position resolution. The device may, for, example, have discrete positions in which it can be stable (e.g. *HandJive* [Fogg 1998]). We could imagine that, instead of a smoothly rotating roller, we could have a roller that moves in discrete increments of 10 degrees. This would likely also decrease the ability to translate the expression of the motion. A separate issue that also has an effect on the expression is the maximum force output. If a motion is occurring at forces above the maximum force output, all expression in the motion (including the intricacies) are lost as the device will be "maxed out".

A device can have any number of objects (with any number of degrees of freedom and resolution) spatially arranged on it. InTouch has three one degree of freedom high force and position resolution rollers arranged in one possible configuration. The larger the number of objects on the device, the more precise the translation of position. The spacing and location of the objects, also obviously affects what can be translated. Imagine a wall with a number of pegs, modestly spaced, protruding from it. If the pegs moved in and out (and also possibly turned) you could translate motion and expression on a singular peg, and position by interacting with different pegs. This notion of position includes not only position of a motion, but the position of the body in relation to the object. Imagine a hand-sized device with a 100x100 grid of pins. Such a device would be good, not only at translating the position of a point motion, but the position of part of the body itself since the entire hand, for example, can interact with the device at once. The peg wall, given its topology, could not translate the position of the hand, but could possibly translate the position of the entire body.

3 Control and Optimization

This chapter describes the control algorithm used for inTouch and inTouch-2 in greater detail. For the networked prototype, inTouch-2, we describe the consequences of delay in communication and propose strategies for minimizing its effect on system performance.

3.1 inTouch-1: Standalone Prototype

As mentioned previously, the control algorithm for inTouch connects corresponding rollers with a simulated, highly damped, stiff rotary spring. The equations to control a single pair of synchronized rollers is shown below:

$$t_0 = -K(q_0 - q_1) - B(\dot{q}_0 - \dot{q}_1)$$
$$t_1 = -K(q_1 - q_0) - B(\dot{q}_1 - \dot{q}_0)$$

$\theta_{0/1}$ = angular positions of the two "connected" rollers
$\tau_{0/1}$ = torque to exert on the corresponding roller
K = spring constant
B = damping constant

Figure 3.1 shows the equivalent linear system.

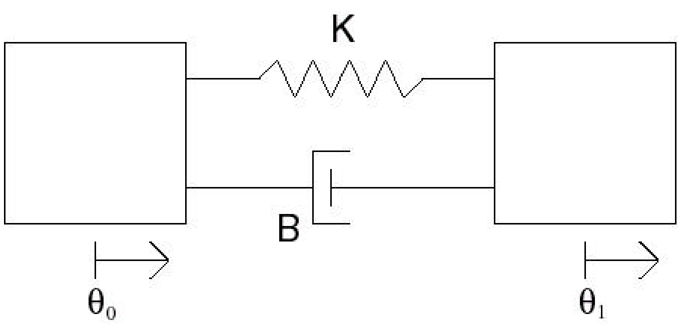

Figure 3.1 Linear equivalent system for equations connecting two corresponding rollers

Since the system architecture uses only optical position encoders for sensing, angular velocity is interpolated from the ten most recent position readings. Rollover of theta is corrected for so that the rollers behave as expected. It should be noted that the algorithm is symmetrical, giving no roller any advantage over its partner roller.

3.1.1 Optimization

To simulate the direct mechanical connection of inTouch-0 as closely as possible, we would ideally like to set the spring constant (K) extremely high. This constant, however, is limited by the discrete nature of the control algorithm (discrete position encoding, force output, and update interval). Too high of a spring constant for the given parameters will result in unwanted vibration. The maximum torque value is also limited by the strength of the motors.

With the control algorithm running at an update rate of 1 kHz, a spring constant equivalent to ~23mNm/rad gave excellent response and no unwanted vibrations. The maximum output torque of 140nNm for the Maxon motors was also high enough to give an excellent feeling of connection. It should be noted that finite K and maximum torque allow connected rollers to be forced apart from their consistent state; however, doing so merely results in a high force attempting to restore both rollers to that consistent state without causing any harm to the mechanical or control systems. The damping constant, B, was set so that the system appeared to be near critically damped.

3.1.2 Synchronizing More Than Two Objects

A slight remanipulation of the control equations makes clear how to extend the algorithm to synchronize more than two objects:

$$t_0 = -2K(q_0 - \frac{q_0 + q_1}{2}) - 2B(\dot{q}_0 - \frac{\dot{q}_0 + \dot{q}_1}{2})$$
$$t_1 = -2K(q_1 - \frac{q_1 + q_0}{2}) - 2B(\dot{q}_1 - \frac{\dot{q}_1 + \dot{q}_0}{2})$$

The equations can now also be seen as applying a restoring force on each roller proportional to its offset from the average position of the two rollers. We could clearly now extend this to three rollers for example, by applying a restoring force on each of the three "connected" rollers proportional to its offset from the average position of the three.

3.2 inTouch-2: Networked Prototype

As stated earlier, the basic control algorithm for the networked design, inTouch-2, is the same as the algorithm for inTouch-1. Each computer simply calculates the forces to impart to its rollers given the state of each local roller and the most recently received position and velocity of the corresponding remote roller:

Computer 0 runs:

$$t_0[t] = -K(q_0[t] - q_1[t-D]) - B(\dot{q}_0[t] - \dot{q}_1[t-D])$$

Computer 1 runs:

$$t_1[t] = -K(q_1[t] - q_0[t-D]) - B(\dot{q}_1[t] - \dot{q}_0[t-D])$$

t = time
D = communication latency (delay)

UDP was chosen as the protocol for communication between distributed objects because it is faster than Transmission Control Protocol (TCP) and the system does not require the reliability of TCP. Absolute position is passed between computers so that a dropped value results in no real loss of data; current values can be assumed to be valid until new values are received. Values are passed between computers along with a count so that values received out of order (i.e. values received that have a lower count than the highest count received so far) are ignored.

3.2.1 Phantom Friction

We have so far distributed inTouch-2 over the local area network in our building (average one-way UDP delay ~2ms). With this small delay, the basic control algorithm described in the previous section works extremely well. Compared to the standalone prototype, inTouch-1, the one difference in performance is that there appears to be more friction on the rollers in the distributed setup. With inTouch-1, the rollers spin relatively freely (a moderate push would keep a roller spinning for several seconds), while with inTouch-2 the rollers were much harder to spin. The reason for this is that the communication delay causes the local control algorithm to see the remote roller a few steps behind where it really is. So if a user spins a local roller, even if the remote roller is trying to keep up, the local setup sees it as dragging behind, resulting in a resistive force.

Figure 3.2a plots the positions of two "connected" rollers when a constant force is applied for 1/10 sec (time = 1000ms – 1100ms) and there is no delay. There appears to be a single line because the two roller positions are nearly the same throughout as we expect. We can see that the short "push" keeps the rollers spinning for a little over two seconds and that they rotate about 90 times. There is obviously some friction on the rollers since they do not continue spinning forever; however, this feels like very little qualitatively.

a) **b)**

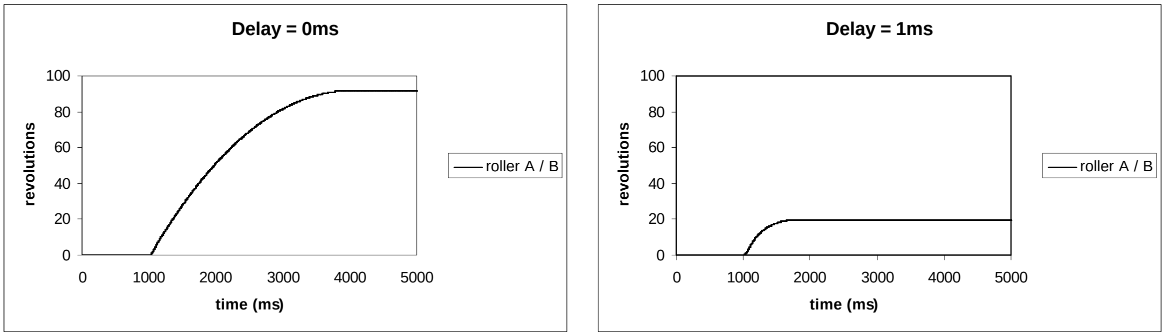

Figure 3.2 Effect of short push on roller position a) with no delay, b) with a 1ms delay

If we now introduce a mere single time-step delay (1ms) we already see a big difference; the rollers remain spinning for less than a second and only revolve 20 times (Figure 3.2b). As delay increases, this trend continues causing higher and higher unwanted friction.

To better understand this *phantom friction*, imagine first that there is no delay and two connected rollers are at the same position moving forward with the same velocity, V, at time t=0. Imagine that the mechanical setup of the rollers in the base is completely frictionless, so we can assume no external forces (we are also assuming no human intervention). There will also be no forces put on either roller at time t=0 by the control algorithm, since the algorithm gives a restoring force relative to the difference in positions of the rollers and the two rollers are at the same position. The rollers will therefore just continue moving forward in synch with velocity, V, as expected (Figure 3.3).

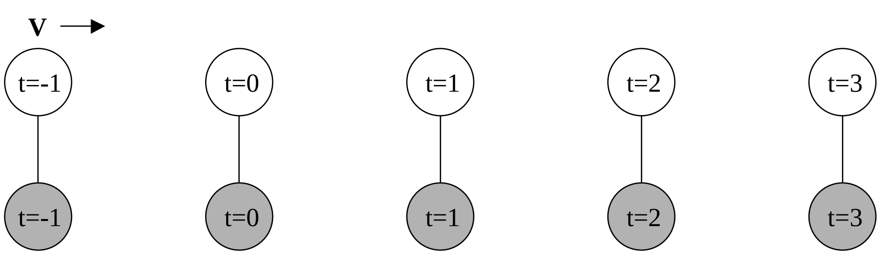

Figure 3.3 Connected rollers moving forward with constant velocity

Now imagine the same situation at time t=0, but with a single time-step delay. Although the two rollers are *actually* at the same position at t=0, the white roller will think that the gray roller is at the position it was at the last time-step, t = -1 (Figure 3.4a). A force will then be put on the white roller, opposing its current forward motion, in an attempt to synchronize it with the old position information from the gray roller. The exact same thing will happen with the gray roller, which will see the white roller's position one step back (Figure 3.4b).

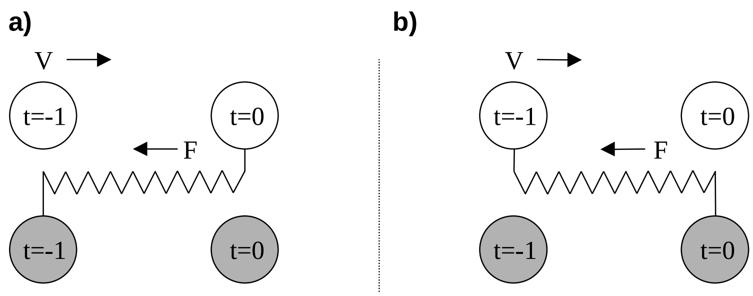

Figure 3.4 A resisting force is exerted on connected rollers when communication is delayed (position information is old)

This force will slow both rollers down equally so that at t=1, the white and gray rollers will be at the same position again but moving at a lower velocity. At t=1, the white roller will see the gray roller's position at t=0, and vice versa, and again an opposing force will be put on both rollers, slowing them further. This will continue until the rollers come to a stop (Figure 3.5).

