M.I.T Media Laboratory Perceptual Computing Section Technical Report No. 432
To Appear: IEEE ISWC proceedings Vol. 1, No. 1, October 1997

Affective Wearables

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Abstract

An "affective wearable" is a wearable system equipped with sensors and tools which enables recognition of its wearer's affective patterns. Affective patterns include expressions of emotion such as a joyful smile, an angry gesture, a strained voice or a change in autonomic nervous system activity such as accelerated heart rate or increasing skin conductivity. This paper describes new applications of affective wearables, and presents a prototype which gathers physiological signals and their annotations from its wearer. Results of preliminary experiments of its performance are reported for a user wearing four different sensors and engaging in several natural activities.

1 Introduction: Why affective wearables?

One of the distinguishing features of wearable computers, as opposed to merely portable computers, is that they can be in physical contact with you in a long-term intimate way. A wearable may not just hang on your belt, but it may also reside in your shoes, hat, gloves, jewelry, or other clothing, providing a variety of kinds of physical contact beyond the traditional paradigm of fingertips touching only a keyboard and a mouse. In particular, when equipped with special sensors and tools from signal processing and pattern recognition, a wearable computer can potentially learn to recognize physical and physiological patterns—especially those which correspond to affective states—such as when you are fearful, stressed, relaxed, or happily engaged in a task.

Sensing physiological patterns is not a new thing; ambulatory medical devices have been under development for years, helping people with various medical complications to monitor heart rate, blood pressure, and more. Affective wearables overlap with medical wearables in that both may sense physiological signals. In particular, both may be concerned with sensing signals that indicate stress or anxiety [HB96], an application of interest not just for people suffering from anxiety attacks or other medical conditions, but also for healthy people who are interested in staying healthy. Affective states of depression, anxiety, and chronic anger have been shown to impede the work of the immune system, slowing down healing and making people more vulnerable to viral infections (See Chap 11 of [Gol95].) Wearables provide a means of monitoring stress and other conditions outside the confines of a medical facility, gathering data as the wearer goes about his or her daily activities. Of course, none of the data collection or analysis implies that the user will choose to change their behavior or lifestyle, but it can help a wearer make informed decisions, and can be shared with one's physician, if the wearer desires, for help in treating chronic problems like back pain and migraine headaches which can be stress related.

Sensing affective patterns, such as stress, also has important implications for developing intelligent and effective human-computer interfaces, as will be described in applications, below. There is a movement in computer science toward developing systems that *learn* what their users want, and try to model their user's interests. However, a natural way that people express want they want, and whether they like or dislike things, is through affective expression. They may speak with a pleased or distressed voice. They may smile or frown. They may gesture, nod, slump, or otherwise indicate that they feel good or bad. A big problem is that current computers are oblivious to most of these affective cues. They ask us to click on menus to indicate whether we like something or not, when instead they could have sensed our response from its most natural form of expression. A wearable has an unprecedented opportunity to "get to know" its wearer.

One of the problems in giving a computer the ability to recognize affective patterns is that, despite decades of research, emotion theorists still do not understand what emotions are and how they are communicated. One of the big problems in emotion theory is determining what physiological patterns accompany each emotion (See, for example, [CT90].) In some individuals, an increase in temperature and blood pressure might co-occur with anger. An acceleration in heart rate and pupillary dilation might indicate the person likes what he is looking at. However, almost all of the studies trying to determine which responses occur with which emotions have been done on artificially elicited emotions in a lab setting, where there is good reason to believe that people might not feel the emotions in the same way as when they are more naturally elicited. This problem has held back progress in emotion understanding. A wearable allows a tremendous opportunity to learn about affective patterns in natural situations. Affective wearables provide a perfect opportunity to bring powerful computational methods to bear on testing emotion theories.

