

Fig. 3. Schematic diagram of integrator.

REFERENCES

- [1] G. J. Hickey, C.-H. Chang, F. Marsilio, W. Trimboli, and E. L. Rickes, "Effects of prednisone on dermal responses in flea-allergen hypersensitized dogs," *Veterinary Dermatology*, vol. 4, pp. 71-77, 1993.
- [2] J. M. Yanni, R. E. W. Halliway, and C. H. Tracy, "Effect of AHR-5333 on flea antigen extract-induced skin reactions in flea-allergic dogs," *J. Vet. Pharmacol. Therap.*, vol. 11, pp. 221-225, 1988.

A Video-Based System for Acquiring Biomechanical Data Synchronized with Arbitrary Events and Activities

Thomas Y. Yen and Robert G. Radwin

Abstract—A video-based data acquisition and interactive multimedia data extraction system are described for measuring and synchronizing large quantities of biomechanical analog data with arbitrary events and activities. Analog signals from up to 32 channels are digitized, frequency-shift key (FSK) coded, and recorded directly onto the audio tracks of a video tape in synchronization with the video information. The data acquisition system includes an A/D converter that digitizes up to 16 multiplexed channels of 8-b data at a fixed sample rate between 60 and 960 Hz, and an FSK modem that transfers the data onto one of two VHS high fidelity (20 Hz–20 kHz bandwidth) audio tracks. Twenty megabytes of digitized data and time codes, along with associated video and normal audio are contained on a conventional 120-min video tape. An analyst interactively reviews the video tape off-line using a computer-controlled VCR and identifies specific events that divide arbitrary activities into time segments. The computer automatically extracts the biomechanical data corresponding to each time segment for further processing or analysis. This system is useful for ergonomics, gait analysis, sports medicine, sleep laboratory, biomechanics, or any application where complex visual events are synchronized with low-frequency analog data.

Manuscript received March 22, 1994; revised February 28, 1995. This work was supported in part by Grant K02 OH 00107-02 from the National Institute for Occupational Safety and Health, and Grant DMI-9158136 from the National Science Foundation.

The authors are with the Department of Industrial Engineering, University of Wisconsin-Madison, Madison, WI 53706 USA.

IEEE Log Number 9413381.

I. INTRODUCTION

The need to record many channels of analog data synchronized with video images of an activity being performed or arbitrary events occurs quite frequently in biomedical engineering. This capability is especially important for ergonomics, rehabilitation, gait analysis, sleep laboratory, and athletic performance, as well as other applications requiring image/data synchronization. The ability to collect and record biomechanical data from electrogoniometers, force sensors, or integrated EMG is necessary for many data acquisition applications. It is often difficult to synchronize visually identifiable events in an activity under study with associated biomechanical data. This is particularly the case for field studies.

Manual synchronization may suffice for simple applications but suffers from obvious shortcomings. Marras and Schoenmarklin [1] synchronized biomechanical data with work activities by having an observer manually indicate specific events as the data were being recorded in real-time. Electrogoniometer signals were digitized and stored on a portable computer along with start and end time marker voltages. This meant that events had to be identified and indicated by an alert observer during data collection. This is not always practical for field studies and does not easily permit synchronization with arbitrary events after the data are recorded.

Quite often, synchronization is accomplished using a video recorder and manually identifying events associated with the analog data stream with a time base superimposed on the video image. Data extraction and analysis are usually very slow and tedious processes. Synchronization can also be accomplished by recording time code data on both the videotape and on the data recorder or computer data acquisition system. This method requires a resynchronization process that does not make the image/data readily available.

Moore *et al.* [2] developed a biomechanical recording system using a custom-made signal processing unit that recorded 10 multiplexed sensor signals and stored the analog data on one of the audio tracks of the camcorder. Electrogoniometer, EMG, and force signals were processed and recorded on the audio track, with a marker placed on another audio track indicating when data collection started and ended. This method allowed video and data to be linked in time but had to be resynchronized. Analysis was performed on video segments that best represented the task from up to five minutes of data. All the collected data were not analyzed.

A new video-based data acquisition and extraction system is described for recording, synchronizing, and processing biomechanical analog data associated with arbitrary activities and manual tasks. Analog signals from up to 32 sensors are digitized using a free-running A/D converter, frequency-shift key (FSK) coded, and recorded directly onto audio tracks of a video tape for synchronizing biomechanical signals between arbitrary events recorded on the video tape. This method uses the inherent timing pulses in the video image signal on the video tape for synchronization with analog data.

