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Real Time Eye Tracking and Blink Detection with USB Cameras

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Abstract

A human-computer interface (HCI) system designed for use by people with severe disabilities is presented. People that are severely paralyzed or afflicted with diseases such as ALS (Lou Gehrig's disease) or multiple sclerosis are unable to move or control any parts of their bodies except for their eyes. The system presented here detects the user's eye blinks and analyzes the pattern and duration of the blinks, using them to provide input to the computer in the form of a mouse click. After the automatic initialization of the system occurs from the processing of the user's involuntary eye blinks in the first few seconds of use, the eye is tracked in real time using correlation with an online template. If the user's depth changes significantly or rapid head movement occurs, the system is automatically reinitialized. There are no lighting requirements nor offline templates needed for the proper functioning of the system. The system works with inexpensive USB cameras and runs at a frame rate of 30 frames per second. Extensive experiments were conducted to determine both the system's accuracy in classifying voluntary and involuntary blinks, as well as the system's fitness in varying environment conditions, such as alternative camera placements and different lighting conditions. These experiments on eight test subjects yielded an overall detection accuracy of 95.3%.

1 Introduction

A great deal of computer vision research is dedicated to the implementation of systems designed to detect user movements and facial gestures [1, 2, 4, 5, 6, 15, 16]. In many cases, such systems are created with the specific goal of providing a way for people with disabilities or limited motor skills to be able to use computer systems, albeit in much simpler applications [1, 15, 16]. The motivation for the system proposed here is to provide an inexpensive, unobtrusive means for disabled people to interact with simple computer applications in a meaningful way that requires minimal effort.

This goal is accomplished using a robust algorithm based on the work by Grauman *et al.* [11, 12]. Some of these methods are implemented here, while some have been enhanced or modified to the end of simplified initialization and more efficient maintenance of the real time tracking. The automatic initialization phase is triggered by the analysis of the involuntary blinking of the current user of the system, which creates an online template of the eye to be used for tracking. This phase occurs each time the current correlation score of the tracked eye falls below a defined threshold in order to allow the system to recover and regain its accuracy in detecting the blinks. This system can be utilized by users that are able to voluntarily blink and have a use for applications that require mouse clicks as input (e.g. switch and scanning programs/games [22]).

A thorough survey on work related to eye and blink detection methods is presented by Grauman *et al.*, as well as Magee *et al.* [12, 16]. Since the implementation of the

BlinkLink blink detection system by Grauman *et al.*, a number of significant contributions and advancements have been made in the HCI field. Gorodnichy and Roth present communication interfaces that operate using eye blinks [8, 9, 10]. Motion analysis methods and frame differencing techniques used to locate the eyes are used Bhaskar *et al.* and Gorodnichy [3, 8, 9]. Detecting eye blinking in the presence of spontaneous movements as well as occlusion and out-of-plane motion is discussed by Moriyama *et al.* [19]. Methods for locating eyes using gradients and luminance and color information with templates are presented by Rurainsky and Eisert [21]. Miglietta *et al.* present results of a study involving the use of an eyeglass frame worn by the patients in an Intenstive Care Unit that detects eye blinks to operate a switch system [18]. There still have not been many blink detection related systems designed to work with inexpensive USB webcams [7, 8]. There have, however, been a number of other feature detection systems that use more expensive and less portable alternatives, such as digital and IR cameras for video input [3, 19, 21, 23]. Aside from the portability concerns, these systems are also typically unable to achieve the desirable higher frame rates of approximately 30 fps that are common with USB cameras.

The main contribution of this paper is to provide a robust reimplementation of the system described by Grauman *et al.* [11] that is able to run in real time at 30 frames per second on readily available and affordable webcams. As mentioned, most systems dealing with motion analysis required the use of rather expensive equipment and high-end video cameras. However, in recent years, inexpensive webcams manufactured by companies such as Logitech have become ubiquitous, facilitating the incorporation of these motion analysis systems on a more widespread basis. The system described here is an accurate and useful tool to give handicapped people another alternative to interface with computer systems.