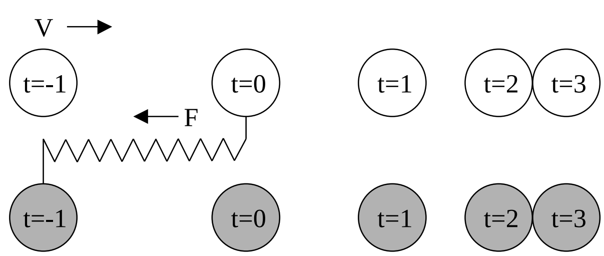

Figure 3.5 The resisting force due to delayed information will eventually stop the rollers forward movement

3.2.2 Prediction

The most straightforward solution to this problem is to add prediction into the algorithm so that the local setup is always estimating the true position of the remote roller given the old information. An easy predictor simply assumes the old velocity stays constant and estimates the new position with:

```
newPos = oldPos + oldVel * delay;
```

Because this simple predictor does not take into account the actual mechanical friction on the rollers, it ends up over-predicting a bit. This was fixed by trial and error, assuming that the friction can be modeled as velocity dependent. The actual algorithm used was:

newPos = oldPos + oldVel * delay – (0.1 * oldVel);

This basic method of prediction worked well up to a delay of around 5ms. Figure 3.6 compares a 5ms delay with and without this prediction.

a) b)

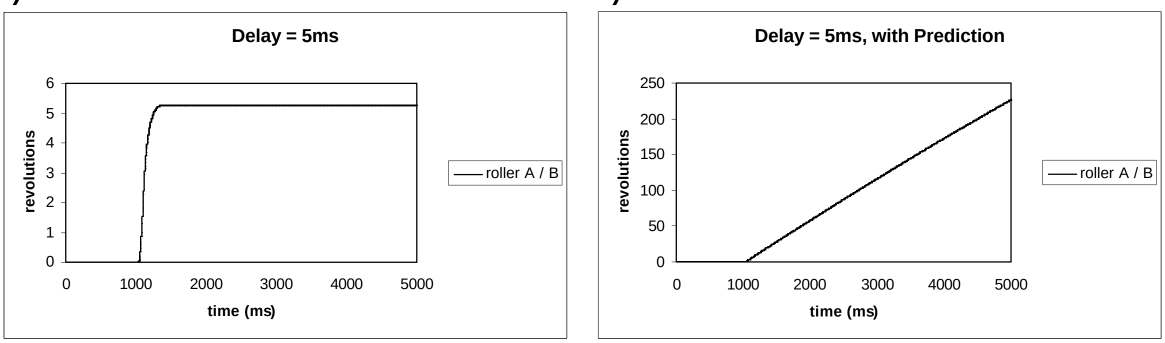

Figure 3.6 Effect of short push on roller position with a 5ms delay a) without prediction, b) with prediction

With a 5ms delay and no prediction, the rollers only revolve around 5 times before stopping. With prediction, however, the rollers behave as if there is no friction at all (not even the real mechanical friction), continuing with continuos velocity for an extremely long time (i.e. longer than I was willing to sit around). For these small delays, we can see that this simple velocity-dependent prediction is extremely helpful in eliminating the phantom friction effect as well as the real mechanical friction on the rollers.

As the delay increases above 5ms, this simple prediction is no longer accurate enough and the system becomes unstable. A more sophisticated prediction algorithm takes into account the forces that are being applied to the remote roller to predict its position. We, of course, don’t know the exact forces that are being applied to the remote roller, since we don’t know its real position. We do know, however, what positions we are sending it. We can then predict what force will be out on the remote roller at each update, given where we think it is and the position of ours we know it to be acting on. This then gives us a new predicted position and we iterate:

```
// Start with old position and velocity
predictedPos = remoteVel[DELAY];
predictedVel = remoteVel[DELAY];

// go through each update step for which you don't know the remote
// rollers position
for (int i = DELAY; i > 0; i--) {
      // at each update, predict what force will be put on the
      // remote roller
      predictedForce =  -K*(predictedPos – localPos[i])
                        -  B*(predictedVel – localVel[i]);

      // now predict what effect this force will have
      newVel = predictedVel + (predictedForce/effectiveMass) * aTime;
      predictedPos = predictedPos + 0.5*(newVel + predictedVel)*aTime;
      predictedVel = newVel;
}
```

This new more sophisticated predictor works well up to around 12ms (approximate average on-way UDP trip from MIT to University of Pennsylvania). But, at this delay we begin to see a new problem: we are predicting assuming no human intervention. This is fine when the delay is small, but as the delay increases, there is more time for a human to throw our prediction off. This problem becomes most obvious when two people are "fighting" over the state of a roller. Imagine that the two rollers are pulled a certain distance apart from each other and held there by both users. The idea behind the basic control algorithm is that this will result in a restoring force guiding the two back together, but what will happen with our new predictor? We will be assuming the correct restoring force is put on the remote roller and that it responds to it. If the delay is long enough, we will predict that it moves all the way back to the correct synchronized position. The resulting force on our roller with then be less than it should be, since the other person is actually holding the roller at the old unsynchronized position.

To fix this, we can also try to predict the actions of the human. Although this has obvious problems for large delays, on the order of tens of milliseconds, we can assume that the remote person's force on the roller remains constant. So if the remote person is resisting movement, for example, we can assume that this is true until we learn otherwise. Appendix 2 shows one simple attempt at doing this that dynamically adjusts the effectiveMass of the remote roller in the predictor to account for resistance placed on the roller by the person. The method is a basic Kalman Filter that looks at how well it predicted last time and adjusts the effectiveMass of the roller to try to account for any discrepancies. At 12ms, this method creates a compelling simulation of connectivity.

3.2.3 Instability

Unfortunately, phantom friction is not the only problem that results from delay. Figure 3.7 shows the effect of a 20 ms second delay, again with a 1/10 sec. push.

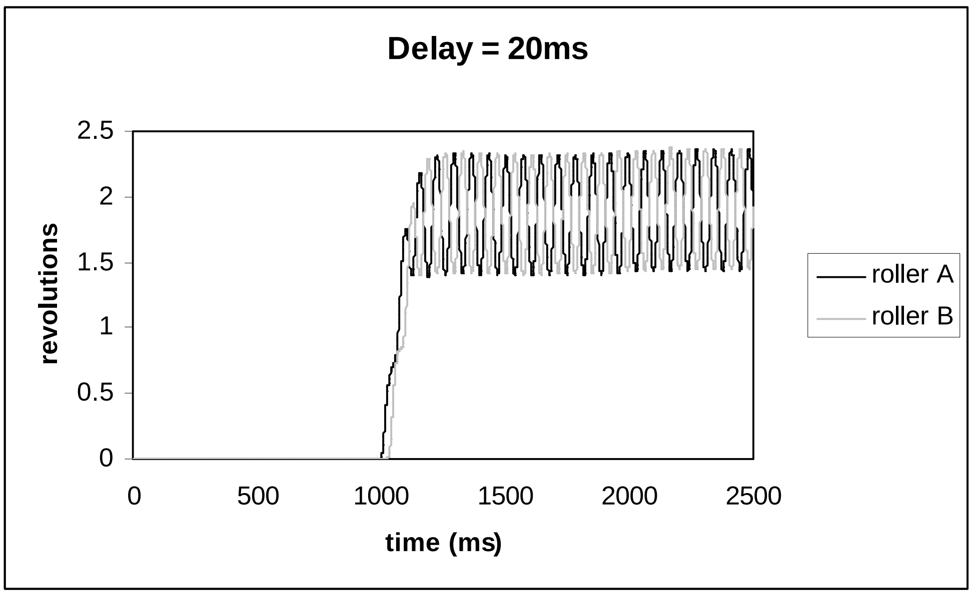

Figure 3.7 Effect of a 20ms delay on system stability

Here we see, not only phantom friction, but also unwanted oscillation. Although phantom friction is undesirable, the oscillation dominates any interaction and makes inTouch unusable. At a 40ms delay, we see the same basic effect only the period of oscillation is longer and the amplitude is bigger (Figure 3.8).

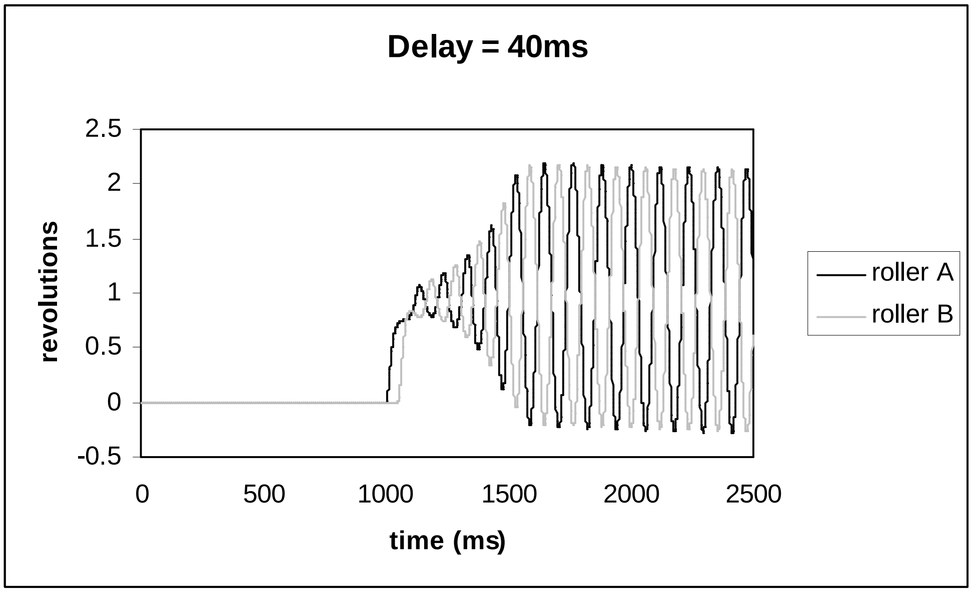

Figure 3.8 Effect of a 40ms delay on system stability

Although I will not go into detail here, simulations of the control algorithm under delay, indicate that the main effect of delayed information is to anti-damp the system. So, at some point, our efforts to damp the oscillation of the spring system with damping constant B is defeated and taken over by the anti-damping effect of delay. Delay also shifts the natural frequency (or spring constant, K) a bit as seen in the differing frequencies of oscillation at 20ms and 40ms, but this is clearly less important. Figure 3.8 (40ms delay) makes clear a beginning tendency toward exponential growth in amplitude of the oscillation, but finite maximum force and motor velocity keep the oscillation from continued growth.