An interactive multimedia computer-controlled data extraction system was developed for identifying activity break points, or events on the video that divide the data into specific time segments. After arbitrary events are identified off-line by an analyst, the computer automatically extracts the biomechanical data from the audio tracks for analysis. By packaging the data recording system into a small portable battery powered unit, data acquisition in the field requires just a camcorder and associated bioinstrumentation.

II. DATA ACQUISITION SYSTEM

The data acquisition system consists of three basic components: 1) a camcorder, 2) an analog-to-digital frequency-shift-keyed modu-

lator/demodulator (A/D FSK modem), and 3) biomechanical sensors and amplifiers.

The VHS camcorder for this system requires a stereo high fidelity audio system having a bandwidth of 20 Hz to 20 kHz and the ability to record audio onto the normal and high fidelity tracks simultaneously. This allows recording verbal documentation on the normal audio track while the biomechanical data are recorded on the high fidelity audio tracks. This feature is not necessary if audio documentation is not needed, and any high fidelity VHS camcorder will suffice. A Panasonic VCR model AG-7350, which has high fidelity (hi-fi) audio and S-VHS video capability was used. This VCR was also equipped with an AG-IA232TC RS-232 serial interface and an SMPTE time code generator and reader.

The A/D FSK modem digitizes the analog signal and converts it into a serial data stream. The serial data are then converted into an FSK-coded signal that can be recorded onto the high fidelity audio tracks. A set of one byte per channel digitized data is synchronized with an image field on the video tape during the recording process.

Data conversion occurs continuously and data are recorded on the video tape whenever the camcorder is recording. The data recording process is directly controlled by the camcorder. Verification that data were recorded successfully is accomplished by playing back the video tape and observing the analog output of the A/D FSK modem on a portable oscilloscope or voltmeter.

Conventional VHS tape is capable of containing two standard and two high fidelity audio tracks. Standard audio tracks have a bandwidth between 20 Hz and 12 kHz, while high fidelity audio tracks have a bandwidth between 20 Hz and 20 kHz. Since the bandwidth for the biomechanical data acquisition system is between DC and 480 Hz, it is necessary to code signals so they can be recorded on the audio track of a video tape having a minimum frequency of 20 Hz. Consequently, a modulation process was used. Time multiplexing was considered since multiple channels of data must be recorded on a single audio track. Digital signals were used for multiplexing and demultiplexing in order to avoid the necessity for the complex timing circuitry needed for time demultiplexing analog FM signals.

Directly recording digital serial data pulses on the video tape audio track produces very poor signal reproduction because of the audio track upper band limits (<20 kHz). A 15-kHz square wave requires a rise time of 25 μ s with a 2% amplitude distortion [3]. Signal reshaping circuitry would then be needed to reestablish the digital serial data. A common technique used for transmitting digital data on an audio bandwidth, frequency-shift keying (FSK) modulation, was therefore employed. FSK modulation converts logic one into a certain frequency waveform, and logic zero into another frequency. The only limitation is that the two frequencies must be within the audio track bandwidth.

By National Television System Committee (NTSC) convention [4], a single frame of video is broken into two images called fields. The first field contains the image odd lines (odd field) and the second field contains the even lines (even field). A standard interleaved image displays the odd field first, then the even field. The display rate is 30 frames/s or 60 fields/s. Physical placement of the video signal on video tape is illustrated in Fig. 1(a). The timing relationships between the fields, frames, and data channels are shown in Fig. 1(b)-(d). The FSK signals (Fig. 1(e)) recorded on the audio tracks represent the TTL serial data and binary values (Fig. 1(f) and (g)). Logic one TTL data are represented by a low-frequency sine wave relative to the high-frequency sine wave for the logic zero TTL data.

