Linear array of photodiodes to track a human speaker for video recording

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Abstract. Communication and collaboration using stored digital media has garnered more interest by many areas of business, government and education in recent years. This is due primarily to improvements in the quality of cameras and speed of computers. An advantage of digital media is that it can serve as an effective alternative when physical interaction is not possible. Video recordings that allow for viewers to discern a presenter's facial features, lips and hand motions are more effective than videos that do not. To attain this, one must maintain a video capture in which the speaker occupies a significant portion of the captured pixels. However, camera operators are costly, and often do an imperfect job of tracking presenters in unrehearsed situations. This creates motivation for a robust, automated system that directs a video camera to follow a presenter as he or she walks anywhere in the front of a lecture hall or large conference room. Such a system is presented.

The system consists of a commercial, off-the-shelf pan/tilt/zoom (PTZ) color video camera, a necklace of infrared LEDs and a linear photodiode array detector. Electronic output from the photodiode array is processed to generate the location of the LED necklace, which is worn by a human speaker. The computer controls the video camera movements to record video of the speaker. The speaker's vertical position and depth are assumed to remain relatively constant– the video camera is sent only panning (horizontal) movement commands. The LED necklace is flashed at 70Hz at a 50% duty cycle to provide noise-filtering capability. The benefit to using a photodiode array versus a standard video camera is its higher frame rate (4kHz vs. 60Hz). The higher frame rate allows for the filtering of infrared noise such as sunlight and indoor lighting–a capability absent from other tracking technologies. The system has been tested in a large lecture hall and is shown to be effective.

1. Introduction

The ATLAS Experiment, one of the largest experiments based at CERN, is being built by a collaboration of almost 3000 physicists who are based at institutions spread across the globe. It is one of the largest collaborative efforts ever attempted in the physical sciences [1]. The success of the experiment depends upon successful long-distance collaboration, and the ATLAS Collaboratory Project [2] was created to address the needs of ATLAS with respect to collaborative tools. For the first few years the activities of our group were limited to recording single lectures, tutorials, and small conferences. There were clearly situations in which large-scale recording is needed, for example at the national meetings of large professional societies such as the American Physical Society (APS) [3], where many parallel talks take place, and where many members are interested but unable to attend. In addition to large national meetings, universities are also exploring the usage of large-scale recorded video and audio of classroom lectures for use as an educational aide. The advantages of having recorded media for students are apparent: the videos help students with course material review prior to exams, support students that are unable to attend lecture, and allow for unlimited repetition to aid in comprehension, especially for students of which English is not their first language [4]. The ATLAS Collaboratory Project group along with the APS received a grant in 2003 from the National Science Digital Library division of the NSF, making possible an increased focus on the prompt compression and posting of web lectures. Our team assembled the appropriate hardware and developed software to gain substantial ground in this pursuit. With the successful completion of the MScribe [5] pilot project at the University of Michigan, which brought lecture recording into the classroom, it has been demonstrated that large-scale automated lecture recording is feasible and imminent.

One feature that is particularly important for performing automated lecture capture is body framing. A video recording that uses body framing – a characteristic of a video recording in which one can clearly discern the presenter's facial features, lips and hand motions through an appropriate zoom – renders the recorded media more effective than a video recording that only captures a wide-angle view of the entire stage. This is apparent by comparing Figure 1a with Figure 1b. Implementing a system with body framing can be done by a camera technician, who pans and zooms a video camera to keep the video framed close to the presenter's body. However, camera operators are costly, and often do an imperfect job of tracking presenters in unrehearsed situations. This spawns the need for robotic tracking to provide reliable, high-quality, smooth video of the presenter. As described by the MScribe pilot project, a tracking system used for large-scale video collaboration must meet the following criteria:

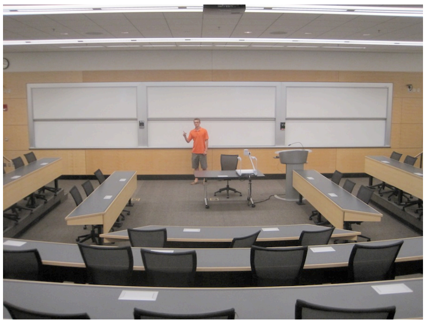


Fig 1a – An image of a speaker recording system without body framing.

