Touch and go — designing haptic feedback for a hand-held mobile device

S O'Modhrain

Increasingly, our mobile devices are acquiring the ability to be aware of their surroundings. These devices are also acquiring the ability to sense what is happening to them — how they are being held and moved. The coincidence of connectedness, awareness and richly multimodal input and output capabilities brings into the hand a device capable of supporting an entirely new class of haptic or touch-based interactions, where gestures can be captured and reactions to these gestures conveyed as haptic feedback directly into the hand. Thus, one can literally shake the hand of a friend, toss a file off one's PDA, or be led by the hand to a desired location in a strange city. In this paper I will propose that, for the mobile user negotiating these multiple frames of reference for their actions, a better understanding of the senses of touch, of the body's motion and its sense of its own motion, may be the key to providing a meaningful bridge between these interleaved and interdependent spaces.

1. Introduction

The telephones and personal digital assistants we carry with us can hear and see their surroundings, and will soon be able to sense their own motion. They are connected to us, to the world and to each other. This coincidence of connectedness, situational awareness, and richly multimodal input and output capabilities, sets the stage for a revolution in interaction design where the external physical world is an integral part of the interface, the communication infrastructure and even the storage and memory of our personal digital devices. These devices are no longer self-contained entities, but intermediaries through which we interact with distinct but interdependent spaces. When these spaces are abstract constructs such as communications networks, we typically construct meaningful interaction models such as Web sites and pages. However, when these spaces have real-world referents, such as location and object, it is possible to use the body itself as a mechanism for revealing meaning in interaction, since the body is far more capable of discovering meaning in the context of the physical world than any artificially constructed metaphor.

the senses of touch are perhaps the most complex human senses

The consequence of this realisation is that, paradoxically, we need to turn to the capabilities of our bodies to sense and act in the real world in order to increase the functionality of our digital devices. In the case of portable devices, to be used on the move, it is important to be aware of the way the body moves and how it moves relative to the environment. In the specific case of hand-held portable devices, it is also necessary to understand the capabilities of the hand. In both cases, touch is key — without a sense of touch we cannot move and without moving we cannot act.

Hitherto, portable devices have responded to touch in a very limited context: 'Has a button been pressed?' They have used haptic output (in the form of vibrotactile feedback) in an equally limited context — silent alarm. In this paper, I shall argue that the coincidence of connectedness, awareness and multimodal input and output capabilities in portable devices will generate a new interaction paradigm that will depend on the body as the meaning-making mechanism. Thus we, as interaction designers, must become well acquainted with the body's motion and its sense of its own motion. More particularly, we must become conversant with the many senses and purposes of touch.

2. The senses of touch

The senses of touch are perhaps the most complex human senses because the organs of touch are distributed throughout our body, embedded in skin, muscles and joints. Moreover, the range of sensations associated with touch is very broad — thermal, chemical, mechanical, inertial. For each of these sensations, there are groups of specialised receptors that respond to specific stimulation — there are, for example, different receptors for sensing heat and for sensing cold. Even within the subset of sensations that result from mechanical stimulation such as pressure, at least four distinct types of receptor are involved in detecting exactly what kind of pressure is being applied — light or heavy, constant or varying.

For all these reasons, touch more than any other sense requires us to ask not how do we sense, but what and why do we sense?

> our senses of touch are key to our ability to manipulate the objects in our environment

To turn this question around, what would it mean to lose our senses of touch? Though such a sensory loss is rare, it is not unknown and its consequences are at first glance unexpected. In his book *Pride and a Daily Marathon* [1], Jonathan Cole documents the case of Ian Waterman who, at the age of 19, contracted a viral infection that resulted in the destruction of the peripheral tactile sensory nerves below his neck. The result was that while he could still transmit motor commands to his muscles, he was unable to monitor the response of these commands via the receptors embedded deep in his muscles and joints. Nor was he able to feel any sensation of light touch on his skin. He could still feel pain and temperature sensations as this subset of nerves within the peripheral sensory system was unaffected by the virus. Jonathan Cole's account documents the way in which Ian learned to retrain his proprioceptive system so that movements normally monitored by the visual, haptic and vestibular proprioceptive subsystems could be controlled through visual and vestibular feedback alone[1]. For Ian Waterman, the only way to ensure that his legs would move in a trajectory rhythm and sequence that would result in walking was to watch their motion and plan the sway of his upper body to ensure he shifted his centre of mass forward, but did not overbalance. Moreover, it was impossible for him to walk at all in the dark or in a crowded place where he could not see his feet. From this, it can be deduced that peripheral sensory neurons in muscles, tendons and joints both regulate self-produced motion and monitor motion imposed by interaction with elements in the environment such as gravity. The haptic sense, then, is clearly fundamental to our ability to move in the world.