3.2.4 Filtering

Theoretically, accurate prediction could alleviate this instability problem as well, but at delays above 12ms, noise in the system compromises the ability to predict accurately and attempting to do so also results in instability.

After recognizing that 1) users rarely try to oscillate the rollers at higher than 5Hz, and 2) the unwanted oscillation is around 15 Hz for a 40ms delay, I decided to put a simple low-pass filter on the position information before it is passed over the network. This solution coupled with a decrease in the spring constant K to 1/3 its previous value stabilized the system up to a delay of 40ms (approximate average on-way UDP trip from MIT to Stanford

University). We then added a small amount of prediction back in to alleviate unwanted drag.

Although I had to make the compromise of decreased responsiveness in the system by using a smaller spring constant, K, and a low-pass filter on positions, I was able to achieve very reasonable performance for a delay approximately representing communication across the United States. Since this was achieved with very crude prediction and low-pass filtering, it is likely that further system analysis and tailoring of the control algorithm could increase the allowable delay significantly.

4 User Reactions

4.1 Simulating Touch

One important question to consider with inTouch is how well interaction through the device simulates the feeling of physical contact with another person. Although there is no clear way to measure this quantitatively, we can gain some insight by looking at users' reactions to the system. To begin with, users frequently comment that inTouch is like shaking or holding hands over distance. Even though there is an object meditating the communication, users tend to consider the interaction as providing a level of intimacy comparable to direct physical contact and impossible with current telecommunications technologies.

Perhaps even more compelling than such verbal testimony of the similarity is the occasional awkwardness people feel with the interaction due to the intimate connotations of touch. For instance, one subject from the one-way communication experiment (see Chapter 5) later admitted feeling somewhat uncomfortable during the testing since he did not know the female grad student with whom he was interacting. He remarked that, although it was acceptable since he could think of it as a scientific experiment, he felt a bit awkward being in physical contact with the stranger for such an extended duration. This reaction has been reiterated by other users as well who on occasion point to more rhythmical movements of the rollers as particularly awkward. Although often brought up as a joking matter, the fact that interaction through inTouch evokes such characteristic emotional responses suggests the effectiveness of the system in simulating touch over distance.

4.2 A New Medium

Of equal importance, however, are the ways in which interaction through inTouch differs from normal physical contact. The subject described above, for example, would most likely have felt more uncomfortable had he been required to actually hold the other student's hand during the trials. Because the interaction through inTouch is more abstract than direct touch, the taboos surrounding physical contact are at least partially avoided. This can be seen as a disadvantage in that it may indicate a corresponding lessening of the interaction's potential emotional impact. However, the advantage is that it may diminish many of the psychological barriers that, in normal situations, relegate touch communication to close personal relationships only or constrain interactions to short formalized gestures. The majority of people who have used inTouch are colleagues and friends who normally interact through touch infrequently. Yet these users are typically comfortable interacting with one another through inTouch for extended periods of time. This increased acceptability suggests new possibilities for exploring touch as a medium for interpersonal communication.

We could imagine, for example, using inTouch in conjunction with traditional audio communication to provide not only an increased sense of physical presence, but also a parallel channel for a form of physical gesturing. Limited testing of this idea has indicated that users do in fact seem to use physical movements as a more affective complement to verbal statements. One user commented that using inTouch during a conversation with a friend gave her a better sense of her friend's emotional state, as well as the sincerity of his words. An interesting question to consider is whether people using inTouch on a regular basis would develop a new language of physical gesture and, if so, how this language might differ among types of relationships and from culture to culture.

Although most users seem to use inTouch primarily for this type of affective communication, a few people have suggested using inTouch more basically as a way to communicate forces to a distant person. One mechanical engineer explained that he could imagine using inTouch to describe physical properties of materials and systems to distant customers. Another related possibility would be to use a Synchronized Distributed Physical Object to teach a physical skill over distance. A pair of linked medical instruments, for example, could allow a student and instructor to share in the performance of a surgical task. Similarly, a pair of linked golf clubs could be used to teach the timing of a correct golf swing.

4.3 "Transmitting Life "

One of the most energetic reactions to inTouch occurred at the Ars Electronica Festival [Brave 1997b] when one woman wandered curiously over to inTouch and placed her hand on the rollers, which were motionless at the time. She began moving the rollers without knowing that they were connected to the other set of rollers a few feet away, where another person was passively feeling her movements. The distant person then actively moved the rollers in response, causing the woman to jerk her hand back and shriek in surprise. After calming down, the woman explained that she was frightened because the rollers seemed to be alive. In fact her reaction was exactly what one might expect if a person went to touch an object or creature they thought was inanimate or unconscious and it touched back. This reaction happened several more times with other participants at the festival although none as extreme as this incident.

It is important to note that this emotional reaction seemed unique to people who were surprised in a tactile way. People would often also be surprised to *see* the rollers move when they did not yet realize the connection to the other rollers. When this happened they would often begin looking around the area to determine what was causing the action. However, the reactions to the visual surprise seemed much less intense than reactions to the tactile surprise. I suspect that there are two reasons for this. The first is that, as I suggested in the introduction to this thesis, as the only proximal sense, touch is uniquely immediate, intimate, and arousing. However, the cause of the reactions in the tactile case also seemed to be in part because the rollers moved in *reaction* to being touched, a property that is uniquely attributed to living things. This sentiment is echoed by one user's comment that inTouch is particularly compelling to him because, despite its simplicity, inTouch seems capable of "transmitting life" over distance.

4.4 Vulnerability and Trust

While interacting with inTouch, one user discovered that he could put his fingers between two rollers in a way that allowed the distant user to "squeeze" his hand. The feeling is quite impressive, as it feels very similar to having your hand directly squeezed by another person. But it is at the same time a bit disconcerting as you quickly realize that the pressure exerted can be strong enough to cause discomfort. Though only used in a humorous and playful way by people interacting with inTouch, the possibility of causing physical harm brings to light some interesting issues related to trust and vulnerability. Part of the emotional impact of touch is likely due to the fact that physical contact brings with it the potential to cause harm. When we shake hands, for example, we are putting ourselves in a fairly vulnerable position by permitting another person to be within reach of us. Since one would only allow such close contact if the person were trusted, the act becomes a powerful signal of camaraderie and intimacy.

The interesting question to consider now is the impact of physical harm in telehaptic communication. One possibility is that the connection between touch, harm, and trust is significantly ingrained in our thought processes so that all that is needed is the signal of touch to evoke related feelings of intimacy; the actual potential to cause harm need not be there. However, judging from users' differing reactions to normal interactions with inTouch and the hand-squeezing interaction, I suspect that the conscious realization of vulnerability does increase the feeling of intimacy. Still, it seems worth noting that providing a communication device with such capability raises significant ethical and legal issues.

4.5 Indicating Contact

In terms of the design of the object itself, one frequent comment from users is that they would prefer having some indication that the device was being touched by the distant person even when the rollers were still. With the current design, contact with the rollers can only be inferred from feeling or seeing them move or from feeling resistance to movement. Often however, people found that they would simply leave their hand resting still on the rollers between periods of active movement and wanted to know when the remote person was doing the same.

There are several possibilities for adding this indication of static contact. The first, which has been suggested by several users, is to display contact as a change in temperature of the rollers. Though somewhat of a technical challenge, we could imagine doing this if we changed the material of the rollers from wood to a better heat conductor, such as metal. Wood was specifically chosen over metal, however, because it tends to be considered more inviting to the touch, while also evoking a more natural and life-like feel. One compromise would be to inset small amounts of a heat conductive material within or just below the surface of the wood. An alternate option would be to superimpose a soft vibration on rollers that were being touched. Some users also commented that they wanted a visual signal of contact. Although we could simply place LEDs into the structure at various locations, a better way to add a visual signal without taking away the natural feel of the device would be to add a more ambient glow, possibly emanating from below the rollers. Sensing contact could be accomplished with electromagnetic field sensors or more simply with the rollers themselves by picking up on the small movements of a resting hand.

5 Experiments

This chapter describes two initial informal experiments with the inTouch system that begin to investigate the properties of the haptic communication channel it provides. The focus of the experiments is on possibilities for communicating information rather than on the interpretation of that information. Although we might also like to quantitatively analyze the emotional significance and subjective impact of interactions through inTouch, we must begin by asking the more objective question of what lower-level information (e.g. quality and quantity of movements) can be transmitted and understood.

5.1 One-Way Communication

The first experiment was intended to consider two things: 1) can a pattern of movement be successfully communicated over inTouch, and 2) which characteristics of a pattern are easier or harder to communicate?

5.1.1 Protocol

Two subjects we seated at opposite ends of a table, with a wall obstructing their view of each other. One half of inTouch-1 (stand-alone version) was placed at either end. The first subject (the sender) was given the sheet of curves shown in Figure 5.1. For each trial, this subject was asked to transmit one of the curves (the order was randomized) to the other subject using inTouch so that he or she could then draw the curve as closely as possible to that on the page. The second subject (the receiver) was blindfolded so that he/she could not see the rollers move and therefore had to use the sense of touch to understand the pattern. Thirty seconds were allowed for the transmission. The blindfold was then removed and the second subject was instructed to draw the curve on a record sheet. This procedure was continued until all eight curves were tested.

I should point out here that the instructions given to the subjects were rather non-specific, with no direction given beyond what is described above. For example, in each trial, the sender was asked to transmit a *single* curve, but there are *three* rollers on inTouch. There was also no labeled axis on the curves indicating whether the vertical axis was roller position, velocity, or anything else. A strict interpretation of the horizontal axis as time also makes the curves with areas of infinite slope technically impossible to replicate. The mapping between the curve and the movement of the three rollers was therefore somewhat ambiguous. I considered making the instructions more precise;

however, I decided to leave them open for interpretation since much of my intention in this exploratory experiment was to see how users tended to manipulate and understand the rollers movement.