2 Applications of affective wearables

There are dozens of applications of affective computing in addition to the medical and health applications mentioned above[Pic].). For example, emotions are known to provide a keen index into human memory; therefore, a computer that pays attention to your affective state will be better at understanding what you are likely to recall on your own. For example, instead of recording everything you hear, it might learn to record (or play back) just those places where your mind wandered. Augmenting a system like Steve Mann's WearCam [Man97] with affective sensing and pattern recognition could help it learn when to "remember" the video it collects, as opposed to always relying on the user to tell it what to remember or forget. Suppose for example that you let the camera roll while playing with a cute little baby. It might notice that you always save the shots when the baby makes you laugh, or smile. By detecting these events, it could become smarter about automatically saving these photos. Moreover, by labeling the photos with these affective events, you can later ask for ones by their affective qualities, "Computer, please show us the funny images." Of course the wearer should be free to override these "smart" settings, but if they are learned continuously, by watching what the wearer chooses, they will help reduce some of the users workload and enable the wearer to offload repetitive tasks.

Analysis of a wearer's affective patterns could also trigger actions in real time. For example, a "fear detector" might trigger the WearCam to save a wide-angle view of the environment, and to transmit the wearer's position, viewpoint, and fear state to a personal "safety net," a community of friends or family with whom you felt secure. To a wearer in a role-playing game, a fear detector might change his appearance to other players, or might reward him for overcoming his fear, with bonus points for courage.

An intelligent web browser responding to the wearer's degree of interest could elaborate on objects or topics that the wearer found interesting, until it detected the interest fading. An affective assistant agent could intelligently filter your e-mail or schedule, taking into account your emotional state or degree of activity.

Another application we are exploring in our research is the relationship between long-term affective state or "mood" and musical preferences. Music is perhaps the most popular socially-accepted form of mood manipulation. Although it is usually impossible to predict exactly which piece of music somebody would most like to hear, it is often not hard to pick what type of music they would prefer—a light piano sonata, an upbeat jazz improvisation, a soothing ballad—depending on what mood they are in. As wearable computers gain in their capacity to store and play music, to sense the wearer's mood, and to analyze feedback from the listener, they have the opportunity to learn patterns between the wearer's mood, environment, and musical preferences. The ultimate in a musical suggestion system, or "affective CD player" would be if it not only took into account your musical tastes, but also your present conditions – environmental and mood-related.

The possibilities are diverse – a wearer who jogs with her wearable computer might like it to surprise her sometimes with uplifting music when her wearable detects muscle fatigue and she starts to slow down. Another wearer might want the system to choose to play soft relaxing music whenever his stress indicators hit their highest levels. He might also want the computer to evaluate its own success in helping him relax, by verifying that, after some time, he did achieve a lower stress level. If the wearer's stress level increased with the music, or with a suggestion of music, then the computer might politely try another option later.

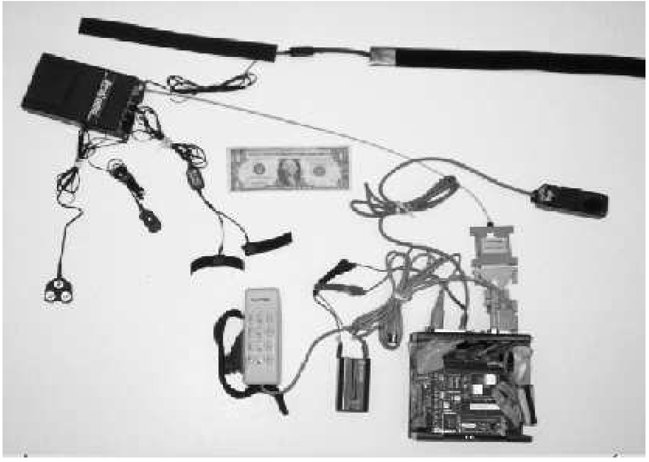

Figure 1: This affective wearable includes a ProComp sensing system (upper left corner) surrounded by four sensors, clockwise from top: respiration, GSR, BVP, and EMG. This unit attaches to a PC104 standard based computer (lower middle) which receives data from a Twiddler handheld keyboard (lower left). and displays data with the Private Eye (far left below respiration sensor.) (Photograph by Jennifer Healey.)