2 Methods

The algorithm used by the system for detecting and analyzing blinks is initialized automatically, dependent only upon the inevitability of the involuntary blinking of the user. Motion analysis techniques are used in this stage, followed by online creation of a template of the open eye to be used for the subsequent tracking and template matching that is carried out at each frame. A flow chart depicting the main stages of the system is shown in Figure 1.

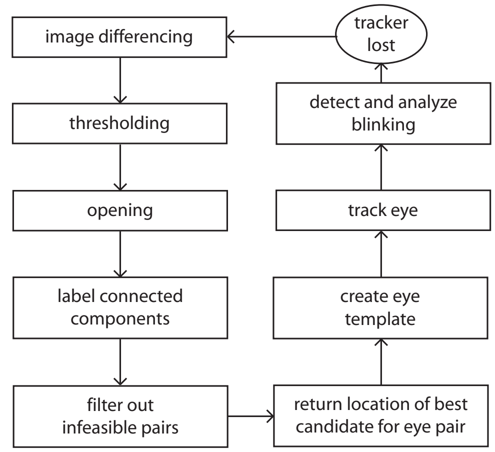

Figure 1: **Overview of the main stages in the system.**

2.1 Initialization

Naturally, the first step in analyzing the blinking of the user is to locate the eyes. To accomplish this, the difference image of each frame and the previous frame is created and then thresholded, resulting in a binary image showing the regions of movement that occurred between the two frames.

Next, a 3x3 star-shaped convolution kernel is passed over the binary difference image in an Opening morphological operation [14]. This functions to eliminate a great deal of noise and naturally-occurring jitter that is present around the user in the frame due to the lighting conditions and the camera resolution, as well as the possibility of background movement. In addition, this Opening operation also produces fewer and larger connected components in the vicinity of the eyes (when a blink happens to occur), which is crucial for the efficiency and accuracy of the next phase (see Figure 2).

A recursive labeling procedure is applied next to recover the number of connected components in the resultant binary image. Under the circumstances in which this system was optimally designed to function, in which the users are for the most part paralyzed, this procedure yields only a few connected components, with the ideal number being two (the left eye and the right eye). In the case that other movement has occurred, producing a much larger number of components, the system discards the current binary

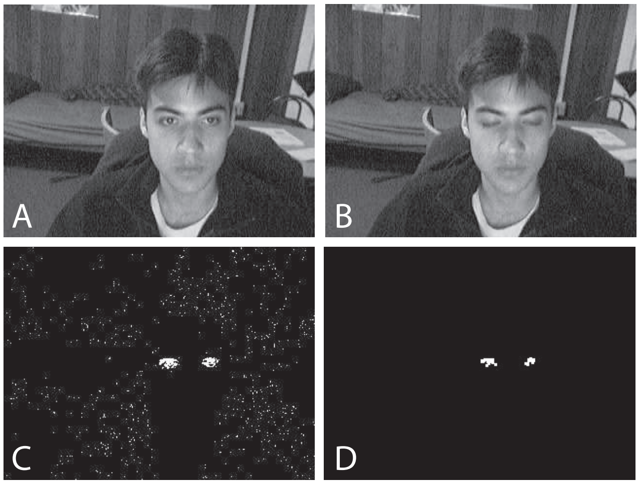

Figure 2: **Motion analysis phase**: (A) User at frame f. (B) User at frame $f + 1$, having just blinked. (C) Initial difference of the two frames f and $f+1$. Note the great deal of noise in the background due to the lighting conditions and camera properties. (D) Difference image used to locate the eyes after performing the Opening operation.

image and waits to process the next involuntary blink in order to maintain efficiency and accuracy in locating the eyes.