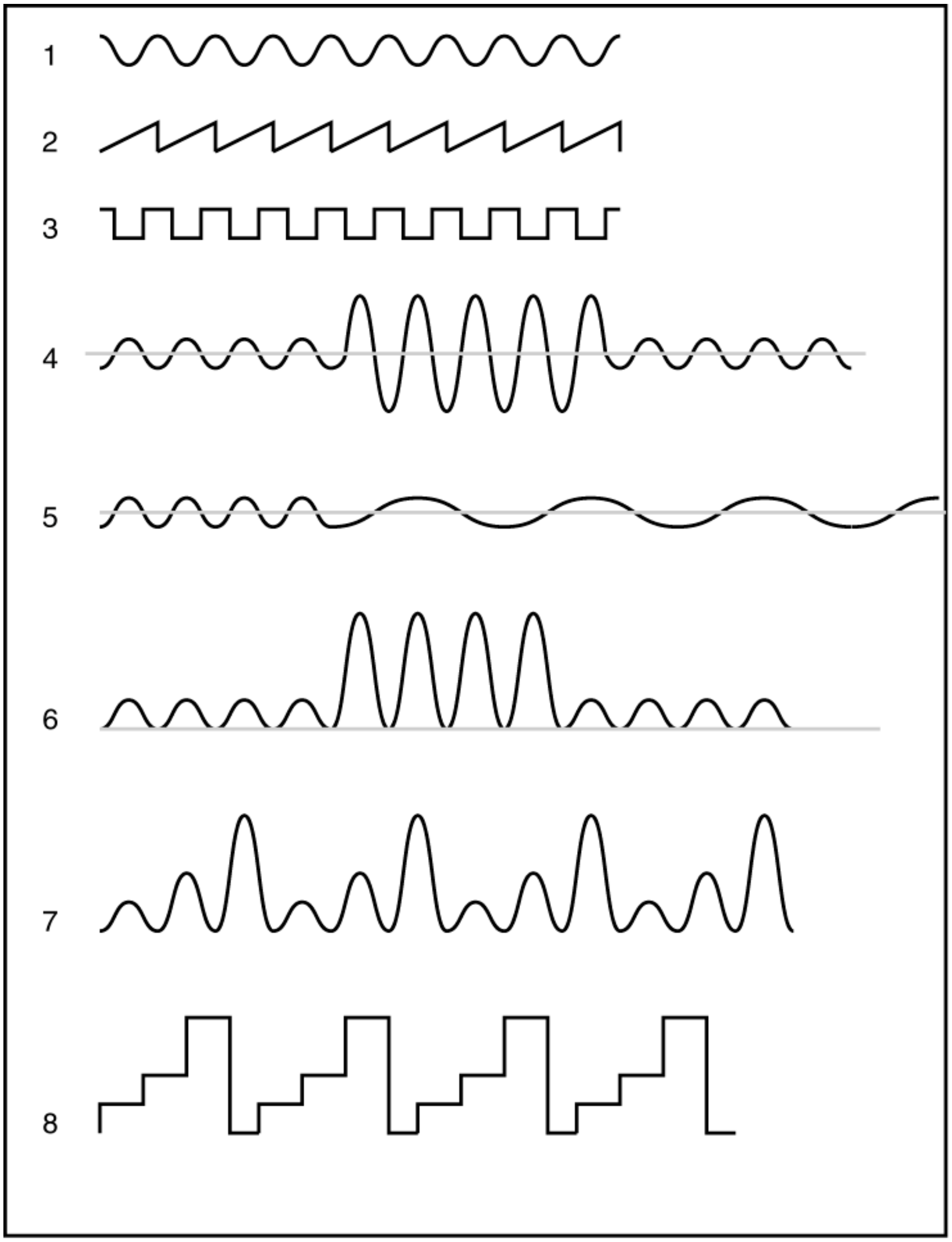

Figure 5.1 Sheet of curves given to sender for transmission through inTouch

Although admittedly somewhat arbitrary at this early stage, the curves were chosen for general variety as well as to investigate a few initial questions. Curves 1, 2, and 3 were intended to explore aspects of slope and "smoothness". I suspected that the "flowing" curve 1 would be easily transmitted and differentiated from the sharper edges of curves 2 and 3. However, it was unclear whether curves 2 and 3 would be as easily differentiated, considering both would likely be expressed with sharp movements. Curve 4 addressed changes in amplitude and curve 5 changes in frequency. Curve 6 was added to complement curve 4, by asking whether absolute position of the curve parts was important. Curve 7 considered more variety in amplitude, as well as presenting more obvious number information (each repetition has three clear segments). Curve 8 was a sharper moving version of curve 7.

5.1.2 Results and Discussion

Figure 5.2 shows the results from one experiment that was run with two graduate students who have occasionally interacted with inTouch. This run is a good example where the curves were communicated with relatively high precision. The first important conclusion to draw from this data is that inTouch is capable of transmitting various patterns of movement. The tested patterns are of course only a small sample of possible patterns, but it is important to see that at least these patterns are recognizable. In many ways, it has been an assumption of mine all along that users can not only recognize the presence of another person on the other end of inTouch, but can communicate various subjective feelings or emotions through movement of the rollers. This assumption has been supported by comments from many users who have tried inTouch, but requires more objective testing to substantiate. There are really three parts to this assumption: 1) users consciously or subconsciously manipulate the rollers in different ways correlating to some feeling or intention, 2) this pattern of movement is communicated, at least in part, to the other person, and 3) the other person interprets this movement in a way that has some correlation to the original intent. This experiment addresses the second of these three parts by exploring users' ability to differentiate various patterns of roller movement. Investigating the first and third parts is left for future work.

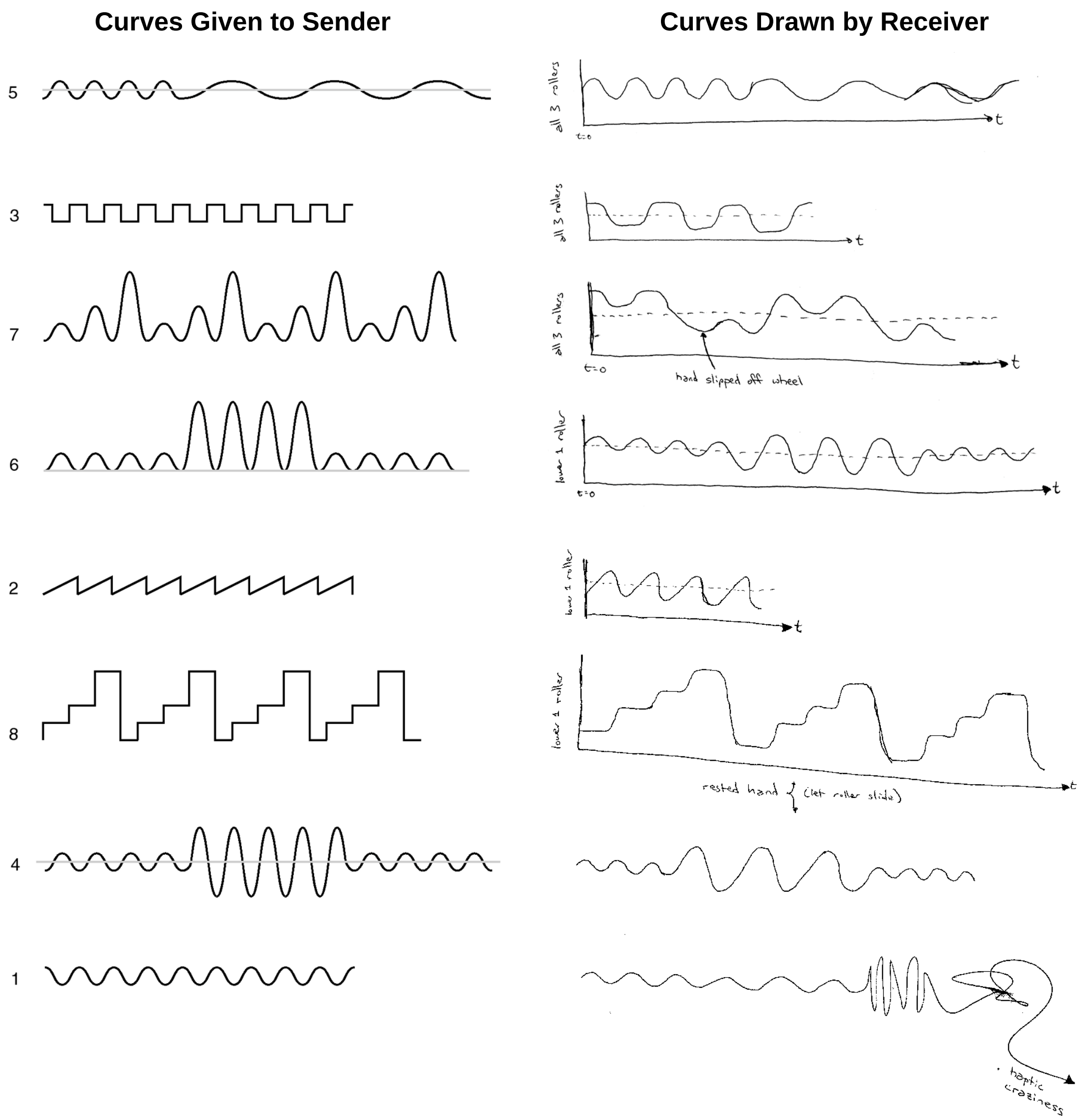

Figure 5.2 Results from a run of the one-way experiment

Looking more specifically at the different curves, we see that curves 4 and 6 were interpreted nearly identically, supporting the hypothesis that absolute position is less important than the shape and amplitude of a pattern. Cures 2 and 3 were differentiated fairly well. Curve 7 appears to have been the most difficult for these subjects to communicate. This difficulty could be on either the sending or receiving end of the pattern. To investigate this we can look at the actual pattern transmitted across inTouch (see Figure 5.3).

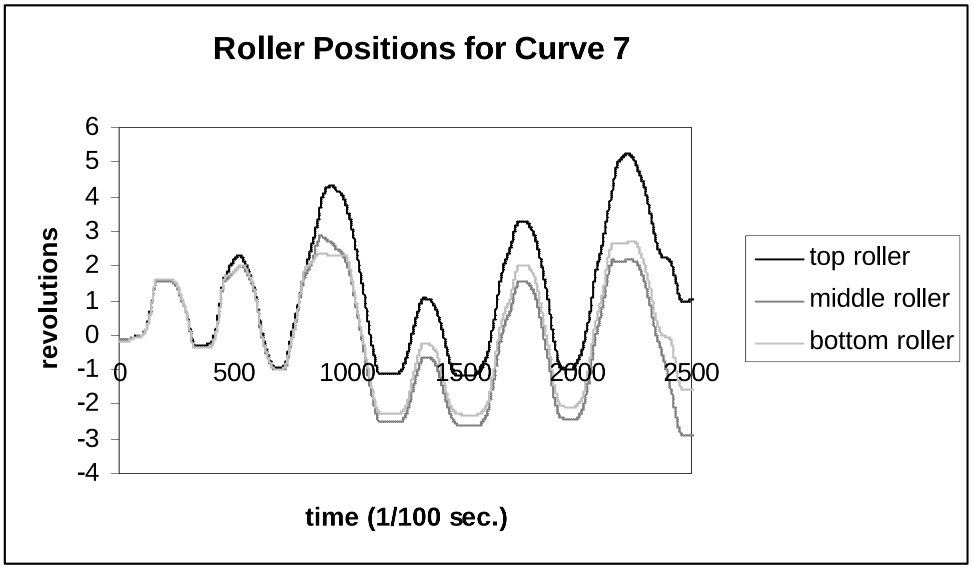

Figure 5.3 Graph of roller positions during the transmission of Curve 7

We can see that there is in fact some ambiguity in the transmitted pattern. Movement of the top roller appears to match the target curve most closely, while movement of the bottom two rollers match the received signal more closely. This graph raises another important issue, which is how users chose to transmit the pattern with the device. The sender in this experiment began using all three rollers simultaneously to transmit the curve. Curve 6 was difficult for him to transmit, however, since he "ran out of room" on the rollers. This is why only the top roller extends the third peak well above the second. After this run, the sender switched to using only a single roller to transmit the curves. This problem was encountered with many of the pairs of subjects and is indicative of the affordances of the inTouch device. Although the rollers themselves are unbounded, users seemed to prefer placing their hand on all three rollers and manipulating the rollers with a forward and back movement. In this way there is a limited range of roller movement and therefore a finite range of recognizable amplitudes. Future designs should take this finding into account.