The whole problem of building *systems which adapt to you* is an important domain for affective wearables. Many times technology only increases stress, making users feel stupid when they do not know how to operate the technology, or making them actually become stupid when they rely on it in a way that causes their own abilities to atrophy. Our goal is to give computers the ability to pay attention to how the wearer feels, and to use this information to better adapt to what its wearer wants. Along the way, however, we need to be careful in considering the role of wearables in augmenting vs. replacing our abilities. For example, we know when a human is highly aroused (as in a very shocking or surprising situation) that she is more likely to remember what is happening–the so-called "flash-bulb memory[BK77]." If the human brain is recording with full resolution at these times, then the wearable imaging system may not need to record more than a snapshot. In contrast, when the human is snoozing during a lecture, the wearable might want to kick in and record the parts the wearer is missing.

3 Prototype of an Affective Wearable Computer

Ideally, an affective wearable would be able to sense and recognize patterns corresponding to underlying affective states, and respond intelligently based upon what it has sensed. We know of no computers that can do all of this yet; there are many difficult problems which need to be solved first. However, we have a prototype that achieves part of these goals, which we will now describe. The rest of this paper will focus on the results we have achieved so far in our efforts to develop the sensing and annotation aspects of an affective wearable computer. (The pattern recognition aspects are also important; these will be presented in a later publication.)

The current version we have built of an affective wearable is an augmentation of Thad Starner's design [1] [SMR$^+$97] using the PC 104 board standard and the Private Eye display, shown in Figure 1. Attached to this is a medically approved bio-monitoring system made by Thought Technologies, which has the ability to simultaneously monitor respiration, skin conductivity (GSR), temperature, blood volume pressure (BVP), heart rate (from BVP), and EMG (electromyogram, for muscular electrical activity). All of these can be sensed painlessly from the surface of the skin. Future versions of the system may include audio and video inputs and displays, wireless links to the Internet and wireless localized sensors.

Current functionality includes the monitoring of four sensors by a linux based operating system. The input from the four sensors can be displayed on a text-based screen such as the Private Eye with an option for concurrent user annotation. The annotations are automatically time-stamped by the system and stored in a separate log file. In the near future, we hope to add a third log file recording the user's location at periodic intervals using GPS for outdoors, and a system of fixed infrared location broadcasting stations for in¡side our lab.

The four biometric sensors can be sampled at up to 20 samples per second by the linux based ProComp system which allows an hour of data to be stored uncompressed in 1.125 MB as four byte floating point numbers. We are currently addressing the problem of down loading accurately time stamped data from the wearable via PCM (Sierra wireless modem) so that monitoring and recording of data can occur continuously even at higher sampling rates.

A difficult challenge of affective computing research is to determine which features of the sensor information should be considered salient, both to reduce the amount of data that is stored and transmitted, and to improve the analysis of the data. For example, it could be that a user is interested in monitoring her relative stress level over an extended period of time. Salient features for measuring stress could include the slope of the skin conductivity, average heart rate, average respiration rate or a combination of these and other signals. This data could easily be assessed and stored at a much lower saving rate (e.g., once per minute). At the end of a day or week, the user could view her daily stress profile. With intelligent annotation from the user—comments such as "begin work," "end work," "begin lunch," "end lunch," "begin meeting supervisor", "begin driving"—the stress profile could then be sorted by activity and presented to the user in a format which communicates the relative levels of stress.

4 Challenges of Ambulatory Affect Sensing

A wearable computer with bio-metric sensors, in constant contact with its user, offers an opportunity to obtain unprecedented amounts of physical and physiological data about a single user. This advantage also presents many challenges. To use the data effectively in learning algorithms, and to interpret the results, the data must be accurately labeled. We are in the early stages of developing ways to record the physical and psychological events of the wearer's life without interrupting their normal activities. Currently, an automatically time stamped notes file allows the user to annotate data from the sensor screen. Adding an audio recording device or video camera would improve the users ability to annotate data after the fact, but would make the annotation cumbersome. We propose to add two sensors to the system to improve annotation: a foot pressure sensor to indicate ambulatory movement and an audio detector that would detect if the wearer was making any vocal sounds (speech, sneezing, etc.) The latter could record and analyze the audio if privacy was not an issue, or if privacy was an issue, it would not record voice, but only use features of the sound signal to prompt the user for annotations, e.g. computer detects speech and prompts the user "Did you just talk to someone?" to which the wearer could respond "Talked to Jane Smith."