The A/D FSK modem consists of five principle components. They include the: 1) multiplexer/analog-to-digital converter (ADC), 2) FSK modulator, 3) FSK demodulator, 4) universal asynchronous receiver/transmitter (UART), and 5) clock/timing logic. Two optional

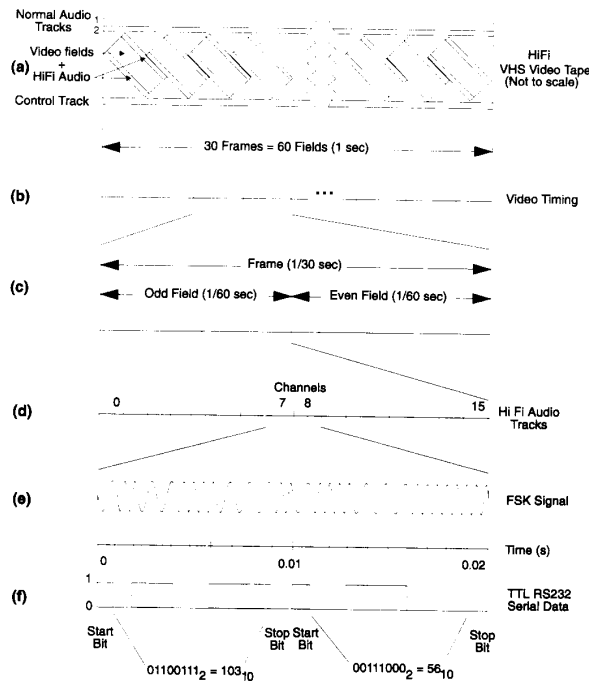


Fig. 1. Video and audio signal timing relationships. (a) Schematic representation of VHS video tape. (b) and (c) Video frame and field organization. (d) Data channel organization within a single field. (e) Representation of FSK signals recorded on the audio track. (f) RS-232 data from the FSK signal.

components are a digital-to-analog converter (DAC), and status indicator circuitry. A block diagram of the A/D FSK modem is shown in Fig. 2.

Analog signals are connected to the multiplexer inputs. The multiplexer input channel is controlled by the timing logic circuitry using a 4-b channel select bus. A 24-dB/octave Butterworth anti-aliasing filter having a 16-Hz, 3-dB cut-off frequency is used between the multiplexer output and the ADC input.

The 8-b ADC START CONVERSION and READ DATA control signals come from the timing logic (see Fig. 2). The ADC conversion rate is controlled by the 960-Hz frequency of the conversion clock. The 8-b digital data are sent to the transmitter section of the UART which converts them into a serial signal using conventional RS232 timing. The serial data are then sent to the FSK modulator and converted into an audio signal.

A video SYNC pulse extractor (LM1881) synchronizes the data conversion and recording process with the video image. This synchronizes a set of 16 data points to a single video field. The vertical SYNC output generates a 59.94-Hz pulse at the beginning of each video image field. The vertical SYNC pulse is connected to a decade and ripple counter clock reset pins in the timing circuitry and resets the counters to count zero. This insures that channel 0 is at the beginning of every video field. The relationship between the video timing and the data is shown in Fig. 1.

Three LED's indicate the modem status. Two LED's receive signals from the UART, one indicating successful serial to parallel conversion and another indicating successful parallel to serial conversion. The third LED illuminates when a signal applied to one of the multiplexer channel exceeds a saturation level of +5 VDC. These displays are useful for verifying that the system is operating correctly, particularly for field studies.

The data acquisition system can record 16 channels of 8-b data on one audio track. An additional 16 data channels can be recorded using both stereo audio tracks for 32-channel capability. A complete replicate of the A/D FSK modem is not required; only the ADC, FSK modulator and demodulator, and UART sections need to be duplicated. The same clock and timing logic circuit can be used for both audio tracks. The data bit resolution can be increased by reducing the number of channels available.

III. DATA EXTRACTION

The data extraction system consists of a: 1) microcomputer, 2) computer-controllable VCR, and 3) A/D FSK Modem. A block diagram of the associated circuitry is shown in Fig. 3.

The microcomputer is an i80386 MS-DOS based system. A video overlay card (Creative Labs, Inc.) permits simultaneous display of video signals from the VCR in a scaled window on the computer VGA video display monitor. The computer software controls the data extraction process. The VCR serial interface allows computer control of the VCR. All VCR functions, in addition to time coding functions, were accessible through the serial interface. The time code generator and reader circuits allow access to individual video frames.

