Chapter 7

Conclusions

7.1 Introduction

The graphic and text input devices currently in use by mobile computers were not *designed* for portability, but were more *re*-designed for portability. These devices were often originally intended for desktop systems and then shrunk down to fit a smaller size of computer. Instead of using modified input devices, mobile computers need input devices specifically designed for them: devices that are as unobtrusive as possible in order to free the computer to take a more efficient shape.

The wide variety of characters, editing commands and other functions needed for text entry makes text input devices much more complex and, consequently, much less portable than graphic inputs. Interfaces like the keyboard are quite efficient on a desktop, but become rather difficult to use when shrunk for use in a mobile environment. In order to minimise the restrictions on the portability of a text input device, it is necessary to find a new approach which does not use board-based interfaces. Graphic input devices tend to be more portable than text input devices because the interaction is simpler. Pointing devices currently exist which are completely unobtrusive and portable. These are usually based on tracking some part of the body and are often expensive, imprecise, or have a limited range, precluding their use on a mass scale. In order to make these devices more feasible, it is necessary to use new technologies to overcome their deficiencies and thereby make new input devices which are designed to be not only portable, but are easy to operate, efficient, and acceptable enough for widespread use.

7.2 Review of Design Goals

A set of four primary goals were developed to provide direction for the design process by outlining the requirements of the final devices. These design goals were as follows:

1. The devices must be operable in a mobile environment. They cannot depend on any external surfaces or objects.

2. The devices must be usable by both nomadic and continuous users. They must not hinder the user in performing real-world tasks.

3. The devices must be able to operate a standard windows-style interface and to perform a wide range of simple text entry tasks.

4. The devices must be able to be used with existing wearable computer systems by using standard communications ports and requiring reasonable levels of computing power.

The Biofeedback Pointer is very well adapted for mobility. No aspect of the device hinders movement nor requires any external devices or surfaces for operation. The Chording Glove has the potential for high mobility as well. The only constraint on its portability is the need for a solid surface to chord against. It is unknown what the limits imposed by this constraint are. The Chording Glove has been experimentally shown to work in a simple mobile environment, but further tests are necessary to determine the effectiveness in more demanding situations.

The devices' usefulness in a mobile environment makes them well suited for the continuous mobile computer user. Both devices are operated by one hand and require no visual supervision. The heads-up use allows the user to keep track of the surrounding environment and the one unused hand allows the user to freely interact with it while computing. The user can stop computing at a moment's notice and have full, unhindered interaction with the real-world, should the need arise. In addition to the mobile computer user, these devices are easily adaptable for use by disabled persons as well. Chording devices like the Chording Glove have been used by people with motor disabilities. The wide range of muscle groups which can be used by the Biofeedback Pointer makes it particularly suited for users who are partially paralysed.

The Biofeedback Pointer is best suited for tasks involving navigation and low precision pointing. This encompasses the standard windows interface as well as basic exploration of two and three dimensional data. The Chording Glove, while slower than a desktop keyboard, is not much slower than existing mobile devices such as a stylus or soft keyboard. With further work, the Chording Glove's input speed may even surpass them by reaching the theoretical input speed of around 40wpm. This implies that the Chording Glove is fast enough for the casual levels of use of existing mobile devices, but further research must be done to determine exactly what range of speeds "casual use" covers.

The Chording Glove can be easily run on commonly existing systems. There is very little computation or memory necessary to run the device, making it easily usable on even the simplest computers. Communication between the prototype and the computer is carried out though the parallel port, but his could be changed to a serial or even a keyboard port if necessary. The Biofeedback Pointer is more complicated, requiring at least a Pentium 133MHz to run. The prototype did not use any specialised hardware, but future versions might. Moving the data sampling and FFT to a specialised device would take a significant fraction of the computing power away from the computer, allowing the pointer to be used on a simpler computer. Data acquisition for the Biofeedback Pointer was performed by an ADC attached to the parallel port. ADCs also exist which can be attached to a serial port or via a PCMCIA card.