It is important to annotate the physical activities of the user because such physical activities can overwhelm the physiological effect of psychological events. Even under "ideal" laboratory conditions, with a resting subject responding to a directed stimulus, scientists have yet to find reliably discernible features of physiological signals for affect detection. In a natural environment where weather, diet, and physical activity are present, the patterns corresponding to particular affective states are at a much greater risk of being obscured. We must identify and account for these confounding variables.

In psychological studies by Lang [LGea93] and Winton, Putnam and Krauss [WPK84], subjects were monitored while looking at a series of photographs which were supposed to elicit an emotional response. These studies showed that heart rate variability was an indication of valence (whether or not the person found the photograph pleasant) and that the ratio of skin conductance to heart rate variability was an indicator of arousal. However, the greatest changes in skin conductance and heart rate in their study were 0.6 micro-Siemens, and 8 beats per minute respectively, in the ten second period after viewing the slides. These results are significant for a resting subject under controlled laboratory conditions, but we have found that such results can be overwhelmed by physical activity in an ambulatory subject.

We conducted experiments in the laboratory to show that the physical activity of ambulatory subjects is an important confounding variable to detecting emotional responses from bio-sensors. Five different subjects were run through the ambulatory bio-sensing task, the results of which are reported in Table 1. The experimental protocol involved subjects wearing the bio-sensors from the FlexComp system while performing a series of ambulatory tasks. The subjects were first shown how to attach the bio-sensors. In this experiment all subjects wore a respiration sensor, BVP, a GSR sensor on the hand and a GSR sensor on the arch of the foot. They were then asked to perform the following tasks: sit in a chair for one minute, resting quietly, stand up and sit down twice, walk around the room for one minute, sit in a chair normally for two minutes, stand up and walk around the room for one minute, sit normally for another minute, jog in place for one minute,

[1] http://wearables.www.media.mit.edu/projects/wearables/ has up to date information as well as a picture of this system.

Activity	Increase in HR (bpm)				
	S1	S2	S3	S4	S5
stand	16.0	15.8	19.7	22.0	15.2
walk	26.4	18.9	27.7	24.6	19.9
jog	68.2	60.8	74.0	80.9	87.4
cough	22.0	22.2	18.8	53.7	14.66

Activity	GSR change for Hand (micro-Siemens)				
	S1	S2	S3	S4	S5
stand	0.5	10.6	0.2	1.7	N/A
walk	2.0	14.3	0.8	2.8	N/A
jog	5.9	16.1	3.5	2.2	N/A
cough	5.4	11.0	2.1	2.7	N/A

Activity	GSR change for Foot Arch (micro-Siemens)				
	S1	S2	S3	S4	S5
stand	0.5	12.6	0.3	4.1	3.7
walk	1.5	10.4	1.7	6.9	3.4
jog	11.5	11.0	5.0	5.0	6.4
cough	6.9	9.9	2.4	5.9	3.2

Table 1: A wearer's activities can cause large changes in physiological signals. These changes need to be understood so that they can be taken into account by the system trying to recognize affect.

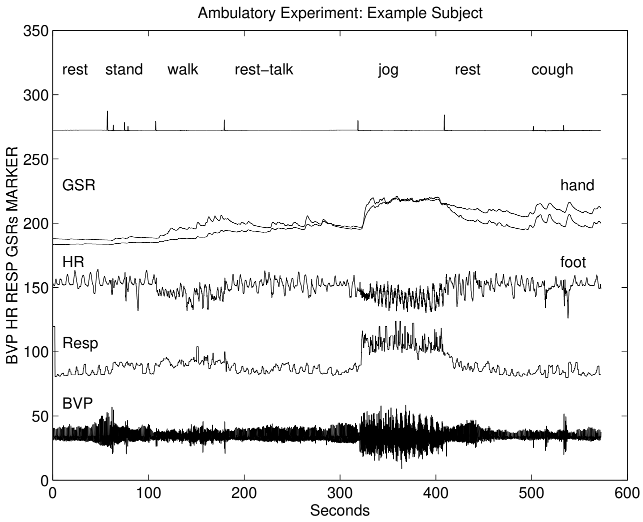

Figure 2: An example of data collected from the ambulatory experiment. Data is scaled and offset for show the relationships between the signals.