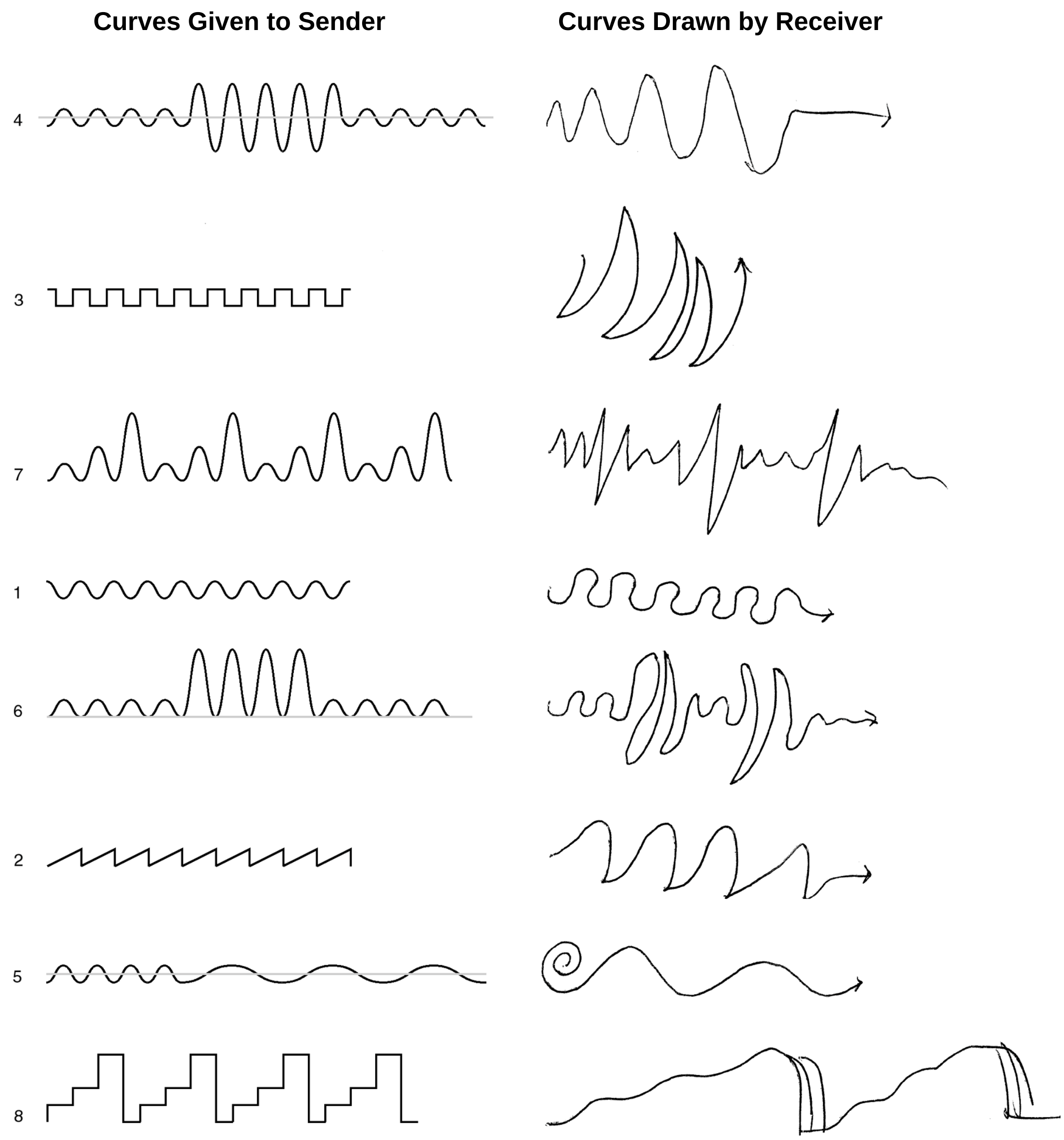

Figure 5.4 Results from a run of the one-way experiment

Figure 5.4 shows the results from another pair of subjects who were less familiar with inTouch. We can see that these users were more successful at communicating the general character of the curve than precise shape. Particularly interesting is the receiver's interpretation of curve 5, where he draws a spiral to represent the initial higher frequency movement in the curve. Although to look at the more objective aspects of the haptic communication channel we have given users a fairly dry and somewhat mathematical task, this user moved toward a more subjective interpretation of the movement. With curve 5, he seems to capture more of the feeling of the movement than the specifics of the movement itself. Although unexpected, this fact suggests that users interpret movement of the rollers as having some character or feeling associated with it. We see a similar more subjective movement at the end of curve 1 for the earlier group (Figure 5.2). This curve was the last one tested for these subject and, after feeling the curve was successfully communicated, the receiver moved the rollers in a more playful way to grab the receivers attention and indicate excitement that the experiment was completed.

5.2 Two-way Communication

One of the novel aspects of inTouch is that the input and output channels are integrated within the same object; the rollers serve as a means to both send and receive haptic information. An interesting question to then consider is whether a user can send and receive simultaneously. Although two users will likely not be able to communicate two complicated patterns (such as those tested in the previous experiment) at the same time, we can imagine one user reacting to actions of the distant user by superimposing force information over his or her movements. To explore whether such reactions can be understood, this experiment tests whether a user in the process of communicating a pattern can register an interrupting signal from the other user.

5.2.1 Protocol

The idea in this experiment is for two users to take turns producing their assigned pattern on the rollers. The first subject begins with several rapid and continuous forward-back motions. Then the second user takes over with a slower oscillation. After several of the slow forward-back movements, the first user again steps in with the faster oscillation and the process continues. The goal is for users to make smooth transitions between the other users movement and their movement, keeping the rollers moving continuously at all times. The twist is that each user knows only how many times to let their partner make his/her movement and not how many times to do their own. This number is given to them, written on a piece of paper, before beginning. So the scenario is that the first user starts moving the rollers back and forth continuously until they feel the other user interrupting and beginning with their movement. Then the second user continues the slower pattern until the first user interrupts.

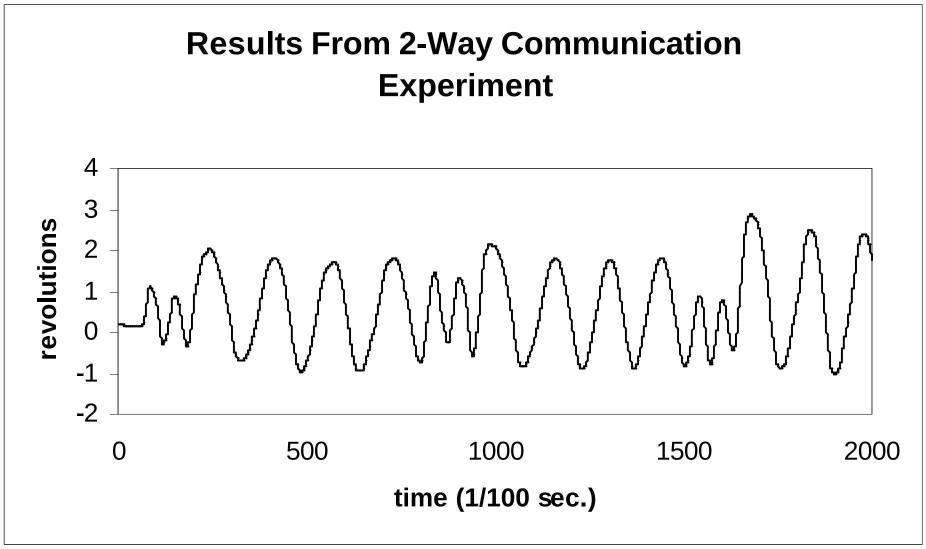

Figure 5.5 Results from a run of the two-way communication experiment

5.2.2 Results and Discussion

Figure 5.5 shows the results from one run with two male graduate students. In this run, the users manipulated all three rollers together, so for clarity I have graphed the position of the bottom roller only. As we can see from the graph, the users were successful at taking turns producing their patterns from the beginning. Following from left to right, the first user began moving in the quick oscillation and then the second subject interrupted after two repeats and began a period of slower movements. This slower movement was repeated four times until the first user interrupted again with the faster movement. This back and forth continued for several iterations. Since the produced pattern is continuous, with no periods of inactivity, it is clear that these users were able to register the interrupting signal from the distant user even while in the process of communicating their own information. Runs with other subjects and different assigned numbers produced similar results. In some cases, the first two transitions were rougher since the point of interruption was not completely clear, but this was always remedied on the second iteration.

To better understand the dynamics of this interaction, as well as introduce some techniques for analysis of collected data, we will take a closer look at the results from this run. Figure 5.6 shows a closer in view of roller position in the first two seconds of the interaction. At this scale we can begin to see subtle differences in the position of the two connected rollers which would be nearly imperceptible at the scale of Figure 5.5. This difference in position is due to the fact that the rollers are not connected solidly together, but are connected with a simulated spring. Thus if one roller starts moving, even if the other connected roller is allowed to follow, it will still lag a small bit behind. If the two users were "fighting" over the state of the roller (i.e. opposing each other's movement) this difference could be much greater. Looking carefully at Figure 5.6 we can see that, as expected, the first user (User A) begins his pattern with an upward movement and User B lags slightly behind. Then, at around one second, User A "turns around" and leads User B back down. This time User B is following a bit closer indicating a bit more cooperation. User A then continues leading back up to start the second oscillation.