After recording data, the video tape contains video images in addition to the FSK-encoded biomechanical data. VHS video tapes are time-coded using the Society of Motion Picture and Television Engineers (SMPTE) standard time code, which provides a unique address to each video frame. This time code allows the computer to access specific video frames in addition to encoded sampled data for any frame on the tape. The video tape can be reviewed by an analyst at any speed desired in either direction. Variable speed allows quick review of long duration tasks at speeds much faster than real time, or detailed review of short duration tasks at speeds slower than real time. The tape can be stopped and the video image frozen to identify an event to a single frame resolution.

In order to retrieve the recorded digitized data, the video tape is played back and the high fidelity audio output is connected to the FSK demodulator. The demodulator converts the audio signal back into TTL RS232 serial data which are sent to the receiver section of the UART. The UART converts the serial data into an 8-b parallel data stream. The 8-b parallel data are then sent to a microcomputer parallel input/output (PIO) interface, along with the 4-b channel select bus signals for data extraction. The parallel data are also sent to the DAC so an analog signal can be viewed on an oscilloscope or voltmeter for reviewing data recording when playing back the recorded video tape in the field.

While viewing the video tape, the analyst locates the video frame of interest and assigns event markers or activity break-points for data segments by pressing a key on the keyboard that represents the event or task element. The assignment of the markers or breakpoints need not be performed in any specific sequence. A code name is assigned to each different event marker. When an event marker is selected, the time code address associated with the video image and data is stored in a list as the start of the activity or task element, and also indicates the end of the previous activity. The analyst reviews the tape and marks events until all the task elements are assigned. If a change is desired, or the analyst reconsiders a selection, the tape may be rewound or shuttled to the point on the tape before the assignment and the time marks are edited. After all event markers or break-points are assigned, a report can be displayed containing event segment times or task times for all elements. The computer then extracts data recorded on the audio channels of the tape element by element, by playing the video tape audio track through the FSK modem. Data analysis can therefore be performed on replicates of individual events or elements.

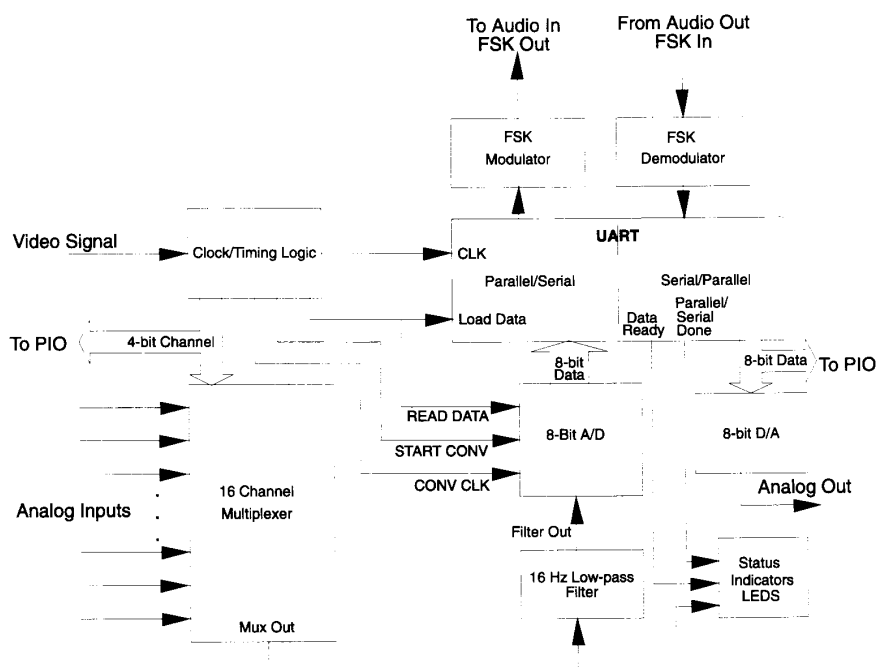


Fig. 2. A/D FSK modem block diagram.