then sit for a minute and finally the subjects were asked to cough as if they had a cold twice. An experimenter was in the room with the subjects at all times during the experiment to instruct the subjects to perform the activities. Subjects sometimes had questions during the experiment, and talking was noted in the experimental record. The rest times between the activities sometimes varied, due to questions, so the beginning of the tasks were marked by the experimenter with a specially designed mouse equipped with a sensor which would make a spike in the recording data when depressed.

The data for this experiment, was saved at 16 samples per second using the FlexComp, with a resolution of 0.01 micro-Siemens. The change in the skin conductivity (GSR) was calculated as the difference between the baseline measurement, taken at the time each task was begun, and the first significant local maximum. The heuristic used for determining the significant local maxia, is that the difference between the local maximum and the following local minimum is greater than 0.5 micro-Siemens, although this number should be scaled with regard to the overall variance of the signal. The heart rate was calculated from the peak-to-peak intervals and stored at 16 samples per second. To calculate the change in heart rate the average of the heart rate for 10 seconds before the task was subtracted from the average for the heart rate ten seconds following the task. An example of data from the experiments is shown in Figure 2.

It is therefore necessary to have an accurate recording of the physical activity of the wearer and to understand how this affects the user's physiology, and expression of affect. From this information we can attempt to decouple the psychological effects from the physical. For example, although the heart rate of the wearer changes drastically with inhalation and exhalation, the heart rate and respiration signals are highly correlated as shown in Figure 3. By recording respiration, we can state which heart rate changes are effected by this source and which changes must be attributed to other sources.

The selection of which signals to measure is another challenge for an affective wearable. There is evidence to believe that physiological signals including accelerated heart rate [Lev92], raised blood pressure, increased skin conductivity, and constriction of the peripheral blood vessels [Hel78] are associated with stress in humans and heart rate variability [WPK84], pupillary dilation and right and left hemispheric activation in the brain [Dav93] are associated with like/dislike.

We are experimenting to determine which physiological signals can be best monitored under ambulatory conditions to produce the most salient affective features with sensors that are comfortable to wear. Such a system would be unobtrusive, lightweight, easy to use and does not require the user to make exceptions to his daily routine. Our goal is to create a sensor system which is comfortable and robust which can extract complex features in both the time and frequency domain and record annotations and context information.

The GSR sensor is one of the most robust wearable sensors because it is a bulk measurement and not very sensitive to exact placement of the sensor. Traditionally, this measurement is taken across the palm of the hand, however, this is one of the least ideal places for sensor placement. Ordinary activities such as washing your hands changes the baseline reading and repetitive motion of the fingers in activities like typing, creates a noise signal that confounds the signal. To alleviate this problem, we have explored the option of placing the electrodes on the toes and measuring skin conductivity across the sole of the foot.

In this experiment, another five subjects were seated and startled with five white noise bursts while wearing skin conductivity sensors on three locations. The sensors were

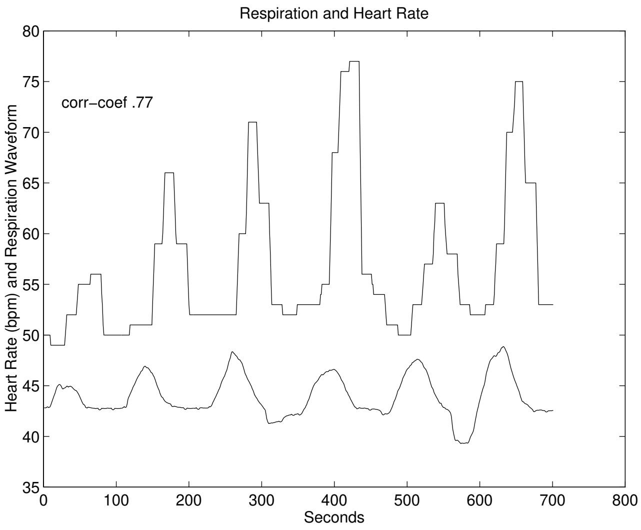

Figure 3: The heart rate and respiration signals from the ambulatory experiment, showing that although respiration has a large effect on heart rate, these effects are well correlated with the respiration signal and can be predicted.