Given an image with a small number of connected components output from the previous processing steps, the system is able to proceed efficiently by considering each pair of components as a possible match for the user's left and right eyes. The filtering of unlikely eye pair matches is based on the computation of six parameters for each component pair: the width and height of each of the two components and the horizontal and vertical distance between the centroids of the two components. A number of experimentally-derived heuristics are applied to these statistics to pinpoint the exact pair that most likely represents the user's eyes. For example, if there is a large difference in either the width or height of each of the two components, then they likely are not the user's eyes. As an additional example of one of these many filters, if there is a large vertical distance between the centroids of the two components, then they are also not likely to be the user's eyes, since such a property would not be humanly possible. Such observations not only lead to accurate detection of the user's eyes, but also speed up the search greatly by eliminating unlikely components immediately.

2.2 Template Creation

If the previous stage results in a pair of components that passes the set of filters, then it is a good indication that the user's eyes have been successfully located. At this point, the location of the larger of the two components is chosen for creation of the template. Since the size of the template that is to be created is directly proportional to the size of the chosen component, the larger one is chosen for the purpose of having more brightness information, which will result in more accurate tracking and correlation scores (see Figure 3).

Since the system will be tracking the user's open eye, it would be a mistake to create the template at the instant that the eye was located, since the user was blinking at this moment. Thus, once the eye is believed to be located, a timer is triggered. After a small number of frames elapse, which is judged to be the approximate time needed for the user's eye to become open again after an involuntary blink, the template of the user's open eye is created. Therefore, during initialization, the user is assumed to be blinking at a normal rate of one involuntary blink every few moments. Again, no offline templates are necessary and the creation of this online template is completely independent of any past templates that may have been created during the run of the system.

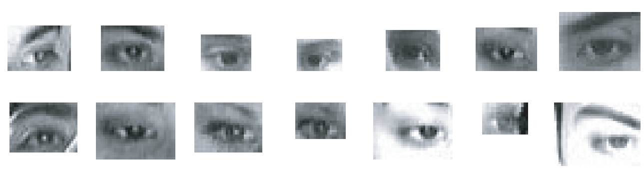

Figure 3: **Open eye templates**: Note the diversity in the appearance of some of the open templates that were used during user experiments. Working templates range from very small to large in overall size, as well very tight around the eye to a larger area surrounding the eye, including the eyebrow.

2.3 Eye Tracking

As noted by Grauman *et al.*, the use of template matching is necessary for the desired accuracy in analyzing the user's blinking since it allows the user some freedom to move around slightly [11]. Though the primary purpose of such a system is to serve people with paralysis, it is a desirable feature to allow for some slight movement by the user or the camera that would not be feasible if motion analysis were used alone.

The normalized correlation coefficient, also implemented in the system proposed by Grauman *et al.*, is used to accomplish the tracking [11]. This measure is computed at each frame using the following formula:

$$\frac{\sum_{x,y}[f(x,y)-\bar{f}_{u,v}][t(x-u,y-v)-\bar{t}]}{\sqrt{\sum_{x,y}[f(x,y)-\bar{f}_{u,v}]^2\sum_{x,y}[t(x-u,y-v)-\bar{t}]^2}}$$

where $f(x,y)$ is the brightness of the video frame at the point (x,y), $\bar{f}_{u,v}$ is the average value of the video frame in the current search region, $t(x,y)$ is the brightness of the template image at the point (x,y), and $\bar{t}$ is the average value of the template image. The result of this computation is a correlation score between -1 and 1 that indicates the similarity between the open eye template and all points in the search region of the video frame. Scores closer to 0 indicate a low level of similarity, while scores closer to 1 indicate a probable match for the open eye template. A major benefit of using this similarity measure to perform the tracking is that it is insensitive to constant changes in ambient lighting conditions. The Results section shows that the eye tracking and blink detection works just as well in the presence of both very dark and bright lighting.

Since this method requires an extensive amount of computation and is performed 30 times per second, the search region is restricted to a small area around the user's eye (see Figure 4). This reduced search space allows the system to remain running smoothly in real time since it drastically reduces the computation needed to perform the correlation search at each frame.