The existing prototypes of the Biofeedback Pointer and Chording Glove have been shown to satisfy most of the basic design goals. There are a few remaining goals which were not directly shown to be satisfied. In some cases the goals were implied to be satisfied by research done on similar devices. In the other cases, the goal was shown to be partly satisfied by experiments which did not test sufficient range to know if the entire goal was reached.

7.3 Summary of Contributions

7.3.1 Review of Input Devices and Mobile Computers

The discussion on text and graphic input devices was intended to provide an overview of the current options for input devices. We were specifically interested in their performance, portability, and ergonomics. By considering these for each type of device we were able to generalise the requirements for graphic and text input devices, and how to make such devices work well in a mobile environment. This was essential in order to efficiently design new input devices.

The analysis of mobile computers discussed the range of technology currently being used and the likely directions the technology will take in the next few years. By examining the state of the art of mobile computers we were able to determine how both the style of the computer and the input devices used effect the portability of the system. From this we were able to conclude that a boardless input device is the most efficient for a wearable computer. This conclusion, plus the design requirements discovered earlier, were used to design new input device which could fully complement the mobile nature of wearable computers.

7.3.2 The Chording Glove

The Chording Glove was designed and built using the design criteria generated from the review of devices and systems. This text input device is worn as a glove, making it unnoticeable when not being used, but it is always there, ready for use, whenever the need should arise.

The device's performance was experimentally tested. After training for 11 hours, users were able to input text at a rate of 16.8wpm, with 17% of the characters made by mistake. This was somewhat worse than expected, or desirable, and was due to inaccurate finger sensors. These need to be replaced in future versions of the device. Consequently the performance of the Chording Glove in this thesis should be used as a lower limit for its potential performance. The Chording Glove was also shown to be usable without loss of performance in a simplified mobile environment. However, further research must be done to determine exactly what range of mobile environments in which the Chording Glove will function.

The chord keymap must be learned before the device can be used. It took users, on the average, 80 minutes to complete a tutorial, in which they learned to chord all 97 characters. After 6 hours of use, users needed to look up forgotten chords around 0.5% of the time. There is evidence that the keymap is remembered after significant periods of non-use, and that the previous performance is quickly re-attained, but this needs to verified with further research.

In creating the Chording Glove a generalised method for developing a chord keymap was designed. In this method, the characters are first grouped into logical groups, such as letters, numbers, and punctuation. These are used for the different shift states of the device. The characters are then assigned to the chords, with frequent characters aligned with the easiest chords. Once a basic keymap is made, it is altered in five steps:

1. Assign shifted chords to provide a logical relationship between them and their unshifted chords (e.g. `P` and `+`)

2. Revise so that finger positions for the chords bear a resemblance to the characters they make.

3. Revise so that frequent digrams and trigrams are made by chord sequences which are easy to perform.

4. Revise so that characters which look similar are made by chords which look similar (e.g. `U` → `W` = ○●○○● → ●●○○●)

5. Clean up the keymap to fix any poorly assigned characters.

This method for creating a chord keymap can be extended to most styles of chord keyboards. Alternatively it can be used to create new keymaps for the Chording Glove, either for use with foreign languages, specialised applications, or personal customisation.

It is easy for a user to customise a standard keyboard by using software to change the layout. However, this is rarely done in practice because it tends to create more problems than it solves. The most obvious problem is that the symbols on the keys conflict with their function. Either the user changes the key labels every time they alter the layout, or they need to memorise the layout and never look at the keys. Another problem is when the user attempts to operate someone else's keyboard. The interference between the two layouts lowers the user's performance. The Chording Glove does not suffer from either of these problems. When the user cannot remember a chord, they can use the <Help> key to display the keymap on the screen, whichever keymap is used. Since the Chording Glove is portable, the user can take their own customised interface with them, avoiding the need to adapt to each new system they come across.