When performing a simple action, such as picking up an object, Ian Waterman can determine whether he has applied the correct force to lift the object only by watching whether it is moving toward him or whether he is moving toward it. The fact that he cannot sense the posture of his own body with respect to the weight of the object requires him to rely on vision to monitor his position with respect to the outside world. If he does not apply sufficient force to lift an object, the object will not move. If he falls toward it, the object was too heavy to lift. If, when grasped, the object falls from his hand, he was not gripping it hard enough; if it is crushed, he applied too much force. In other words, without the help of skin receptors to sense slip, proprioceptive receptors to sense body position, and kinaesthetic feedback to monitor interaction forces, he must rely on vision to successfully move the object. Our senses of touch, then, are key to our ability to successfully act on and manipulate the objects in our environment.

The foregoing example serves not only to illustrate the complexity of touch, but also to highlight the interdependence of its various senses. The tactile sense, mediated by receptors in the skin, relies on movement between the skin and an object's surface in order for any sensation to be perceived — without movement, objects disappear from our tactile view. The kinaesthetic sense, mediated by receptors in muscles and joints, must support the tactile sense by providing information about motion and self-motion. The proprioceptive sense, in turn, orients the entire system with respect to gravity and the outside world[2].

In summary, the complexity and interdependence of the touch senses requires an approach to the design of applications that use touch where its various roles in sensing, motion and action are well understood and supported by appropriate sensory cues.

3. Some of the purposes of touch

When considering the design of any application that incorporates the senses of touch, particularly in a hand-held mobile context, it is worth reflecting on situations where touch plays a significant role in existing interactions with the world. That is not to say we could not create entirely new forms of interaction, but starting from existing experience is likely to provide valuable information upon which such novel interactions can be built.

3.1 Touch and action

As has already been suggested, one area where touch plays a vital role is in direct physical interaction with objects in the environment. Such objects can either be the focus of our attention, as when exploring a new gadget, or they can be tools which mediate our interaction with something else in the environment such as a spoon for stirring coffee, a brush for sweeping the floor or a crane for moving a heavy load. The important consideration for designing for touch is that it should always be clear to the person using the interface to which properties of the mediated environment a particular touch effect relates. For example, in the case of the coffee spoon, one could choose either to provide an interface that preserves the tangible properties of the spoon — the shape of the handle, etc — but simulates the resistance of coffee when the handle is moved. Alternatively, one could provide some sort of generic grip, but simulate the coldness of a metal handle and the distribution of mass along its length so that when it is moved in the simulated liquid it feels heavy enough to be a spoon. Both approaches are equally valid. The first, where the tool handle is preserved, is typically used when it is

[1] The term 'proprioceptive', refers to the body's ability to monitor its position in the world. The proprioceptive system receives input from many sensory channels including the visual system, the kinaesthetic system and the vestibular system. Together these allow us to control and monitor the position and motion of our bodies, with reference to both our own body space and also to gravity and the external world.

[2] See Heller and Schiff [2] for a detailed discussion of the senses of touch.

desirable to allow a skill acquired in the real world to be more easily transferred to a simulated environment, as is the case in surgical training. Typically, haptic devices for surgical applications preserve the handles of familiar tools and simulate the feel of the operations of these tools on virtual tissue using force feedback devices [3] [3]. In this way, a trainee surgeon can practise a skill as many times as is necessary and also experience different 'cases' of a condition to be treated. The disadvantage of this approach is that these tools are designed with specific 'affordances', that is to say specific opportunities for action that are relevant only to the task being performed — pinching, rotating, puncturing, etc.