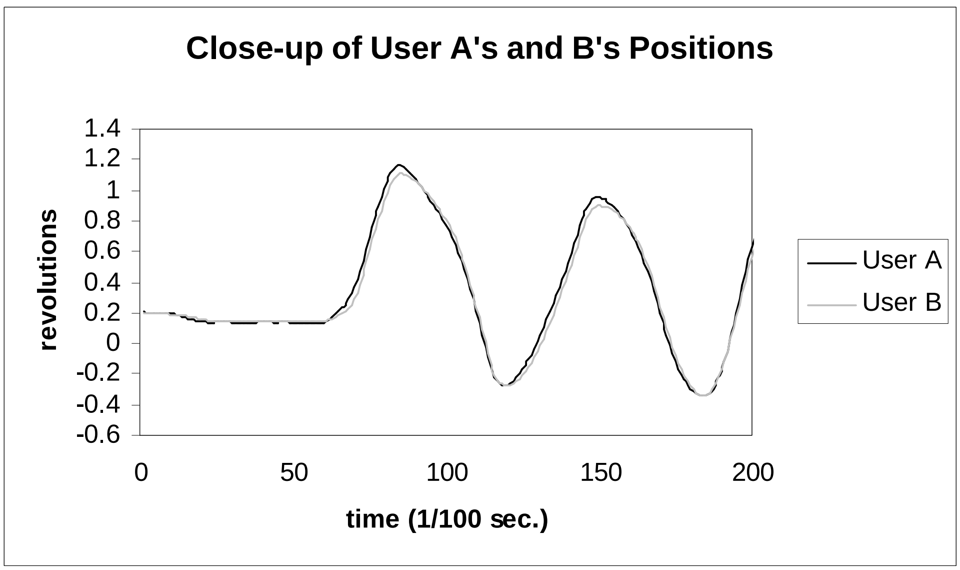

Figure 5.6 Close-up view of the positions of the two connected bottom rollers during initial two seconds of the interaction

In general, zooming in to find these subtle position differences can be quite tedious, so we can instead simply plot the relative position of two connected rollers. Figure 5.7 shows such a plot for the first five seconds of the interaction. Remember that the control algorithm imparts a torque on connected rollers proportional to their difference in position, so this type of plot is also an indication of restoring force. The larger the difference, the more the two users are resisting each other, and thus the higher the torque imparted to bring the rollers back together.

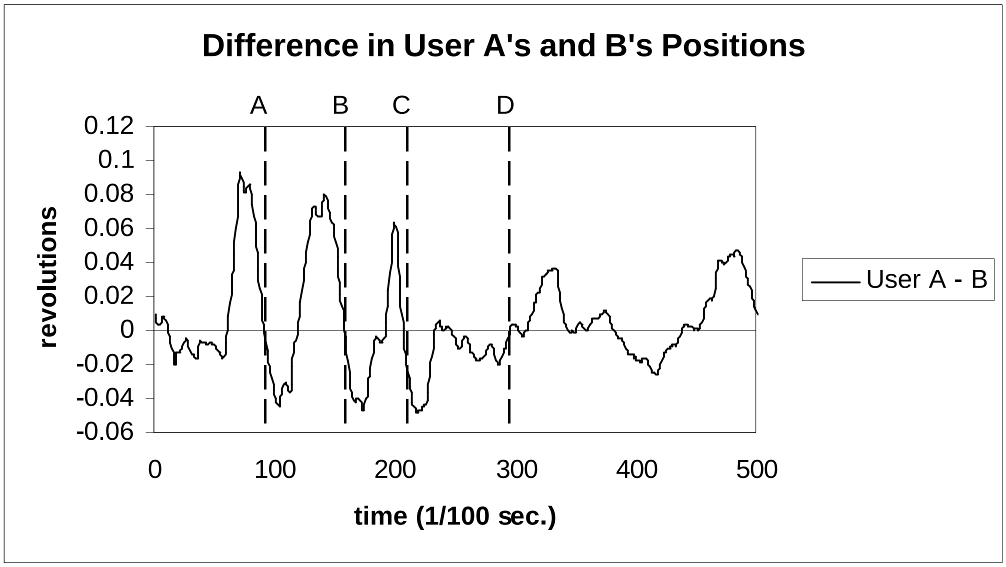

Figure 5.7 Relative position of the two connected rollers during the first five seconds of the interaction

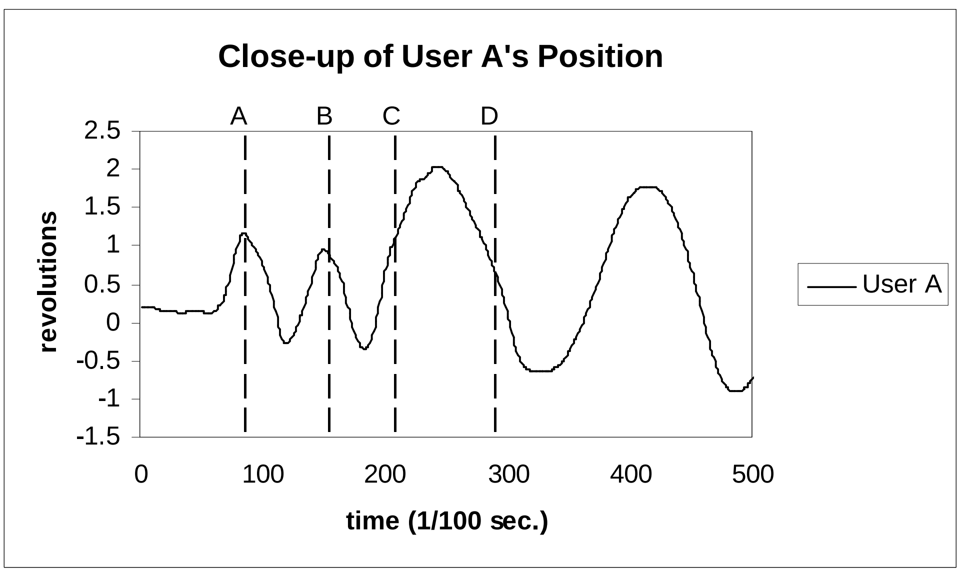

Figure 5.8 Position of User A's bottom roller during the first five seconds of the interaction

Looking at this plot by itself can give a general understanding of the magnitude of resistance during the interaction, but a better understanding of the information requires us to consider it along with roller position. Figure 5.8 plots the position of the bottom roller for the same time period. We have again chosen to plot the position of only one of the two connected rollers since we have the relative position information in Figure 5.7.

As User A begins the upstroke of his first oscillation (directly before Point A in Figure 5.8), we see that the relative position graph in Figure 5.7 indicates that User A is above User B, which confirms what we determined earlier from Figure 5.6. Then as User A changes direction, the relative position graph flips in sign showing that User A is now below User B, or leading on the way down. This same pattern continues through Point B as User A continues to lead. Then at Point C we see a switch in sign of the relative position graph again, but this time without a corresponding change in direction of roller movement. So what we are seeing is User B taking over and beginning to lead the interaction; User A is now *below* User B on the way *up*.

When User B is producing his pattern, we see a bit different of an interaction than when User A was leading. Between Points C and D, we see that User A is below User B most of the time. This means that on the down stroke of User B's pattern, User A actually starts out leading. We can actually see a small blip above the zero line about half way between Points C and D in Figure 5.7, where User B dropped briefly below User A which signaled A that he was going to start moving down. User A simply decided to cooperate and help out by beginning to move down with him. Then at point D, user A relinquishes control to User B so that he can initiate the next change of direction.

6 Distributed Tangible Interfaces

This chapter considers the implications of Synchronized Distributed Physical Objects in the broader space of distributed multi-user systems. In particular, I describe a theoretical extension of the methods developed for inTouch to enable distributed Tangible Interfaces.

6.1 Tangible Interfaces

For many years our conception of human-computer interaction has been focused on the Graphical User Interface (GUI) (Figure 6.1a). GUIs allow interaction with digital objects and online information through the generic screen, keyboard, and pointing device. Current systems for Computer Supported Cooperative Work (CSCW) are largely based on extensions of the GUI to a distributed multi-user context, providing distant users with shared access to online digital environments (Figure 6.1b). When direct communication between distributed users is desired, these systems are traditionally augmented with voice/video conferencing technologies.

In the real world, touch and physical manipulation play a key role in understanding and affecting our environment [Johnson 1987]. Traditional interfaces to the digital world, in contrast, largely fail to address our sense of touch, offering only the generic keyboard and pointing device as tools for indirect manipulation of digital objects.

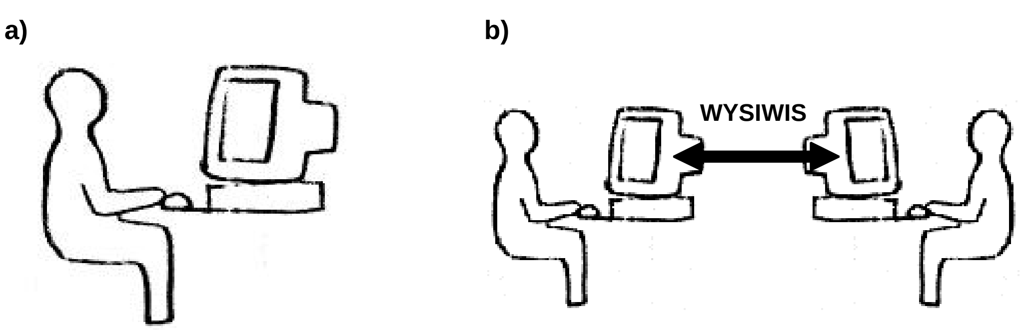

Figure 6.1 a) Graphical User Interface (GUI) b) Real-time, distributed CSCW based on GUI

a) b)

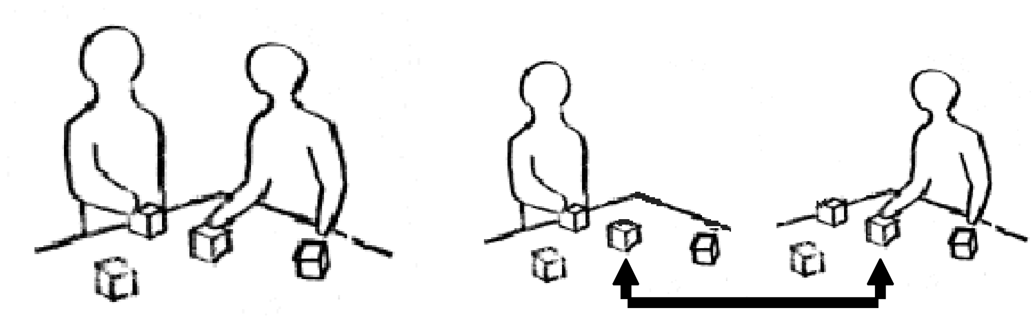

Figure 6.2 a) Tangible User Interface (TUI) b) Real-time, distributed CSCW based on TUI

Section 1.2.2 introduced Tangible User Interfaces (TUIs) as an alternative to the GUI that makes greater use of physical space and real-world objects as interface tools (Figure 6.2a). One strong advantage of Tangible Interfaces is that they well support co-located multi-user interactions. Since a generic pointing device is not needed to mediate interactions, many users can interact with a Tangible Interface system in parallel. In Illuminating Light, for example, multiple users can simultaneously grasp and manipulate the optical components to cooperatively create and explore simulated holography layouts.

An important next question is, how can such an object-based interface be extended for use in a distributed context? One solution would simply be to give each *separate* space their own interface objects and then project a video capture of remote spaces onto the local setup, in a way similar to TeamWorkStation [Ishii 1990] (also see [Kreuger 1991]). This may be unsatisfactory, however, as each user would be limited to modifying the portion of the workspace which physically resides in their local space. Synchronized Distributed Physical Objects presents an alternate method that can allow distant users to truly share a group of physical objects over distance, by creating the illusion that each object exists in multiple physical locations simultaneously. Synchronized Distributed Physical Objects thus enable the full extension of Tangible Interfaces into the space of distributed multi-user interactions (Figure 6.2b).