2.4 Blink Detection

The detection of blinking and the analysis of blink duration are based solely on observation of the correlation scores generated by the tracking at the previous step using the online template of the user's eye. As the user's eye closes during the process of a blink, its similarity to the open eye template decreases. Likewise, it regains its similarity to the template as the blink ends and the user's eye becomes fully open again. This decrease and increase in similarity corresponds directly to the correlation scores returned by the template matching procedure (see Figure 5).

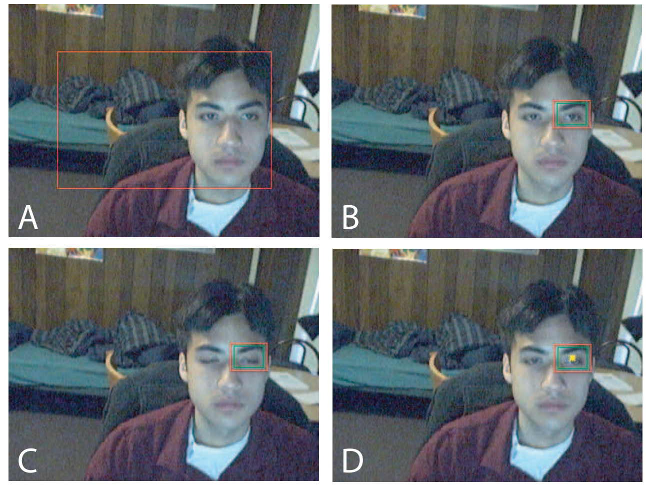

Figure 4: **Sample frames of a typical session**: (A) The system is in this state during the motion analysis phase. The red rectangle represents the region that is considered during the frame differencing and labeling of connected components. (B) The system enters this state once the eye is located and remains this way as long as the eye is not believed to be lost. The green rectangle represents the region at which the open eye template was selected and the red rectangle now represents the drastically reduced search space for performing the correlation. (C) User at frame f, with eyes already closed for the defined voluntary blink duration and (D) user at frame $f+1$, opening his eyes, with a yellow dot being drawn on the eye to indicate that a voluntary blink just occurred.

Close examination of the correlation scores over time for a number of different users of the system reveals rather clear boundaries that allow for the detection of the blinks. As the user's eye is in the normal open state, very high correlation scores of about 0.85 to 1.0 are reported. As the user blinks, the scores fall to values of about 0.5 to 0.55. Finally, a very important range to note is the one containing scores below about 0.45. Scores in this range normally indicate that the tracker has lost the location of the eye. In such cases, the system must be reinitialized to relocate and track the new position of the eye.

Given these ranges of correlation scores and knowledge of what they signify derived from experimentation and observation across a number of test subjects, the system detects voluntary blinks by using a timer that is triggered each time the correlation scores fall below the threshold of scores that represent an open eye. If the correlation scores

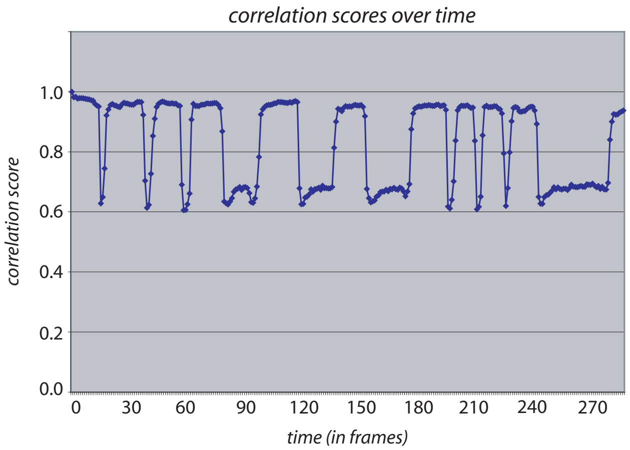

Figure 5: Correlation scores for the open eye template plotted over time (in frames). The scores form a clear waveform, as noted by Grauman *et al.*, which is useful in deriving a threshold to be used for classifying the user's eyes as being open or closed at each frame [11]. In this example, there were three short blinks followed by three long blinks, three short blinks again, and finally one more long blink.

remain below this threshold and above the threshold that results in reinitialization of the system for a defined number of frames that can be set by the user, then a voluntary blink is judged to have occurred, causing a mouse click to be issued to the operating system.