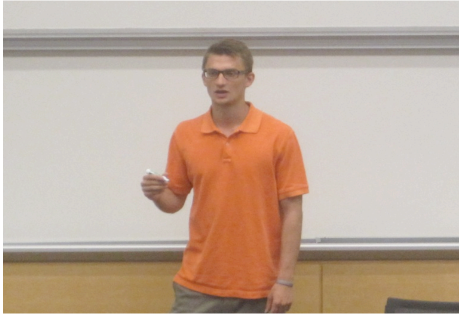


Fig 1b – An image of a speaker recording system with body framing.

- Portable
- Accurate
- Robust
- Affordable
- Operate without expert intervention
- Require minimal setup or calibration

In 2005-2007 a robotic tracking system [6] was developed by MScribe a part of the ATLAS Collaboratory Project, to meet the aforementioned requirements. This original system uses two identical models of off-the-shelf pan/tilt/zoom (PTZ) video cameras and a special necklace that is worn by the speaker comprised of continuously illuminated infrared (IR) LEDs. One camera is equipped with appropriate IR filters so that it detects only the LEDs and follows the necklace around the room. Based on this position information, the second camera is pointed appropriately at the instructor to provide color video footage.

The focus of this paper is on improvement of the robustness of this original robotic tracking system. The principal drawback of this system is its inability to record the presenter when IR noise is present in the environment. Examples of IR noise are: incandescent lights, IR communication ports found on laptops and assisted listening systems, stairway lights (Figure 2a), and sunlight (Figure 2b). The original tracking system developed in 2005-2007 cannot differentiate the noise IR signals and the necklace IR signal. This results in unreliable operation.

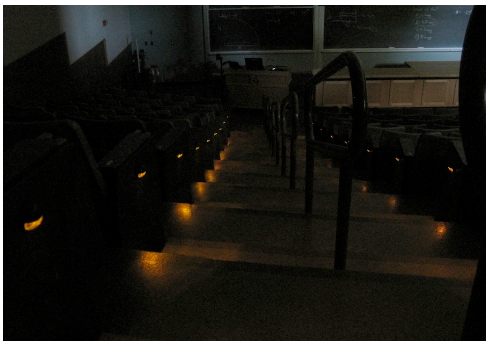


Fig 2a - Stairway lighting.

Fig 2b - Sunlight reflecting off of moving leaves.

A commercial example of a system that records presenters without a camera technician is the Polycom EagleEye Director [7]. A system such as this uses both audio triangulation (sound source localization) and face-finding techniques to pan/tilt/zoom the camera to the speaker. This system is not sufficient for lecture recording because it is relies on being able to see the presenter's face. This is problematic when he/she is turned away from the front of the room, which is common as presenters wander around the room or write on a whiteboard. Another drawback of this system is that in many large-scale events presenters use a microphone, which would confuse the EagleEye Director since the system would be tracking multiple audio sources.

This article explores a system that is similar to the original tracking system developed by the MScribe pilot project with the exception of the sensing hardware. The system described below is uses a linear array of photodiodes, as apposed to the two-dimensional charge-coupled device (CCD) sensor to find the location of the presenter used by the original tracking system developed by our group. The motivation for improving on the original tracking system is to lower cost and to improve robustness to account for IR noise sources with a faster frame rate.

2. System Overview

This section gives a brief overview of the linear-array tracking system's components.

2.1. Infrared LED Necklace Segment

The target speaker wears a special IR LED necklace, pictured in Fig 3a and Fig 3b. Eight vertically aligned LEDs, which form a wearable necklace, were used for testing the linear array sensor. This LED arrangement works well when the speaker is facing the audience, as in Fig 3a. However, cases where the speaker is writing on a blackboard or is facing away from the audience require a more conventional circular LED arrangement. Our MScribe group developed the necklace shown in Fig 3c in 2005. The reason that this necklace was not used for testing the linear photodiode array is that it lacks the ability to flash the LEDs.