6.2 Vision

Imagine that you and a remote colleague are trying to plan the arrangement of furniture in a new research lab space. You sit down at a table and place on it a blueprint and a number of scaled models representing each of the pieces of furniture you wish to arrange.

Your remote colleague has the same blueprint and set of models and places them on her table. Using both hands, you begin to arrange the physical furniture models in the office space. At the same time you are positioning and adjusting the office furniture, you notice the physical models representing the computer terminals beginning to move around on your table in the region designated "group area". Recognizing your remote colleague's struggle with fitting in all the computers, from her frequent subtle yet unsuccessful tweaks, you grab two of the terminals and suggest a new arrangement by moving them to the other side of the room. On her table, she sees the models move as you make the suggestion and then begins to move her gaze around the table space to get a few different views of the area and your changes.

The above scenario is representative of the broader Synchronized Distributed Physical Objects vision. Traditional CSCW systems have long allowed distributed users to share *digital* objects and environments (Figure 6.3a). Synchronized Distributed Physical Objects allow distant users to share *physical* objects and environments as well (Figure 6.3b).

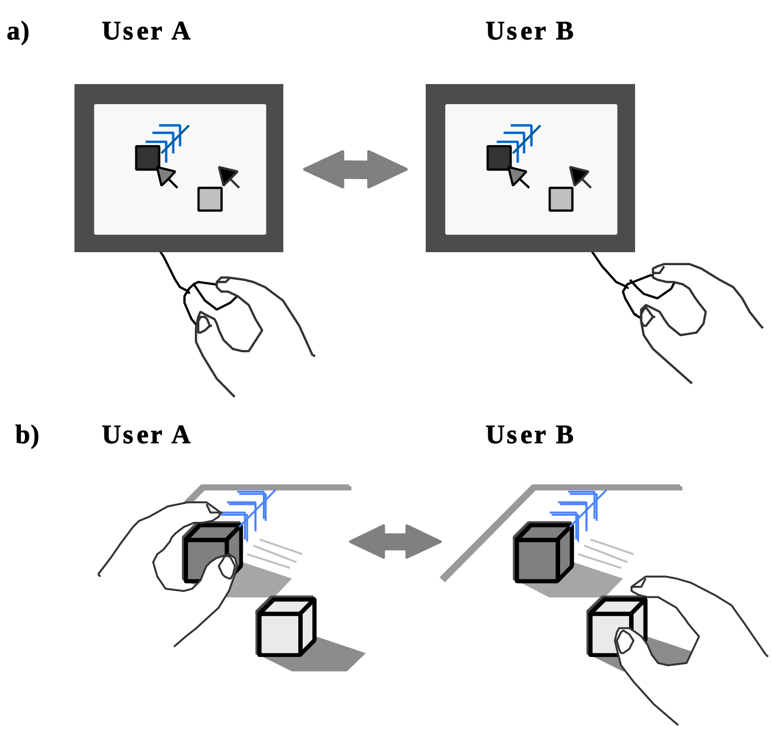

Figure 6.3 Distributed shared spaces. a) A shared digital space. b) A shared physical space.

In this larger context, inTouch can be seen as a special case of Synchronized Distributed Physical Objects, in which two users are manipulating a single object simultaneously (Figure 6.4). This situation would occur if, for example, two users in the floor planning application were both grabbing the same model chair at once.

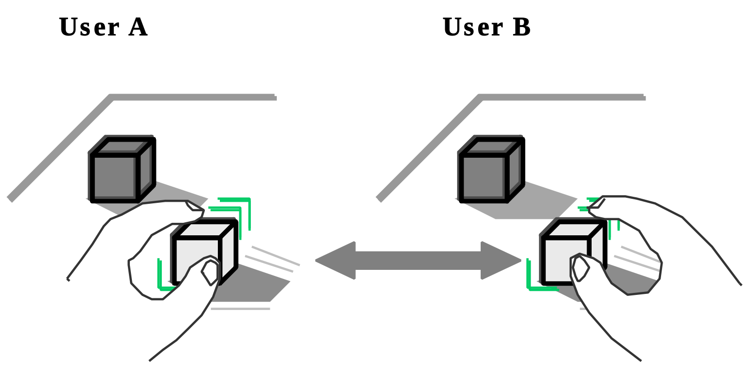

Figure 6.4 Synchronization of a shared physical object being simultaneously manipulated by multiple users.

6.3 PSyBench

PSyBench is a first system aimed at realizing this vision of distributed Tangible Interfaces. Objects on an augmented tabletop are synchronized with identical objects in a remote space, allowing distant users to share a physical workspace over distance. An initial prototype of PSyBench is constructed from two augmented and connected motorized chessboards from Excalibur (Figure 6.5).

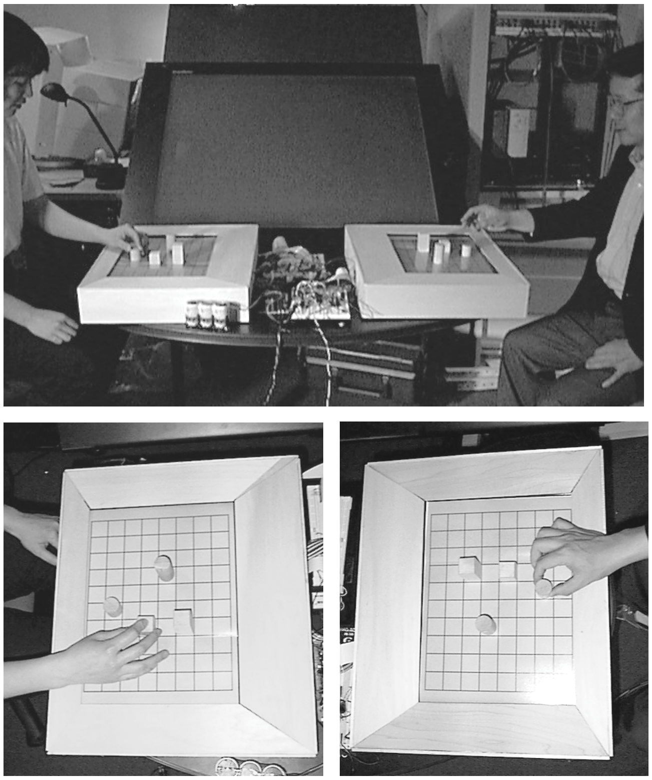

Figure 6.5 Early prototype of PSyBench.

Positions of objects on the surface of PSyBench are sensed by a ten-by-eight array of membrane switches. When a user moves an object on one of the surfaces, the corresponding object in the remote space is moved as well by an electromagnet mounted on a 2-axis positioning mechanism under the surface. Each board is outfitted with custom electronics, based upon the PIC microcontroller, to handle the control and serial communication between boards. Figure 6.6 shows this system architecture.

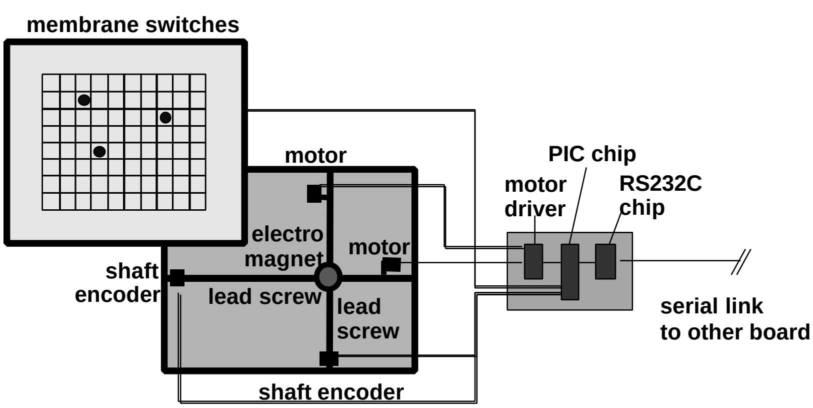

Figure 6.6 System architecture for PSyBench prototype.

Although ideally we would like to tightly synchronize all objects in the shared space, allowing simultaneous manipulation as we did with inTouch, this is often not technically feasible or worthwhile. Since this type of interaction is infrequent in the shared workspace context, PSyBench focuses on creating an effective illusion in the case where only one person is handling each object at any one time. If two users do move an object simultaneously, PSyBench simply resynchronize the distributed copies after at least one user has released the object. This early prototype has obvious limitations; most notably, positioning is discrete and there is no mechanism for synchronizing the orientation of objects. However, the system has been extremely helpful in bringing to light many design and implementation issues, while presenting a compelling demonstration of the potential for creating shared physical workspaces over distance. Work is in progress on a full-scale version of PSyBench, which employs *Glimpser* (the machine vision system used in Illuminating Light) for sensing and a larger magnetic linear positioning system for actuation.

6.4 Tangible Presence

PSyBench primarily provides a means for geographically distant users to collaborate in a shared physical workspace, extending the benefits of Tangible Interfaces into a distributed CSCW context. Initial experiences with the prototype system, however, have suggested that PSyBench also presents a new form of "awareness" of the *physical* presence of remote collaborators. The actions of remote users are manifested in a physical and tangible way, as motion of grasped objects, that suggests form and movement of a motivating physical body. Much in the way that a player piano compels us to imagine a real body sitting at the piano bench with arms extending to the keys, many initial users have found the movement of objects on PSyBench to evoke strong feelings of physical presence.

This feeling is particularly compelling considering that the objects affected by remote users are not in some distant or removed space, but in the same space you yourself are sitting and acting in. Objects manipulated by distant users are effectively the same objects that you can touch and feel with your hands; they may even get in your way or touch you as they move. In this way, the shared workspace of objects and your physical interpersonal space are seamlessly integrated, much in the way that *ClearBoard* integrates the two spaces on a visual level [Ishii 1992].

Taking this idea of shared space a bit further, we can imagine placing objects throughout our space that are synchronized with those in a distant space. The illusion would then be created of a ghostly presence that shared our space with us, a presence that could walk around and interact with the same world that we are a part of. Perhaps even our doors could be shared objects that might open as a remote presence passed through. With synchronized objects spread throughout space in this way, we also begin to take advantage of a more ambient awareness of others. Much of our sense of connection with others in the real world comes not from deliberate foreground communications, but from the feeling of simply being around other people that emerges from our peripheral awareness of activity. Using the physical world itself as a display of remote presence therefore takes advantage of our natural ability to process information in the background while focusing on other foreground tasks.