3 Experiments

The system was primarily developed and tested on a Windows XP PC with an Intel Pentium IV 2.8 GHz processor and 1 GB RAM. Video was captured with a Logitech Quickcam Pro 4000 webcam at 30 frames per second. All video was processed as grayscale images of 320 x 240 pixels using various utilities from the Intel OpenCV and Image Processing libraries, as well as the Microsoft DirectX SDK [13, 20, 17]. Figure 6 shows the interface for the system. The experiments were conducted with eight test subjects at two different locations (see Figure 7).

Reviewing the work done by Grauman *et al.*, it is apparent that similar results were obtained with experiments based on testing the accuracy of the system and experiments based on testing the usability of the system as a switch input device [11]. Intuitively, this makes sense as good

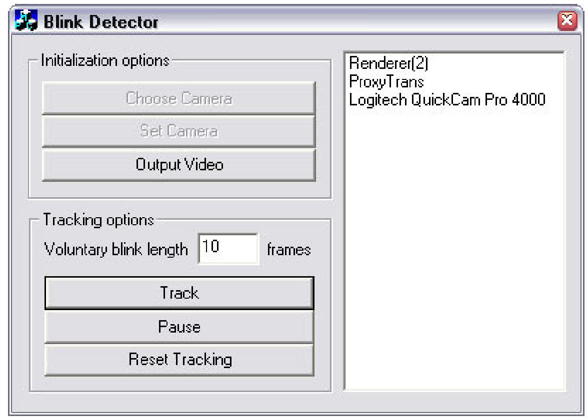

Figure 6: **System interface**: Notable features include the ability for the user to define the voluntary blink length, the ability to reset the tracking at any time, should a poor or unexpected template location be chosen, and the ability to save the session to a video file.

detector accuracy should yield correspondingly high accuracy results for the usability tests, subject to the user's understanding and capabilities in carrying out the given tasks, such as simple reaction time and matching games, as described by Grauman *et al.* [11].

Therefore, the experiments conducted for this system were more focused on detector accuracy, since this is a more standard measure of the overall accuracy of the system across a broad range of users. In order to measure the detection accuracy, test subjects were seated in front of the computer, approximately 2 feet away from the camera. Subjects were instructed to act naturally, but were asked not to turn their heads or move too abruptly, since this could potentially lead to repeated reinitialization of the system, making it difficult to test the accuracy. In addition, this constraint allowed for a closer simulation of the system's target audience of handicapped users.

Similar to the tests done by Grauman *et al.*, subjects were also asked to blink random test patterns that were determined prior to the start of the session [11]. For example, subjects were asked to blink two short blinks followed by a long (voluntary) blink, or were asked to blink twice voluntarily followed by a short (involuntary) blink. These test results serve to show how well the system distinguishes between the voluntary and involuntary blinks, which is the crux of the problem. Tests involving the voluntary blink length parameter were also conducted, with values ranging from 5 to 20 frames (1/6 of a second to 2/3 of a second).

In addition, as a further contribution, numerous other experiments were also conducted to determine the fitness of the system under varying circumstances, such as alternative camera placements, lighting conditions, and distance to the camera. Such considerations are crucial when ruminating on the possible deployment of such a system in a clinical setting. As mentioned in the Introduction, an eye blink detection device based on the use of infrared goggles has been tested with a switch program in a hospital [18], where a number of potential problems could arise with this system, such as the wide range of possible orientations of the user and distances to the camera. Some of the experiments conducted aim to simulate these conditions in order to gain insight into the plausibility of utilizing this system for a diverse population of handicapped users.