The LEDs on the vertical necklace of eight LEDs were flashed at a frequency of 70 Hz. This frequency is high enough to differentiate itself from reflections of sunlight off of moving tree leaves that reflect IR, and it also avoids inference from the AC lighting, which has a frequency of 60 Hz. An Arduino board was used for blinking the LEDs at a 50% duty cycle. The LEDs have a peak output wavelength at 850nm and output 45 mW/sr each with a viewing angle of 120 degrees [8].

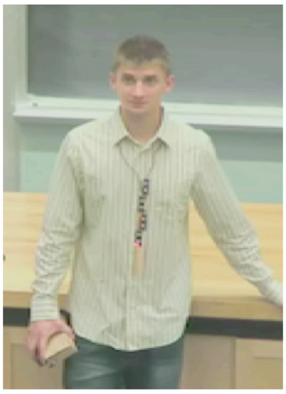


Fig 3a: A speaker wearing the prototype necklace.

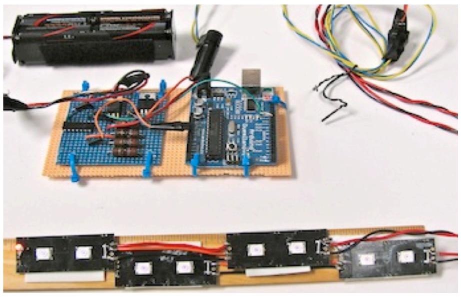


Fig 3b: The prototype flashing necklace.

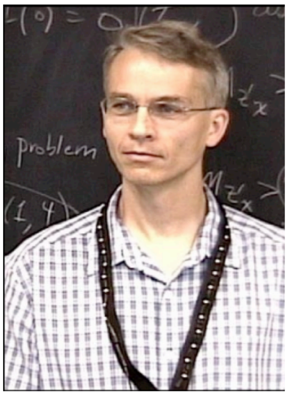


Fig 3c: An ideal circular necklace, can be viewed when the speaker is facing away from the camera.

2.2. Linear photodiode array

The linear array of photodiodes consists of 128 horizontal photodiodes and has physical dimensions of 5 cm x 2.5 cm (Figure 4b). The IR light from the LEDs strikes the photodiodes via a converging lens (Figure 4a). The linear array sensor used was the Hamamatsu S8865-128 [9] in combination with a Hamamatsu C9118 driver circuit, and can be seen in Figure 4a. The linear array outputs an analog signal representing the amount of IR light falling on each photodiode for all 128 photodiodes at a maximum frame rate of 4kHz. It is essentially a one-dimensional video output. The frame rate used for testing was 448Hz. The cost of this particular array and driver circuit is about $750. The individual photosensitive diodes on the linear array board have a width of 0.3 mm and height of 0.6 mm.

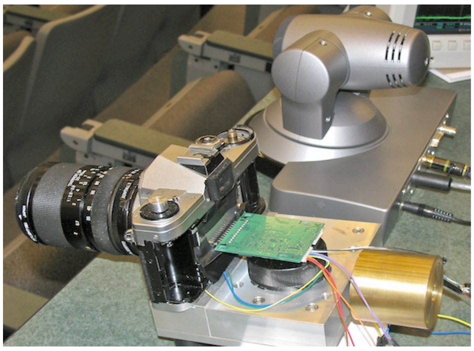


Fig 4a – Lens and array (bottom), PTZ camera (top).

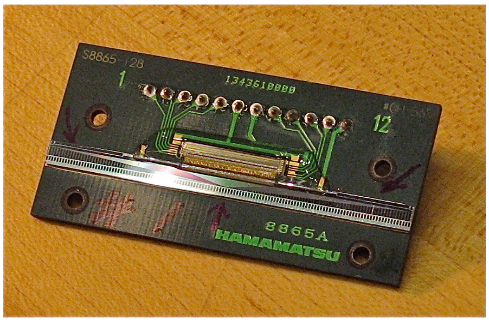


Fig 4b – Close up of linear array.