Activity	Correlation Coefficients for GSR				
	S1	S2	S3	S4	S5
hand-toes	.93	.90	.97	.53	.86
hand-arch	.86	.86	.99	.95	.81
arch-toes	.89	.96	.98	.57	.86

Table 2: The similarity between skin conductivity readings measured from the palm of the hand and the arch of the foot offers the possibility of placing sensors in the wearer's shoe instead of on the hand.

placed on the two middle sections of the first and second finger on the dominant hand, on the two middle sections of the first and second toes on the same foot, and on the either end of the arch of the same foot. An electret microphone was used to record the startling tone burst as a reference. All skin conductivity data was sampled and saved at 16 samples per second with 0.01 micro-Siemens resolution. An example of the data recorded during these experiments is shown in Figure 4.

The startle experiment was designed to test the correlation of the hand and foot responses under extreme audio stimuli. The correlation coefficient was used to measure similarity between the signals taken from the three locations. The results of these correlations are reported in Table 2. In the natural sciences, the correlation coefficient is used in the Pearson correlation to test significance of traits, based on the number of data points. If we consider all samples of the signal data points for this test, all the results are extremely significant with $p>0.01$, however if we consider only some subset of the points e.g., those that represent the magnitude of the startle, then the results are only significant for three of the five subjects, with the most significant result corresponding to the subject who was least susceptible to startle. Therefore, the correlation

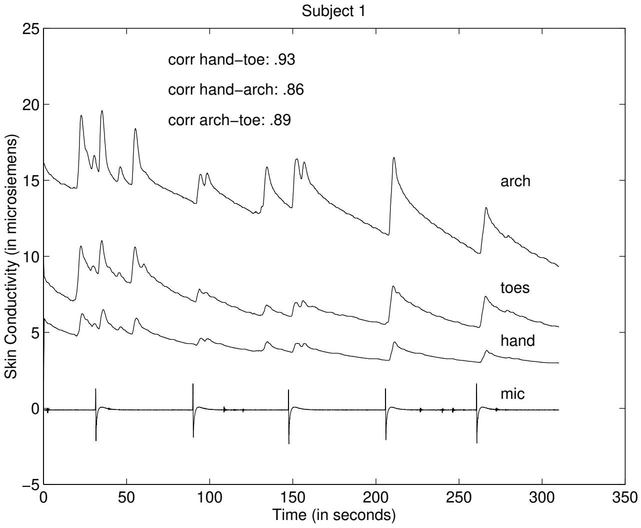

Figure 4: An example of data collected from the multiple startle experiment. This experiment was designed to test the correlation of the hand and the foot responses under extreme conditions.

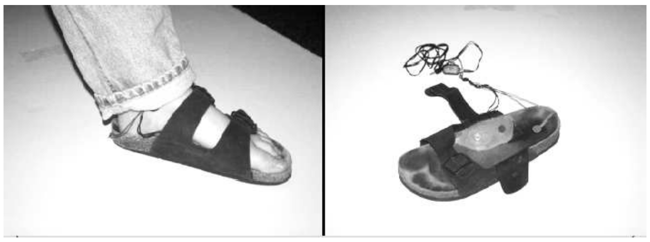

Figure 5: The shoe provides a convenient location for sensor placement. Here, a skin conductivity sensor is placed in the arch of the shoe and a pressure sensitive resistor is placed on the heel. Sensors look unobtrusive when worn.(Photograph courtesy of Fernando Padilla)

coefficients themselves are reported.

We also found strong correlations between the hand and foot responses in the Ambulatory study with a correlation coefficients of .90, .85, .83 and .88 for the first four subjects respectively (the fifth subject detached the hand GSR during the experiment). From these results we concluded that the skin conductivity responses of the hand and the foot were highly correlated. Therefore, either placement of the sensor could be used to measure the GSR response.