6.5 WYSIWIS for the Physical World

What You See Is What I See (WYSIWIS) has long been a guiding principle for the design of shared *digital* spaces. Synchronized Distributed Physical Objects offer an extension of the WYSIWIS abstraction into the *physical* world. Synchronized Distributed Physical Objects can be seen first as Physical WYSIWIS, since all users will *see* other users' manipulation of the shared physical object. In implementations that use a tight coupling, such as inTouch, What You Feel Is What I Feel will also hold, since all users will be able to simultaneously manipulate and *feel* other users' manipulation of the shared object. As with PSyBench, the idealized notion of strict synchronization may need to be relaxed for technical and/or interface reasons—which is often true with WYSIWIS as well [Stefik 1993]. However, the general principle of Synchronized Distributed Physical Objects can be used as a guide in the design of distributed Tangible Interfaces.

7 Conclusion

7.1 Summary

In this thesis I have introduced inTouch, a new interpersonal communication device that allows distant users to interact through touch. inTouch is based on the concept of Synchronized Distributed Physical Objects, which employs force-feedback technology to create the illusion that distant users are interacting through a shared physical object. I have described the design and implementation of inTouch from the initial mechanical mockup to a working networked prototype. The effect of communication latency in the networked system has also been considered and potential solutions proposed. Basic prediction and filtering techniques have yielded stable system behavior for delays corresponding to communication spanning the continental United States, showing promise in providing two-way haptic communication over arbitrary distance.

This thesis has also discussed preliminary evaluation of inTouch through both user observations and informal experimentation. Subjective user reactions have suggested that inTouch provides an intimate connection with distant users, which evokes various emotional responses associated with direct physical contact. I have also pointed to new possibilities for using touch as a parallel channel for physical gesturing during audio communication. Two initial experiments have begun to address more objective properties of the haptic communication channel provided by inTouch, as well as illuminated techniques for analysis of interaction data.

Finally, I have discussed the broader implication of Synchronized Distributed Physical Objects to the design of distributed multi-user systems. PSyBench was introduced as an example extension of shared physical objects to enable distributed Tangible Interfaces. When viewed together, inTouch and PSyBench represent an important new departure from traditional multi-user systems, which aims to provide a greater sense of physical co-presence with distant users. Current interfaces to online multi-user environments and telecommunication systems tend to give us the distinct feeling that distant users are in a space that is separate from our own. They are, for example, trapped in the digital world on the other side of our computer screens where we are unable to touch them or share our physical world with them. Synchronized Distributed Physical Objects presents a method capable of breaking through this barrier, allowing distant users to physically reach into our world and affect what we consider to be our “personal” and “real” space.

7.2 Future Directions

7.2.1 Robust Control

A clear technical direction for future work involves the development of more advanced techniques for providing robust system control under arbitrary delay. There is much room for improving prediction techniques, for example, both through more sophisticated system analysis as well as a greater understanding of characteristic movements and responses of users. While the former requires further understanding of delayed-feedback systems, the latter will likely be advanced through in depth experimentation following the lead of the example experiments presented in Chapter 5. Advanced filtering techniques will also be sought to improve system stability while minimally compromising performance.

7.2.2 Object Design

inTouch presents only one possible design for a haptic communication device based on Synchronized Distributed Physical Objects. Although successful at creating a compelling feeling of physical contact over distance, the current design is not without limitations. As we described in section 4.5, for example, many users have commented that they would prefer a better indication of static remote contact with the object. Our discussion of PSyBench also pointed to the importance of designing interfaces that suggest the physical location of remote users within the local space. With inTouch, understanding the actions of remote users in terms of an equivalent local interaction often requires users to imagine the remote users hand on top of their own. Designs that suggest more feasible co-located situations may therefore prove more successful and creating a sense of “ghostly presence” and shared space.

Future design explorations should also consider the location of the shared object in reference to the user. One of the less desirable aspects of inTouch is that interaction with the device tethers the user to the table upon which it lies. Integrating a haptic communication device into a hand-held object, perhaps even the handset of a mobile telephone, presents one appealing option. Another possibility would be to locate the device on the body itself—integrated into a piece of jewelry, for example—providing a more personal communication object.

7.2.3 Social and Psychological Implications

Another important direction for future work is further investigation of the social and psychological effects of creating a physical link across distance. A better understanding of the true emotional impact of long-distance touch communication, for example, would help to illuminate the best areas for application as well as further general understanding of touch psychology. In this thesis, we have also touched upon several important social issues raised by telehaptic communication including taboo, vulnerability, intimacy, and trust, which should be explored through extensive, long-term user testing. Further, in a world where we are increasingly communicating with others who are physically distant from us, the ability to establish physical contact across distance could have drastic effects on our conception of the online self.

7.2.4 Active Objects

Finally, Synchronized Distributed Physical Objects suggests a new way of interacting with the online world that makes use of physical objects not only as input to the computer, but also as active output. For example, although we discussed PSyBench in terms of providing a shared space for distant users, there is no reason why the computer can't also directly manipulate the objects itself to display information, react to our manipulations, or assist us in our interactions. We could also imagine physical interfaces that employ force-feedback technology, in the spirit of inTouch, to change both internal state and physical properties depending on the desired application. Such reconfigurable interfaces would combine the richness of haptic interaction in the physical world with the effortless malleability of the digital world. Future work in Tangible Interfaces should explore such uses of active objects, as well as work to develop a framework for understanding this new more balanced relationship between the world of bits and atoms.

REFERENCES

[Brave 1997a] Brave, S., and Dahley, D. inTouch: a medium for haptic interpersonal communication. *Extended Abstracts of CHI'97* (Atlanta GA, Mach 1997). ACM Press, 363-364.

[Brave 1997b] Brave, Scott and Dahley, Andrew. "MiLOs". Artist Statement. *FleshFactor: Informationsmacschine mensch: 1997 Ars Electronica Festival Catalog,* Linz, Austria, SpringerWeinNewYork, September 1997, 278-279.

[Burdea 1996] Burdea, G.C. *Force and Touch Feedback for Virtual Reality*. John Wiley & Sons, Inc., New York NY, 1996.

[Buxton 1991] Buxton, W. The three mirrors of interaction: a holistic approach to user interfaces. *Proceedings of Friend21 '91 International Symposium on Next Generation Human Interface* (Tokyo, Japan, November 1991). 25-27.

[Buxton 1995] Buxton, W. Touch, Gesture & Marking. Chapter 7 in R.M. Baecker, J. Grudin, W. Buxton and S. Greenberg, S. (Eds.) *Readings in Human Computer Interaction: Toward the Year 2000.* Morgan Kaufmann Publishers, San Francisco CA, 1995.

[Colton 1983] Colton, H. *The Gift of Touch*. Seaview/Putnam, New York NY, 1983.

[Fogg 1998] Fogg, B.J., Cutler, L., Arnold, P., and Eisback, C. HandJive: a device for interpersonal haptic entertainment, in *Proceedings of CHI '98* (Los Angeles CA, April 1998), ACM Press, 57-64.

[Goldberg 1993] Goldberg, K., and Wallace, R. Denta-Dentata, in *Visual Proceedings of SIGGRAPH '93*. ACM Press.

[Gorbet 1998] Gorbet, M., Orth, M., and Ishii, H. Triangles: Tangible Interfaces for manipulation and exploration of digital information topography, to appear in *Proceedings of CHI '98* (Los Angeles CA, April 1998), ACM Press, 49-56.

[Hardison 1980] Hardison, J. *Let's Touch: How and Why We Do It*. Prentice-Hall, Englewood Cliffs NJ, 1980.

[Ishii 1997] Ishii, H., and Ullmer, B. Tangible Bits: towards seamless interfaces between people, bits and atoms, in *Proceedings of CHI '97* (Atlanta GA, Mach 1997), ACM Press, 234-241.

[Ishii 1992] Ishii, H., Kobayashi, M., and Grudin, J. Integration of inter-personal space and shared workspace: ClearBoard design and experiments. in *Proceedings of CSCW '92* (Toronto, November 1992), ACM Press, 33-42.

[Ishii 1990] Ishii, H. TeamWorkStation: towards a seamless shared workspace, in *Proceedings of CSCW '90* (Los Angeles CA, October 1990), ACM Press, 13-26.

[Jackson 1995] Jackson, B., and Rosenberg, L. Force feedback and medical simulation, in Morgan, K., Satava, R., Sieberg, H., Mattheus, R, and Christensen, J. (Eds.) Interactive Technology and the New Paradigm for Healthcare (Amsterdam, January 1995), IOS Press, 147-151.

[Johnson 1987] Johnson, M. *The Body in the Mind*. The University of Chicago Press, Chicago IL, 1987.

[Katz 1989] Katz, D. *The World of Touch*. Lawrence Erlbaum Associates, Hillsdale, NJ, 1989.

[Krueger 1991] Krueger, M. K. *Artificial Reality II.* Addison Wesley Publishing, Reading MA, 1991

[Massie 1994] Massie, T.H., and Salisbury, J.K. The PHANToM haptic interface: a device for probing virtual objects, in *Proceedings of the 1994 ASME International Mechanical Engineering Congress and Exhibition* (Chicago IL) VOL DSC 55-1, ASME Press, 295 - 302.

[Montague 1978] Montague, A. *Touching: The Human Significance of the Skin*. Harper and Row, New York NY, 1978.

[Morris 1971] Morris, D. *Intimate Behavior.* Random House, New York NY, 1971.

[Reeves 1996] Reeves, B, and Nass, C. *The Media Equation*. Cambridge University Press, Cambridge, MA 1996.

[Schena 1995] Schena, B. Design of a Global Network of Interactive, Force-Feedback Sculpture. Master's Thesis in the Department of Mechanical Engineering, Stanford University, 1995.

[Stefik 1993] Stefik, M., Bobrow, D. G., Foster, G., Lanning, S., and Tatar, D. WYSIWIS revised: early experiences with multiuser interfaces, in Baecker, R. M. (Ed.), *Readings in Groupware and Computer-Supported Cooperative Work, Assisting Human-Human Collaboration*. Morgan Kaufmann Publishers, Inc., San Mateo CA, 1993, 585-595.

[Strong 1996] Strong, R., and Gaver, B. Feather, Scent and Shaker: Supporting Simple Intimacy, in *Videos, Demonstrations, and Short Papers of CSCW '96* (Boston MA, November 1996), 29-30.

[Ullmer 1997] Ullmer, B., and Ishii, H. The metaDESK: models and prototypes for Tangible User Interfaces, in *Proceedings of UIST '97, User Interface Software Technology* (Banff, October 1997), ACM Press, 223-232.

[Ullmer 1998] Ullmer, B., Ishii, H, and Glass, D. mediaBlocks: physical containers, transports, and controls for online media, to appear in *Proceedings of SIGGRAPH '98* (Orlando FL, July 1998), ACM Press.

[Underkoffler 1998] Underkoffler, J., and Ishii, H. Illuminating Light: an optical design tool with a luminous-tangible interface, in *Proceedings of CHI '98* (Los Angeles CA, April 1998), ACM Press, 542-549.

[White 1986] White, N., and Back D. Telephonic Arm Wrestling, shown at *The Strategic Arts Initiative Symposium* (Salerno, Italy, Spring 1986). See http://www.bmts.com /~normill/artpage.html