2.3. Interface

A National Instruments USB-5132 high-speed digitizer was used to interface the linear array driver circuit and the computer. It captured three signals: the analog video signal from the photodiodes, the signal to trigger a new video frame scan, and the signal that triggers the start of each of the 128 pixels.

2.4. Software

National Instruments Labview software was used to process the data from the digitizer. Microsoft Visual Studio was used to create the commands to the PTZ camera. More detail on the band-pass filter is given is Section 4.

2.5. Camera

The camera used for recording the color video recording was a Sony EVI-HD1 PTZ camera. A computer processes the signal from the linear array, performs noise-filtering computations, and instructs the camera where to pan via RS-232 VISCA commands. VISCA is the camera control protocol used by this Sony camera.

3. Single LED Characteristics

3.1. Accuracy

As the presenter wearing the LED necklace moves across the stage, different diodes within the linear array output a high signal, which is sent to the computer for processing. An important measureable characteristic of a tracking system such as this is the amount of movement that is required for a new position to be detected by the linear array. This is characteristic is considered the system's accuracy.

A single LED was used to determine the accuracy of the linear array. The LED was affixed to a train set to provide controlled and measurable motion as pictured in Figure 5a; the IR LED is circled in the photo. The basic concept of this test is illustrated in Figure 5b. The red line uses the pinhole approximation for a converging lens to represent how the red IR light passes through the lens and onto the photodiode elements. As the IR necklace moves across the stage area, the IR light will strike new photodiode elements in the array.

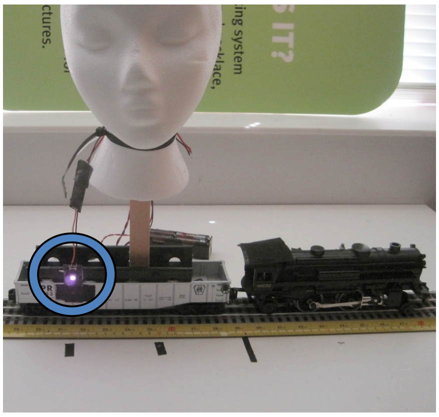


Fig 5a – A single LED used for the accuracy test.

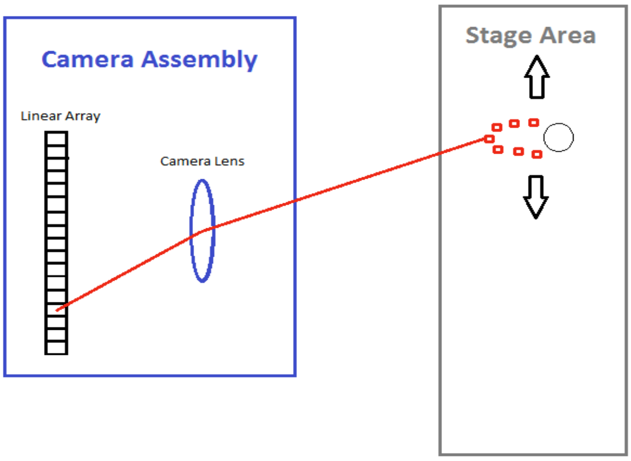


Fig 5b – Optical principal of linear array sensor.

The results of this test are shown below in Figure 6, which shows a composite of multiple locations of the LED as it is moved across the field of view. Each row of diamonds represents a photodiode element that detected light exceeding a threshold. The graph exhibits a near linear relationship between the actual and calculated locations of the IR LEDs. A perfect system would exhibit a straight line, as it would correctly calculate each change in location of the LED. In the worst-case, four different locations of the target correspond to the same calculated location. Each location of the target is separated by ½ inch, thus the system accuracy in this experiment (at 22 feet) is +/- two inches.