A theoretical method for testing chord keymaps was developed along with the Chording Glove. These tests use the relative probability for each character along with Seibel's (1962) DRTs and error rates for all 31 chords. The first test is the normalised finger work. Strong fingers like the thumb and index finger should be used most, and weak fingers like the little finger should be used least. The work for each finger is found by the sum of all probabilities of the characters made by chords using that finger. Each result is normalised by dividing by the sum of the results for all fingers.

The second test and third tests determine the theoretical speed and error rate of the device. Seibel measured the DRT and error rate for each chord. The DRT is the time it takes to make each chord and the error rate is the probability of entering the wrong chord. The theoretical speed is determined by totalling the product of each chord's DRT and its probability. The theoretical error rate is equal to the sum of each chord's probability multiplied by its percent error. In other words, for chord c with probability $p(c)$, digram time DRT(c) and error probability of $\epsilon(c)$:

$$\text{time per character} = \sum_c p(c) \cdot \text{DRT}(c) \tag{7.1}$$

$$\text{error rate} = \sum_c p(c) \cdot \epsilon(c) \tag{7.2}$$

Equation 7.1 can be converted into words per minute by Equation 4.1.

7.3.3 The Biofeedback Pointer

In designing the Biofeedback Pointer, the benefits of using the EMG, EEG, and GSR were considered. The EMG was used because the signal was the most consistent and the easiest to measure. Hiraiwa et al.'s (1993) method for EMG analysis determined to be the most promising and was adapted to work with the Biofeedback Pointer. This neural network was simplified to produce only an x and y value instead of the angles of all the finger joints. These two values could be generated by any two independent motions, making the system usable with just about any muscle group. The Biofeedback Pointer's simplified network was less computationally expensive, allowing a higher refresh rate. However, the side effect was a reduction in accuracy. This was compensated for by using more EMG sensors. Instead of using special hardware to train the device, the training was performed by requiring the user to follow the pointer's motion on the screen. This may not be quite as accurate as using a motion sensor, but it enables the Biofeedback Pointer to be used with any standard PC without requiring specialised hardware.

The Biofeedback Pointer succeeds very well in its intent to be truly portable. Electrodes and amplifiers are very small and can be worn underneath clothing. The box containing the hardware is around the size of a cassette case and can be clipped to the belt. If a long sleeve shirt is worn over the electrodes and wires, the device is completely invisible. Even when it is used it cannot be seen.

A user can train the Biofeedback Pointer in about half a minute. This is fast enough that, in case of problems with the neural network, retraining is not a nuisance. As the user starts using the pointer, they also start learning how to manipulate the device to fine tune their control using biofeedback.

The mouse and Biofeedback Pointer were experimentally compared using Fitts' Law to measure the performance of each device. The index of performance of the Biofeedback Pointer was 1.06, and the mouse was 7.1. This gives a ratio of the Biofeedback Pointer to the mouse of 0.14. Existing mobile pointing devices have IP ratios ranging from 0.26 to 1.09. The Biofeedback Pointer is just over half the lowest performance in that range. Future enhancements, such as a more sophisticated neural network or better training methods will be useful in closing this gap.

7.4 Conclusions

The size of mobile computers has always been limited by the input devices. Notebook computers have been limited in size by the standard keyboard, which quickly loses its efficiency when shrunk. Usable handwriting recognition systems were a significant factor in the current boom in handheld computers. The mobile computer is now limited to a new, smaller size, but the shape is still limited to a notepad-style interface. The next step in mobile computer evolution is to make an interface which frees the computer from the constraints of the input devices to allow an entirely wearable system. The devices described in this thesis are wearable computer input devices which put no constraints on the size of the system. They work in the same manner with a desktop computer as they would with one the size of a matchbook. The Chording Glove and Biofeedback Pointer meet all of the design requirements set out in this thesis, but work still needs to be done to improve their performance. It is recommended that further research be done to enable these devices to achieve their potential.