The second, more generalised approach which uses a common handle, provides a greater degree of flexibility. Here, one can simulate a variety of tool behaviours as well as a wide variety of environmental variables. Thus a multiple-degree-of-freedom force feedback device such as the PhanToM can simulate a cutting tool as well as the clay to be sculpted [4], or a microscopic probe and the topology of the sample to be examined [5].

it is important to understand which of the many touch sensations will be invoked

An important step in the design of any system that includes artificially generated touch effects, whether in the form of tactile, vibrotactile, thermal or force feedback, is to understand which of the many touch sensations will be invoked. For example, rendering the temperature of a spoon in a virtual cup of coffee will stimulate the thermal skin receptors, but will not create a response in haptic receptors embedded deep in muscles and joints. Conversely, simulating the forces created as the spoon is moved through the viscous coffee will create responses in the skin and muscle receptors which respond to inertial forces[4]. Finally, if it were possible to do so, simulating the moisture generated by steam rising from a hot cup of coffee would stimulate yet another set of moisture sensors in the skin. And all are parts of our touch-related experience of coffee. As will be illustrated in section 5, the decision for the designer is to define the task that the touch effects will support, to select the touch sensations that are most relevant for the successful completion of this task, and then to select the technical solutions that will make it possible to generate the appropriate touch effects.

[3] Force feedback devices such as the PhanToM [4] simulate the forces that might be experienced by a limb as it contacts, explores and manipulates an object. Typically these forces are transmitted to the hand of the user via a hand-held probe attached to a series of computer-controlled motors. As the user moves the probe in the device's workspace, their motion is sensed, and is resisted or assisted according to predetermined algorithms. The result is that the user can experience resistance to the penetration of object boundaries, textured surfaces, and visco-elastic properties of compliant materials, all through the modulation of forces generated in response to the speed and direction of the motion of their hand-held probe.

[4] A growing body of work by Turvey and colleagues [6—8] suggests that there exists a specialised dynamic touch sense whose purpose is to interpret inertial forces that relate to the motion of limbs and the motion of wielded objects. This sense has been shown to contribute to our ability to discover, through touch, specific properties of wielded objects, such as the size and shape [7], and the sweetspot of a tennis racket [8]. This dynamic touch sense, as yet relatively unexplored, is likely to be crucial to our future understanding of perception and action.

3.2 *Touch for communicating expression*

A specific subset of actions that should be considered in this context are actions which carry some expressive nuance. They are interesting because they represent an opportunity to reintroduce into mobile applications some of the richness of human interaction. Consider current trends to personalise SMS messages by supporting 'hand-written' signatures. In the binary world of the key press, there is no room for non-verbal cues. And yet, as Matt Locke [9] points out, all the information is there to be captured if our keyboards could only feel the touch of the person sending the message. One option, which has been explored by Oakley and O'Modhrain [10], is to capture a gesture, in this case the tossing of a ball, and send it as an adjunct to an instant message, to be replayed on a haptic feedback device when the message is read. Because the gesture is simply captured and passed through, much of its expressive nuance, such as the velocity and direction of the ball, is retained. In a similar project, Chang et al [11] built a mobile device that could transmit a form of haptic handshake (see Fig 1). When the device was squeezed, the pressure profile of the squeeze was measured, transmitted and converted into a series of vibrations displayed on the receiver's telephone. While the device could not reproduce the squeeze of a hand, it could capture the time-varying intensity of the original gesture, a mapping that proved to be remarkably effective given the relatively reductionist translation of force input at the sender's device to vibration output at the telephone of the receiver. This system was designed to be used as a parallel communication channel to speech and, when tested, was found to be used for negotiating turn-taking in conversation and adding emphasis to spoken phrases.

The pat on the back, the tap on the shoulder, the gentle caress of a bow on the string of a violin, all of these represent expressions of feeling mediated by the senses of touch.

front back

Fig 1 ComTouch.

Indeed, it is impossible to imagine a human gesture which does not embody expressive nuance. Capturing human motion, therefore, is the capturing of human expressive motion, for the two cannot be decoupled.