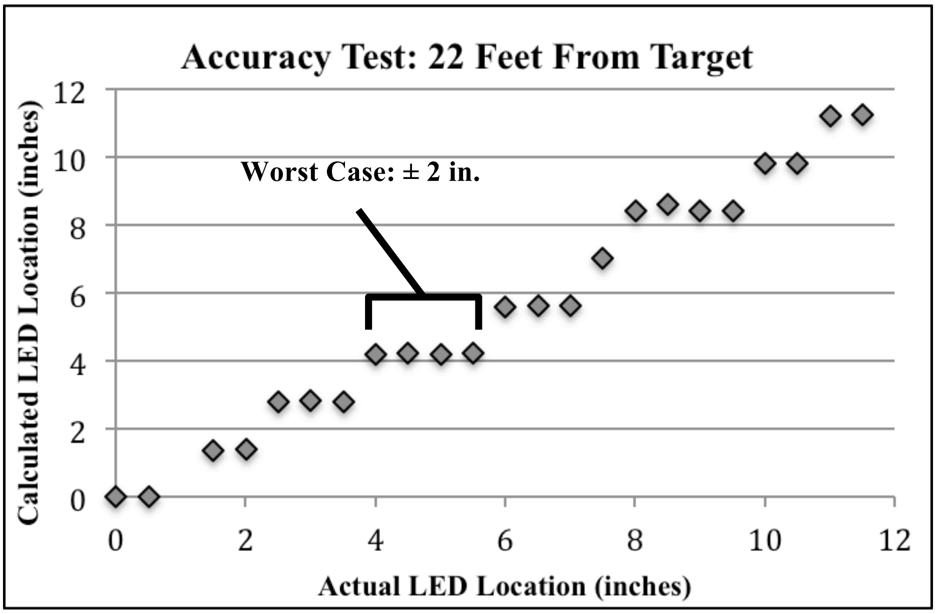


Fig 6 – A plot of actual vs. calculated locations for the single LED target.

3.2. Allowable Vertical Movement

In addition to horizontal accuracy, the vertical displacement is another important characteristic to measure for a speaker tracking system. The principal drawback of this system is its inability to determine the vertical position of the IR LEDs. A single LED was tested to have an allowable vertical movement range of 3.5 inches at a distance of 22 feet from the linear array sensor. In most cases it is assumed that the height of the speaker will not change, and the system performs well. However, rooms with elevated stages, angled stages, or steep stadium seating present difficulty when the speaker travels the depth of the stage.

4. Noise IR Filtering

A presenter tracking system that tracks an IR necklace must be able to ignore IR noise signals to be considered a robust system [5]. To test this function, the linear array system was set up in a large lecture hall, shown in Fig 7a. The array was 44 feet from the speaker pictured at center stage. Three noise sources–an overhead projector and two halogen lamps–were added at a similar height as the speaker to replicate equipment typically found in a lecture hall.

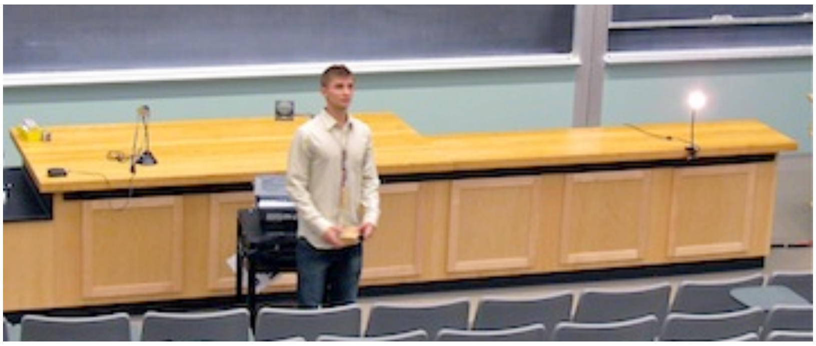


Fig 7a – The speaker is shown in the large lecture hall with three sources of IR light that can confuse an IR tracker.