Video of each test session was captured online and post-processed to determine how well the system performed. The number of voluntary and involuntary blinks detected by the system were written to a log file during the session. Afterwards, the actual number of times the user blinked voluntarily and involuntarily were counted manually by reviewing the video of the session. False positives and missed blinks were also noted.

4 Results

A large volume of data was collected in order to assess the system accuracy. Compared to the 204 blinks provided in the sequences by Grauman *et al.* [11], a total of 2,288 true blinks by the eight test subjects were analyzed in the experiments for this system. Disregarding the sessions involving the testing of the voluntary blink length parameter for reasons to be discussed later, there were 43 missed blinks and 64 false positives, for an overall accuracy rate of 95.3%. Incorporating all sessions and experiments, there were 125 missed blinks and 173 false positives, for an accuracy rate of 87.4%. See Figure 8 for a summary of the main results of the experiments.

Summary of results

- total blinks analyzed 2288
- overall system measures
  - total missed blinks 43
  - total false positives 64
  - detector accuracy 95.3%
- experimental system measures
  - total missed blinks 125
  - total false positives 173
  - detector accuracy 87.4%

voluntary blink length	5	10	20
missed blinks	1.09%	1.01%	2.53%
false positives	1.49%	1.44%	2.80%

Figure 8: The *experimental system measures* include the experiments involving the adjustments in the voluntary blink length parameter, while the *overall system measures* disregard these outliers, which are detailed in the table.

The first rate of 95.3% should be considered as the overall accuracy measure of the system because of the nature of some of the extended experiments that inherently function to reduce the accuracy rate. For example, in sessions tested with the default, most natural voluntary blink length of 10 frames (1/3 of a second), there were only 23 missed blinks and 33 false positives out of 1,242 blinks. On the other hand, in sessions tested with a voluntary blink length of 20 frames (2/3 of a second), out of 504 such blinks, more than double the number of blinks were missed (58), and nearly double the number of false positives were detected (64). This leads to the choice of the word "natural" to describe the default blink length of 10 frames (1/3 of a second). The test subjects found this to be the most intuitive length of time to consider as the prolonged blink, with lower values being too close to the involuntary length, and with higher values such as 20 frames (2/3 of a second) producing an unnatural feeling that was too long to be useful as a switch input. This feeling was well-founded, as this longer blink length lead to a severe degradation in the detector accuracy. Nearly all of the misses and false positives in these sessions were caused by users not holding their voluntary blinks long enough for the system to correctly classify them.

In fact, the other experiments, designed to test how well the system would fair in an environment whose conditions are not known a priori, only resulted in 20 missed blinks and 31 false positives (see Figures 9 and 10). Thus, the vast majority of missed blinks and false positives across all experiments can be attributed to poor choices in the voluntary blink length, which should not be considered a problem for the accuracy of the system since these trials were purely experimental and a length of approximately 10 frames (1/3 of a second) is known to be ideal for high performance.

Figure 7: Sample frames from sessions for each of the eight test subjects.

Figure 9: Sample frames from sessions testing alternate positions of the camera. The system still works accurately with the camera placed well below the user's face, as well as with the camera rotated as much as about 45 degrees.

Figure 10: Sample frames from sessions testing varying lighting conditions. The system still works accurately in exceedingly bright and dark environments.

5 Discussion and Conclusions

The system proposed in this paper provides a binary switch input alternative for people with disabilities similar to the one presented by Grauman *et al.* [11]. However, some significant improvements and contributions were made over such predecessor systems.