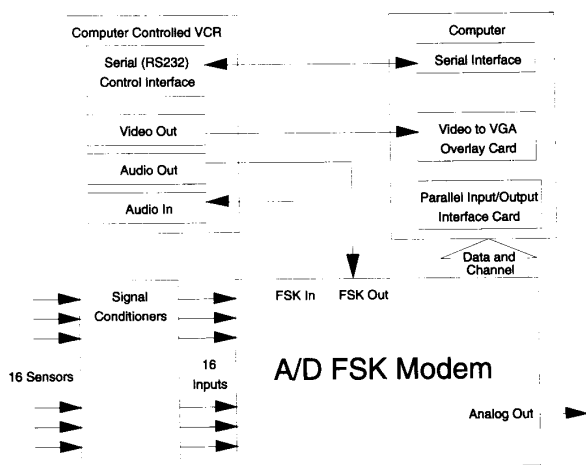


Fig. 3. Functional diagram of the data extraction system. A computer-controlled VCR is used to extract the data recorded on the video tape audio track. The FSK modem converts the audio signal into digital form. The video overlay allows viewing of both the computer screen and the recorded video to facilitate arbitrary event selection.

IV. DISCUSSION

This data acquisition system has been successfully used in the laboratory and in the field for biomechanical evaluation of repetitive manual work [5], [6]. The major advantage is that video images and data synchronization are integral parts of the system. This permits automatic data extraction. Previous methods involved using an external synchronization pulse that is recorded on a data channel, taking up valuable storage space, and a resynchronization process is needed when the data are retrieved [1], [2]. This inherent video/data

synchronization is important for many biomedical engineering purposes, such as human performance in rehabilitation, ergonomics, gait and movement analysis, sleep laboratory, and sports medicine.

An 8-b ADC was considered sufficient for many biomechanical data acquisition purposes. For example, electrogoniometer data typically has a range of 180° with a 1° error or more. This resolution is also sufficient for integrated EMG, often used as an indicator of muscle contraction or as a coarse predictor for force [7].

The video-based system is capable of sampling at 960 Hz with one channel. The bandwidth for many biomechanical data applications are often between DC and 10 Hz. Angular joint motion seldom exceeds 6 Hz, except for very short duration during athletic activities [8]. Strain gages having bandwidths between DC and 60 Hz are commonly used for measuring physiological signals [8]. Although surface EMG signals may have a bandwidth between 0.01 Hz and 1 kHz, integrated or RMS values may have a bandwidth less than 10 Hz. Temperature measured using thermistors or thermocouples has a bandwidth less than 1 Hz. Acceleration of the human body measured using accelerometers has a bandwidth between DC and 30 Hz [9]. A bandwidth between DC and 30 Hz, which is the Nyquist frequency for a 60-Hz sample rate, provides up to 16 multiplexed channels.

The current system uses readily available technology. Recording both the video and data digitally is prohibitive because of the video bandwidth and storage capacity of a conventional VCR. Digitally storing an S-VHS resolution video image with only 256 colors at full rate (30 frames/s) for two hours would require over 500 Gbytes and considerable computer processing power. Storage media such as hard disks, optical drives, or digital audio tape (DAT) drive may provide the necessary capacity when used with compression technology. Recording the video image in conventional analog form and the data in digital FSK-modulated form requires only conventional equipment, making it very cost effective.

A summary of the system performance is presented in the specification table (Table 1). The data synchronization error is 1/30th of

TABLE I
A/D FSK MODEM SPECIFICATIONS

Parameters	Values
Number of Channels	≤ 32
Recording/Reproduction Method	FSK (10.125 kHz, 18.5 kHz)
S.N Ratio	49 dB (8-bits)
Bandwidth	DC to 480 Hz
Sampling Frequency	60 Hz to 960 Hz
Error Correction	RS232 Standard
Synchronization Error	16.67 ms (max.)
Analog Input Range	0 to 5 VDC
Analog Output Range	0 to 5 VDC
Digital Output	8-bits data + 4-bits channel + 2 bits error detection

TABLE II
SYNCHRONIZATION ERROR COMPARISON (MILLISECONDS)

	Mean Error	Std. Dev.	Max. Error	Min. Error	No. Replications
FSK Video-based System	16.6	0.1	16.6	15.1	11848
Computer sampling/Time code synchronization	36.4	0.7	39.6	34.0	99500

a second, based on the resolution of the SMPTE longitudinal time code (LTC). The inherent synchronization error of the circuitry (i.e., the timing error between the recorded video image and the digital data for a given event) is 16.6 ms maximum. Manual synchronized events using human reaction time, such as a keypress response to a visual stimulus, typically require at least 115 ms [10].