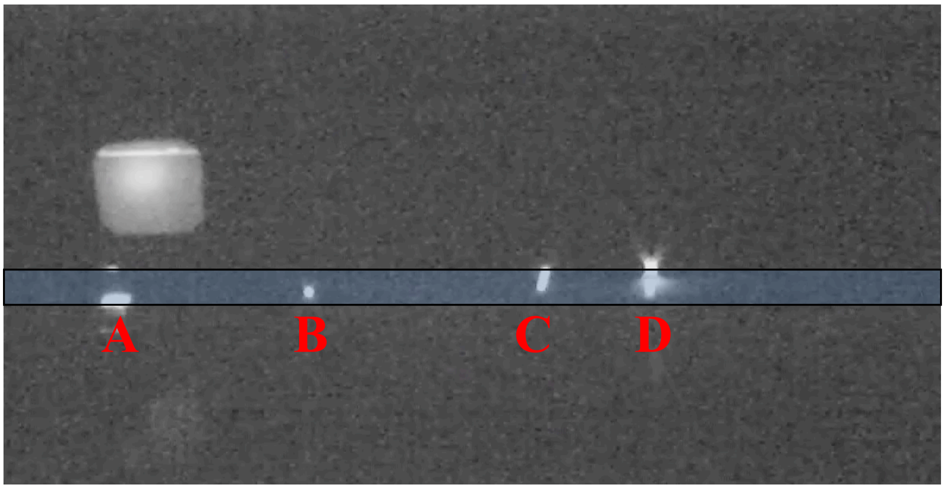


Fig 7b – An IR image of the stage shown in Fig 7a. The horizontal grey bar represents the limited vertical viewing angle of the linear array sensor.

Fig 7b is a wide-angle IR image of the entire lecture stage. The objects that emitted IR light are labeled: A–overhead projector, B–flashing desklamp (4Hz), C–LED necklace (70Hz), D–DC desklamp. A narrow rectangle is added to Fig 7b to represent the limited vertical viewing capability of the linear array sensor system. Only IR objects that fall in that vertical range are sensed by the linear array – if the speaker were to change his/her height due to stepping on the stairs into the audience, his/her position would be lost.

The method used to filter the non-necklace IR signals in this system is a digital band-pass filter, implemented in Labview. The software behind the linear array tracking system operates as follows: the output voltages from each of the 128 photodiodes is recorded for 4-5 cycles of the LEDs' flashing, and then passed through the band-pass filter corresponding to 70 Hz. Then, a peak detector function calculates a position value to the peak of the surviving voltage peak. In the case of the test ran in Fig 8, this surviving peak on the bottom graph is the LED necklace. This value is written to a .txt file. Microsoft Visual Studio then runs C code to read from this .txt file and to send VISCA panning commands to the color camera to follow the speaker to this new location.

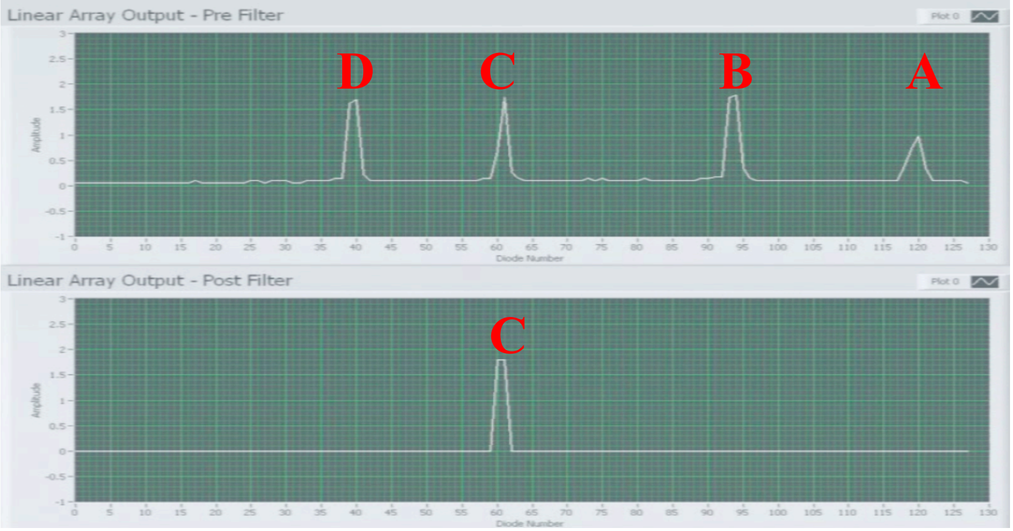


Fig 8 – Graphical representation of the signal from the linear array photodiode sensor. The x-axis is diode number [0-127] and the y-axis is voltage (volts). The top plot is before the band-pass filter; the bottom plot is after the filter.