The automatic initialization phase (involving the motion analysis work) is greatly simplified in this system, with no loss of accuracy in locating the user's eyes and choosing a suitable open eye template. Given the reasonable assumption that the user is positioned anywhere from about 1 to 2 feet away from the camera, the eyes are detected within moments. As the distance increases beyond this amount, the eyes can still be detected in some cases, but it may take a longer time to occur since the candidate pairs are much smaller and start to fail the tests designed to pick out the likely components that represent the user's eyes. In all of the experiments in which the subjects were seated between 1 and 2 feet from the camera, it never took more than three involuntary blinks by the user before the eyes were located successfully.

Another improvement is this system's compatibility with inexpensive USB cameras, as opposed to the high-resolution Sony EVI-D30 color video CCD camera used by Grauman *et al.* [11]. These Logitech USB cameras are more affordable and portable, and perhaps most importantly, support a higher real-time frame rate of 30 frames per second.

The reliability of the system has been shown with the high accuracy results reported in the previous section. In addition to the extensive testing that was conducted to retrieve these results, additional considerations and circumstances that are important for such a system were tested that were not treated experimentally by Grauman *et al.* [11]. One such consideration is the performance of the system under different lighting conditions (see Figure 10). The experiments indicate that the system performs equally well in extreme lighting conditions (i.e. with all lights turned off, leaving the computer monitor as the only light source, and with a lamp aimed directly at the video camera). The accuracy percentages in these cases were approximately the same as those that were retrieved in normal lighting conditions.

Another important consideration is the placement and orientation of the camera with respect to the user (see Figure 9). This was tested carefully to determine how much freedom is available when setting up the camera, a potentially crucial point when considering a clinical environment, especially an Intensive Care Unit, which is a prime setting that would benefit from this system [18]. Aside from horizontal offset and orientation of the camera, another issue of concern is the vertical offset of the camera in relation to the user's eyes. The experiments showed that placing the camera below the user's head resulted in desirable functioning of the system. However, if the camera is placed too high above the user's head, in such a way that it is aiming down at the user at a significant angle, the blink detection is no longer as accurate. This is caused by the very small amount of variation in correlation scores as the user blinks, since nearly all that is visible to the camera is the eyelid of the user. Thus, when positioning the camera, it is beneficial to the detection accuracy to maximize the degree of variation between the open and closed eye images of the user. Finally, with respect to the clinical environment, this system provides an unobtrusive alternative to the one tested by Miglietta *et al.*, which required the user to wear a set of eyeglass frames for blink detection [18]. This is an important point, considering the additional discomfort that such an apparatus may bring to the patients.

Some tests were also conducted with users wearing glasses (see Figure 11), which exposed somewhat of a limitation with the system. In some situations, glare from the computer monitor prevented the eyes from being located in the motion analysis phase. Users were sometimes able to maneuver their heads and position their eyes in such a way that the glare was minimized, resulting in successful location of the eyes, but this is not a reasonable expectation for severely disabled people that may be operating with the system.

With the rapid advancement of technology and hardware in use by modern computers, the proposed system could potentially be utilized not just by handicapped people, but by the general population as an additional binary input. Higher frame rates and finer camera resolutions could lead to more robust eye detection that is less restrictive on the user, while increased processing power could be used to enhance the tracking algorithm to more accurately follow the user's eye and recover more gracefully when it is lost. The ease of use and potential for rapid input that this system provides could be used to enhance productivity by incorporating it to generate input for a task in any general software program.

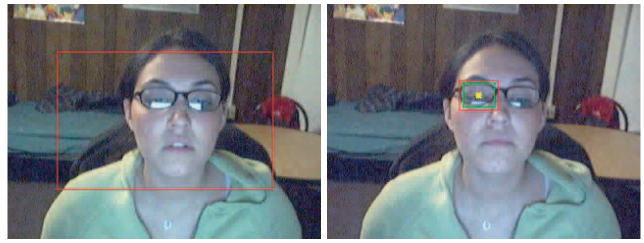

Figure 11: Experiment with a user wearing glasses. In some cases, overwhelming glare from the computer monitor prevented the eyes from being located (left). With just the right maneuvering by the user, the system was sometimes able to find and track the eye (right).

Acknowledgments

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