4. Framing the senses of touch

As the preceding discourse has suggested, the challenge for the designer of a mobile application is to provide meaningful support for someone using the system to negotiate the interleaved spaces the application must reference — the world-centred space through which the person is moving, the body-centred space of their gestures, and the device-centred space of the on-screen application interface. Of course, as moving living beings we are certainly well acquainted with relating our motion in the world to the motion of parts of our body with reference to each other. We are also adept at decoupling the motion of objects caused by our actions from motions of the same objects caused by forces outside our bodies [6]. The questions highlighted in this paper primarily arise because increasingly technologies make it possible to decouple the locus of action from the locus of the perceived response to that action. For example, tapping the screen of a PDA is a device-centred action but the response to this input might be to cause a document to be printed, which is an action in the world-centred frame of reference. If the printer is local, the result of the action will be perceived as the document appearing out of the printer, a response which the operator perceives as situated in the world-centred frame of reference. If the printer is remote, an on-screen indicator may change to indicate the success or otherwise of the printing action, which is a response delivered to the operator within the device-centred frame of reference. For such actions which are ballistic in nature, i.e. which, once triggered, are beyond the control of the operator, this potential conflict between frames of reference is not particularly significant since the operator can have little or no effect on the process once it has been started. However, for actions that provide continuous feedback and which allow for continuing intervention on the part of the operator, disparities between spatial and temporal frames of reference are likely to become more significant. Previously, such issues have been primarily the concern of domains of teleoperation such as remote vehicle operation, remote object manipulation (telemanipulation) and keyhole surgery. In each of these areas, an extensive body of work exists that highlights both the perceptual and technological challenges faced by the designers and operators of such systems. However, as has already been suggested, the rapid advances in the domain of sensing and actuation in mobile devices suggest that such concerns will soon be faced by a much wider design community, the designers of mobile applications. In this section, I will examine in turn the potential for device-generated touch effects to support the body's own haptic system in its capacity to relate physical space, motion and action through the senses of touch.

4.1 Touch feedback to support action in the device-centred frame of reference

In the context of mobile applications, particularly those centred on hand-held devices, device-centred application interfaces are those which rely on no external frame of reference, i.e. application interfaces where actions performed on or using the device result in some change of state of an application running on the device. With respect to touch, hand-held devices provide a unique opportunity since, if the motion of the device can be sensed, hand gestures can be used to control such actions as scrolling through documents and lists [12].

> the challenge for the designer is to provide meaningful support for someone using the system

Moreover, because in our interaction with the world the hand represents a closed-loop system for controlling the manipulation of objects, there exists a tight coupling between actions performed and the ability to sense, through touch, the results of those actions [13]. In hand-held devices, therefore, it becomes possible to create mappings between gestures or actions of the hand on a device, and the haptic responses of the device to these actions.

In order to further explore this potential, we have recently constructed a device that extends the functionality of a pocket PC by adding inertial sensing and high-fidelity vibrotactile feedback [14]. Using this system, we created a simple maze game where the tilting of the device causes a virtual ball to roll around on the screen. Using vibrotactile feedback, we generate low-amplitude vibrations to give the impression of friction as the ball rolls across the device and distinct vibrotactile events when the ball reaches the edges of the screen to give the sense of a physical ball contacting the inside of the device's case (see Fig 2).

Fig 2 Tilting maze.

From the perspective of haptic feedback design, this application is somewhat interesting because it relies on a combination of the user's own sense of the angle of the device in their hand with respect to gravity to move the ball through the maze, while taking advantage of artificially generated touch effects to inform them about the consequence of the tilting action, namely the event of the ball hitting the side of the device. Strictly speaking the maze application does reference the external world through the sensing of the position of the device with respect to gravity, but no external infrastructure is necessary to support this reference, at least for earth-bound users.

4.2 Touch feedback to support action in a body-centred frame of reference

In the context of mobile application design, body-centred applications refer to the movement of the device with respect to the body of the user. This is the most exciting area for the domain of touch-based mobile application design, since the bridge between physical and virtual spaces is effectively closed within the hand. The location-aware device, held in the hand, responds to the motion of the hand in a collocated physical and virtual space, with a reaction that can be felt. In this way, actions with precise referents in the real world of the body space are perceived to have simultaneous consequences in real and virtual environments such that the felt reactions are equally meaningful in both. An example which illustrates this is Angesleva's Body Mnemonics [15], an interface to portable devices where the body space of the user becomes a means of organising the information in one's PDA (see Fig 3). Information is stored and subsequently accessed by moving the device to different locations around one's body.