The video/data synchronization performance of this video-based system was compared to using a computer-data acquisition board system (Keithley-Metrabyte DAS1600) installed in a 486DX2-66MHz computer (see Table II). The data were read into RAM first via software-polling in synchronization with the time-code output from a time-code generator (Horita VG-50), then stored on a hard drive. The time code was simultaneously recorded on the video tape using the video-based system described in this paper. Sixteen channels of 12-b data were collected.

SMPTE time code resolution is 1/30 s or 33.3 ms, requiring that all the data and time code be collected within this time period to remain synchronized within the video frame. The video-based system with a maximum error of 16.6 ms was well within the time period needed to maintain frame synchronization (see Table II). The video-based system was capable of maintaining field synchronization for 1/60 s or 16.667 ms. The data acquisition board was unable to acquire the time codes and data within the 33.3 ms interval. Since the standard deviation of the computer/data acquisition board system was within the time code resolution, an additional processing step may be needed to correct for the synchronization error. This correction is dependent on successfully calibrating the individual software with the specific hardware. Any software or hardware change would require recalibration. The video-based data acquisition is inherently synchronized and does not require calibration.

V. CONCLUSIONS

A video-based data acquisition and multimedia data extraction system were described for measuring and synchronizing biome-

chanical analog data with arbitrary events and tasks. Field data acquisition and activity synchronization were greatly simplified with this system. Just a camcorder and sensors comprise the necessary equipment. This system synchronizes analog data with the video image. By simultaneously recording the video and data onto the same medium, an inherent video/data synchronization is achieved, which is extremely useful for low-frequency biomedical applications where arbitrary events are associated with analog data.

REFERENCES

- [1] W. S. Marras and R. W. Schoenmarklin, "Wrist motions in industry," *Ergonomics*, vol. 36, pp. 341-351, 1993.
- [2] A. Moore, R. Wells, and D. Ranney, "Quantifying exposure in occupational manual tasks with cumulative trauma disorder potential," *Ergonomics*, vol. 34, pp. 1433-1453, 1991.
- [3] D. M. Huber, *Audio Production Techniques for Video*. Carmel, IN: SAMS, 1987, p. 102.
- [4] FCC, Document 53-1663, 1953.
- [5] R. G. Radwin, M. L. Lin, and T. Y. Yen, "Exposure assessment of biomechanical stress in repetitive manual work using frequency-weighted filters," *Ergonomics*, vol. 37, pp. 1945-1957, 1994.
- [6] R. G. Radwin and T. Y. Yen, "Development of an instrument for assessing exposure to physical stress in repetitive manual work," in *Proc. 1993 NSF Design Manufacturing Syst. Conf.*, Charlotte, NC, pp. 1151-1158, 1993.
- [7] D. A. Winter, *Biomechanics and Motor Control of Human Movement*. New York: Wiley, 1990.
- [8] ———, *Biomechanics of Human Movement*. New York: Wiley, 1979.
- [9] W. H. Olson, "Basic concepts of instrumentation," in *Medical Instrumentation: Application and Design*, J. G. Webster, Ed. Boston: Houghton Mifflin, 1987, ch. 1, pp. 1-48.
- [10] L. Kaufman, *Perception—The World Transformed*. New York: Oxford Univ. Press, 1979.

Tissue Spectroscopy with Electrical Impedance Tomography: Computer Simulations

H. Griffiths

Abstract—A method is proposed by which bioelectrical spectroscopy could be combined with electrical impedance tomography (EIT) to provide noninvasive characterization of tissue. Multifrequency (2–200 kHz) EIT measurements were simulated with a numerical model for a volume of porcine liver immersed in an electrolytic tank. From the reconstructed EIT images the tissue characterization method was then applied enabling a plot of complex resistivity to be drawn for any selected pixel in the image. Simulations were performed for a small volume of degraded tissue embedded in the normal tissue to examine its effect on the derived spectroscopic parameters. The method could have an application in transplant surgery for screening organs for tissue degradation.

Manuscript received June 17, 1993; revised March 14, 1995. This work was supported by a Medical Research Council/INSERM French Exchange Fellowship.

The author was with INSERM U281, 69424 Lyon, Cedex 03, France. He is now with the Department of Medical Physics and Bioengineering, University Hospital of Wales, Heath Park, Cardiff CF4 4XW, U.K.

IEEE Log Number 9413380.