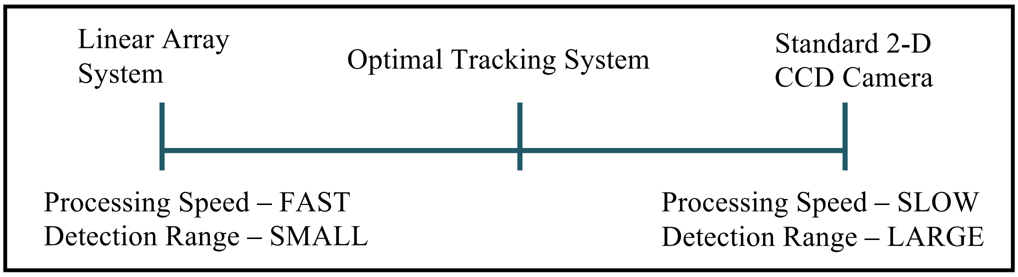
The graph in Fig 8 plots diode number [0-127] (x-axis) versus voltage (y-axis). The top plot in Fig 8 is unfiltered and consists of the same IR sources from Fig 7b. The IR sources are reversed left to right. The bottom plot is filtered through the band pass filter and shows only the 70Hz necklace.

A demonstration video of the linear array tracking and recording system is available on our research webpage: 'http://atlascollab.umich.edu/' under Projects → Robotic Tracking. This demonstration was done in the same lecture hall seen in Fig 7a, and shows that the system does a good job of following the speaker as he walks back and forth along the stage.

5. Conclusion

An IR-based tracking system is presented to meet the growing need for large-scale, automatic video recording that frames the speaker's body in video capture. The first system created by the ATLAS Collaboratory project in 2005-2007 did a good job of accomplishing automated lecture recording in an environment with a single IR light source. However, the system failed to work well in the presence of other IR sources (incandescent lights, sunlight), which commonly exist in lecture rooms. This first system created by our group used a CCD sensor. To add noise-filtering capability, the sensor was simplified to have 128 horizontal linearly arranged diodes. This is a large reduction from the hundreds of thousands to millions of effective pixels found in CCD sensors of today's standard and HD video cameras. This reduction in the number of pixels on the sensor means less data from the sensing hardware must be processed, thus a faster frame update rate can be achieved.

The main advantage of the linear array system is its processing speed. In an application such as human speaker tracking, having an IR-based detection system with a fast processing speed allows for effective noise filtering via a software-based band-pass filter, which is necessary to reject other sources of IR light. Another benefit to using the linear array for speaker tracking is its relatively low cost compared to using a PTZ camera for tracking.



Linear Array System

Optimal Tracking System

Standard 2-D CCD Camera

Processing Speed – FAST
Detection Range – SMALL

Processing Speed – SLOW
Detection Range – LARGE

Fig 9 – Detection range and processing speed show an inverse relationship.

The main limitation of this system is its inability to capture vertical movements performed by the speaker. Rooms with elevated stages, angled stages, or steep stadium seating present difficulty to a system that does not account for vertical movements and adjust the tilt of the camera accordingly. Fig 9 suggests an optimal medium between a linear array system and a video camera with a full 2-D CCD sensor. The reason that a full 2-D CCD sensor is not used with this technique is that it is too processing intensive (128 vs. >100,000 pixel values) and the frame-scanning rate is too slow. A more robust and optimal system would stack 3-10 linear arrays on top of one another in the film plane to detect change in vertical positioning of the speaker, and would possess much fewer pixel values than a CCD sensor.

References

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