The system relies on a combination of the user's own proprioceptive sense to place and retrieve information in the body space, and device-generated vibrotactile cues to give additional feedback, such as task status, right into the hand. Just as one would rely on kinaesthetic and tactile memory to reach into one's physical pockets and identify elements of one's personal portable database by their feel (notebook, wallet, etc), so this application uses the same touch senses to

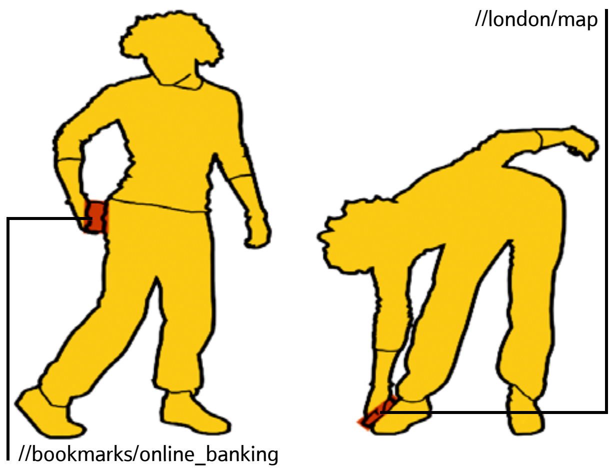

Fig 3 Body Mnemonics.

allow one to reach into one's digital pockets in the same way. The frame of spatial reference, here, is an egocentric space, grounded in the anatomy of the user's body and motion in that space reveals information in a parallel space, the on-line database of personal information. But the meaning-making mechanism, the mechanism which makes it possible for the user to negotiate this space, is their own kinaesthetic sense — without the ability to accurately move the device to the parts of their body where they have placed information, the interface is useless.

the challenge is to decide exactly what cues build on the body's abilities

In this application it is true to say that there is a meaningful mapping between the task of organising and finding one's information, the sensory cues supported by the application and the capabilities of the hardware used. This, for me, is the basis of a truly powerful interaction design.

4.3 Touch feedback to support action in a world-centred frame of reference

In the context of mobile applications, world-centred actions relate to the movement of the person, with the device, in the world. As such, these applications require some external referent to situate the person in time and space. Many such applications are piggy-backed on existing infrastructure, such as networks for mobile telecommunications, or the global positioning system. Other systems, such as museum exhibits, use physical electronic tags. The important capability that they provide in the context of this discussion is to incorporate aspects of how a person is moving through a space as a way to reveal information relating to their immediate physical surroundings. Thus while these applications may not always explicitly use artificially generated touch effects, they rely on a person's ability to relate their own motion and speed of motion to the physical environment around them. Examples of such applications are now fairly common in domains such as dynamic street maps, situated narratives [16] and situated mobile gaming [17].

4.4 Summary

While the preceding sections have sought to illustrate the design space of touch-enhanced mobile applications by distinguishing between different frames of reference for action, in reality such distinctions are likely to be somewhat artificial and even constraining. In fact, the real power of well-designed touch applications is in the opportunity they provide to leverage the body's existing and highly-tuned mechanisms for disambiguating the sources of touch stimuli in the world. As the tilting maze example has already illustrated, we can in fact 'design in' some of the body's assumptions and make them work to our advantage — we do not need to display information about the tilt of the maze, as this can be directly perceived by the tilted aspect of the device in the hand. All we need to provide are the touch cues relating to the motion of the ball. The challenge, then, is to decide exactly what cues are required to support actions in order that we can build on the body's abilities rather than creating touch effects which are at best ambiguous and at worst potential sources of interference and error. The following section presents a simple thought experiment for the design of a touch-enhanced mobile application, in the context of which some preliminary suggestions are made about how to approach the design of touch effects for this application domain.

5. The design of a touch-enhanced mobile application — a thought experiment

In order to consider the foregoing discussion in context, let us conduct a simple thought experiment. The central argument in this paper has been that the body's motion and its sense of its own motion can become a meaning-making mechanism in a context where actions and motions in different frames of reference in the physical world will have consequences in the representational space of a mobile application. Further, it has been suggested that the body's ability to extract this meaning depends on the sensitivity of the design to the various senses of touch. How, then, should one approach the design of such an application? Let us explore this process by considering the design of a personal navigation system. Let us further imagine that the design constraints are that the system should be based on a telephone or PDA and that it should be usable in an eyes-busy environment'.

The first question to ask is: 'What is the task?'

Here for the purposes of the exercise, we might define the task as the guidance of a moving person along a predetermined route in an eyes-busy environment.