The blood volume pressure sensor uses photoplethysmography, a technique where an LED is used to "look" at the amount of blood flowing in the vessel. From this reading both the heart beat and constriction of the blood vessel can be determined. This sensor is sensitive to correct placement and motion artifacts; however, in a single-subject experiment we conducted driving through Boston at rush hour, where the wearer moved the hand with the sensors routinely to shift gears, adjust the radio, and turn the steering wheel, we found that although the signal was disturbed during motion, the signal re-stabilized after movements. Nonetheless, the wires felt like they were in the way. We are interested in moving them off the hands to sense what people are feeling during certain consumer tasks such as diapering an infant. This is a particularly challenging task as it is important not to drag the wires through the dirty diaper, or let the infant grab them and pull them, or put them in his mouth. In other words, we are investigating options for moving the sensors off the hands.

Respiration is the easiest sensor to wear and is the most immune from motion artifacts. It uses a constrained Hall effect sensor to measure the expansion and contraction of the chest cavity. The confounding variables of this measurement mostly audio (e.g. talking, sneezing, coughing and sighing) all of which we hope to compensate for with the audio detector.

We have been investigating the optimal placement for the EMG sensor to detect stress. The greatest challenge of EMG placement is to find a muscle to which the EMG electrode pad will stick well and which is not involved in muscle motion. To solve the problem of affixing the sensors we are currently considering the use of new electrodes and glue designed by the Boston University Neuro-muscular Research Center which have been demonstrated to stay affixed through rigorous physical activity. To solve the problem of motion we may need to create sensors which detect motion and use this to correct the straight EMG reading.

In the future we hope to create a wireless interface for all of these sensors. We have currently designed working prototypes of skin conductance and respiration sensors which transmit data via an IR signal using an iRx PIC series chip. This data is collected from multiple receivers in a room (See Figure 6).

5 Technology, Interface, and Human factors issues

This work raises a variety of concerns on many fronts. One of these is the need for lightweight, efficiently-powered computation, which is comfortable to wear, i.e., that does not interfere with a person's ordinary comfort or activities. Another need is the development of robust sensors with reliable contact. Whether these are flexible rubberized electrodes attached with jewelry, or small sensors for temperature sewn into our garments, or stretchy fabric comprising parts of a sports bra, these interfaces need to provide accurate signal collection and be comfortable enough not to disturb their wearer.

Figure 6: PIC chips on iRx boards can be used to sample data from sensors and transmit the digital signal using infrared. Small self-contained sensor systems such as this allow affective information to be wirelessly transmitted to a larger computer for analysis. (Photograph courtesy of Frank Dabek).

One of the many interface concerns involves how to present affective information to the wearer and to those with whom the wearer wants it communicated. If you are willing to transmit your mood to your spouse 0at the end of the day, how should this information be presented? As a synthesized facial expression, modulated vocal announcement, or, encoded in something more subtle, such as a note announcing the arrival of fresh flowers at the local store which is on your way home? Of course, privacy is also a priority, since the good mood you are in might be great for your family to know about, but not something you want taken advantage of by a salesperson.

6 Conclusions

Many issues need to be considered in developing an affective wearable computer. Bio-metric sensors need to be developed that are both accurate and robust to motion artifacts yet unobtrusive and comfortable to wear. Sensors, such as GPS, which can allow the wearable to be aware of the users context (home or office), and level of physical activity (sitting or walking) need to be considered. Pattern recognition and analysis techniques for affect recognition which integrate this context information and which are able to operate in real time on a single user need to be developed.

Acknowledgements

We gratefully acknowledge BT PLC., NEC, Ricoh, and the Media Lab's Things That Think consortium for their support of this research. We would like to acknowledge Thad Starner for the design of the base wearable system and contributing to the ideas of the Affective CD player. Frank Dabek helped create a prototype of the Affective CD player. Rob Gruhl, Smriti Banthia, Katherine McCoy, and Frank Dabek helped write software integrating the sensing hardware into the unix environment. Peter Chien, Grant Gould, and Kaechy Chen assisted in the development of wireless skin conductance and respiration sensors. The ideas of the safety net and of adapting music while jogging arose in conversations with Steve Mann.

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