> the senses of touch hold the key to the design of truly embodied mobile applications

The second question to ask is: 'What are the sensory cues associated with the task?' This is the point when we need to analyse the nature of the task and find a metaphor that will provide the user with a representational model of the interaction. Candidates for this metaphor might be a guiding hand or the notion of a guide-at-a-distance. The important thing to note is that the choice of metaphor will determine to a large extent the kind of sensory feedback that is relevant and appropriate for the task.

- The guiding hand

  To implement the notion of a guiding hand, we might expect to be able to give a user the sense of being taken by the hand and led along a predetermined path. Thus, we might want to find some way of integrating touch feedback and, moreover, touch feedback that can indicate direction in a device that can be hand-held or at least carried. Given this constraint, a number of approaches might be taken, which will largely depend on the technological resources at our disposal. We might choose to display the direction to be taken as the position of an arrow on a tactile dial [18] or as a series of pulses delivered to the body's surface [19—22]. One important difference between these two solutions relates directly to the perceived frame of reference for action. The tactile arrow indicates the direction of motion in a device-centred frame of reference; the user feels the arrow and must interpret the intended direction relative to the orientation of the device in their hand — upright or horizontal, tilted or level. In the case of the body-mounted display, information can be provided in the body-centred frame of reference, allowing the user to orient their body with respect to the direction of travel. A further advantage of this approach, as Traylor and Tan point out [23], is that it is less susceptible to disorientating effects such as sensory overload, a fact which has been shown to be particularly useful in altered gravity situations.

- The guide-at-a-distance

  This metaphor, suggestive of the kind of guidance provided by an air traffic control tower, would provide dynamic instructions to someone as they executed a predetermined route. Many such systems already exist for in-car navigation and some are currently under development for personal navigation devices [24]. The important consideration for this discussion is that such systems operate in a world-centred frame of reference, providing directions with respect to external physical landmarks. Because of the need to communicate information such as the names and descriptions of landmarks, such systems are likely to be more suited to speech feedback, though this might be augmented by non-visual directional cues in either audio or haptic channels.

In all cases, once the metaphor has been selected and the required sensory cues defined, the next question is to ask: 'What display capabilities are necessary or sufficient to support this task?' It is beyond the scope of this paper to detail all the possible solutions that are currently available for delivering various forms of haptic effects. Suffice it to say that, if the sensory cues required for a task are well defined, the particular technology used to implement these cues can be selected to conform to constraints such as size, cost, weight, and so on. The goal here has not been to suggest how to design an application interface incorporating touch technology, but rather to suggest how a designer might get to a point where the technology to be used can be defined.

6. Concluding thoughts

In this paper, I have suggested that the coincidence of connectedness, location awareness, and richly multi-modal input and output capabilities in the coming generation of mobile devices requires an entirely new approach to interaction design. This new interaction paradigm, that must support actions in physical space that have consequences in both the real world in which a person is moving and the representational world of the application, will, I suggest, depend on the body as the meaning-making mechanism. Thus it is imperative for interaction designers to become conversant with the body's motion and its sense of its own motion. Since the body's sense of motion is inextricably linked to the senses of touch, I suggest that touch will play a crucial role in unlocking the potential of this new interaction paradigm.

While we are far from defining a design methodology for this new touch-centred interaction paradigm for mobile devices, some of the examples upon which I have drawn, in particular Body Mnemonics [15], begin to suggest simple heuristics that could become the basis of such a methodology. In particular, I suggest that a key to the design of a successful application is in ensuring a good mapping between the task to be performed, the sensory cues required to support that task and the capabilities of the system on which the application is to be implemented.

If, as I suggest, the senses of touch do hold the key to the design of truly embodied mobile applications, and if the body's motion and its sense of its own motion can become the meaning-making mechanism which disambiguates the interrelated frames of reference of physical and representational spaces, then unlocking this potential in design is likely to have as much of an impact on increasing the functionality of these devices as any technological breakthrough in device design or network performance.

References

1 Cole J: 'Pride and a daily marathon', MIT Press, Cambridge, MA (1995).

2 Heller M A and Schiff W: 'The Psychology of Touch', Lawrence Erlbaum Associates, New Jersey (1991).

3 Rosen J, Hannaford B, MacFarlane M P and Sinanan M N: 'Force controlled and teleoperated endoscopic grasper for minimally invasive surgery-experimental performance evaluation', IEEE Transactions on Biomedical Engineering, 46, No 10, pp 1212—1221 (1999).

4 Sensable Technologies: The PhanToM Haptic Interface — http://www.sensable.com/

5 Maekawa H and Hollerbach J M: 'Haptic display for object grasping and manipulating in virtual environments', Proceedings of the International Conference on Robotics and Automation (ICRA 98), pp 2566—2573 (1998).

6 Carello C and Turvey M T: 'Rotational invariants and dynamic touch', in Heller M (Ed): 'Touch, Representation and Blindness', pp 27—66, Oxford University Press (2000).

7 Burton G, Turvey M T and Solomon H Y: 'Can shape be perceived by dynamic touch?', Perception and Psychophysics, 48, pp 477—487 (1990).

8 Carello C, Thuot S, Anderson K L and Turvey M T: 'Perceiving the sweet spot', Perception, 28, No 3, pp 307—320 (1999).

9 Locke M: 'Light Touches', — http://www.receiver.vodafone.com/09/articles/index00.html

10 Oakley I and O'Modhrain S: 'Contact IM: Exploring Asynchronous Touch Over Distance', Proceedings of CSCW 2002, New Orleans, LO (2002).

11 Chang A, O'Modhrain S, Jacob R, Gunther E and Ishii H: 'ComTouch: design of a vibrotactile communication device', Proceedings of DIS, England (June 2002).

12 Harrison B L et al: 'Squeeze me, hold me, tilt me! An exploration of manipulative user interfaces', in ACM CHI'98, ACM Press, Los Angeles, CA (1998).

13 Poupyrev I, Maruyama S and Rekimoto J: 'Ambient touch: designing tactile interfaces for handheld devices', in ACM UIST'02, ACM Press, Paris, France (2002).

14 Oakley I, Angesleva J, Hughes S and O'Modhrain S: 'Tilt and feel: scrolling with vibrotactile display', Proceedings of EuroHaptics'04, Munich, Germany (2004).

15 Angesleva J, Oakley I, Hughes S and O'Modhrain S: 'Body Mnemonics: portable device interaction design concept', Proceedings of UIST'03, Vancouver, Canada (2003).

16 Donovan B, Wood A, Davenport G and Strohecker C: 'Nature Trailer', — http://storynetworks.mle.ie/projects/remote/natureTrailer.html

17 Newt Games, Mogi — http://www.newtgames.com/

18 Miller J: 'Wireless Navigation for the Blind and Visually Impaired', — http://www.calit2.net/research/labs/features/2-5_04_wireless_nav.html

19 Tan H Z, Gray R, Young J J and Traylor R: 'A Haptic Back Display for Attentional and Directional Cueing', Haptics-e, 3, No 1 (2003) — http://www.haptics-e.org/

20 Shoval S, Borenstein J and Koren Y: 'The NavBelt — a computerized travel aid for the blind based on mobile robotics technology', IEEE Transactions on Biomedical Engineering, 45, No 11, pp 1376—1386 (November 1998).

21 Nokia Corporation: 'Navigation System', EP1220179 (July 2003).

22 van Veen H, Spapé M and van Erp J: 'Waypoint navigation on land: different ways of coding distance to the next waypoint', Proc of EuroHaptics'04, Munich, Germany (2004).

23 Traylor R and Tan H Z: 'Development of a wearable haptic display for situation awareness in altered-gravity environment: some initial findings', Proceedings of the 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, IEEE Computer Society, Orlando, FL, pp 159—164 (2002).

24 Ipaq Navigation — http://uk.insight.com/apps/brands/mfg.php?mfgcode=HP&page_id=2925

Sile O'Modhrain leads the Palpable Machines group at Media Lab Europe. Her research focuses on human-computer interaction, especially interfaces incorporating haptic and auditory feedback.

She earned her master's degree in music technology from the University of York and her PhD from Stanford University's Center for Computer Research in Music and Acoustics (CCRMA). She has also worked as a sound engineer and producer for BBC Network Radio.

In 1994, she received a Fulbright scholarship, and went to Stanford to develop a prototype haptic interface augmenting graphical user interfaces for blind computer users. In 1998, she received a Stanford Centennial Teaching Award in acknowledgement of outstanding performance in teaching.