

Automatic Threshold Adjustment for Predictive Level Crossing Sampling Data Converters

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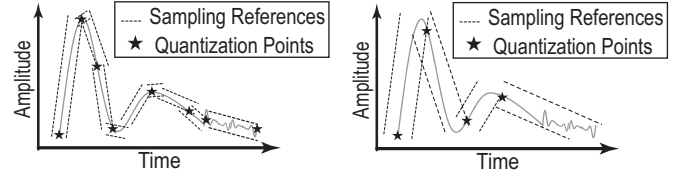
Abstract—This paper presented an automatic threshold adjustment circuit design for selecting the reference voltage levels in predictive level crossing sampling data converters. The automatic adjustment is based on counting the rate of triggered events in a timing window. The threshold voltage is then adaptively adjusted based on the event rate using closed-loop feedback. The threshold voltage increases while the event rate is too high, or vice versa. Such adjustment does not affect the reconstruction process, and the system does not need to store the change or absolute value of threshold voltage changes since the predictive level crossing sampling records the precise digital values at a fixed sampling clock rate. The event rate is adjustable depending on specific applications. Simulation results of ECG sensing are performed to demonstrate the performance of the proposed method. The proposed circuits provide a relatively stable output data throughput, which is friendly for the following data storage and processing devices.

Index Terms—Event-driven sensing, Nonuniform sampling, Dynamic predictive sampling, Adaptive Event Rate.

I. INTRODUCTION

Biosensors usually contain a data acquisition system that converts the input biomedical signal into a digital data stream for further storage and processing [1]. The primary challenge in such a system comes with the trade-off between the limited power supply and the limited digital resources [2]. Since such systems are often deployed in wearable or implantable devices, it is expected to be powered by batteries with small physical size, which reduces their performance for data storage, communication, and signal processing. The performance of such systems is required by application specifications including digital resolution, sampling speed, power consumption, and data throughput. These performance metrics are primarily determined by the type of analog-to-digital converters (ADC) in the system. For example, one of the most popular solutions is the successive approximation register ADC (SAR ADC), which samples at a fixed sampling rate and converts each sampling into a fixed resolution digital data. However, since biomedical signals are often sparse in the time domain, such a method may generate lots of unnecessary data when the input signal is inactive, which wastes both power and data resources.

To overcome such a problem and improve the power efficiency of the biosensing system, other data conversion methods and circuits are expected. For example, level-crossing sampling ADCs (LCS ADC) [3], [4] have been proposed in various biosensors [5]. LCS ADC compares the input voltage with reference voltages and records the event when the input voltage crosses the reference voltage. The known reference



Predictive Level Crossing Sampling with a smaller (left) and larger threshold (right)

Fig. 1. Predictive Level Crossing Sampling uses the prediction with an error voltage threshold as the sampling reference to select the turning points for quantization. The events are triggered when the difference between real input and prediction is larger than the threshold. By adjusting the threshold, the event rate can be controlled to balance data throughput and accuracy.

voltages and the timing information between events could be used for reconstructing the original input waveform. LCS ADC fits better in applications with a sparse input in the time domain since no sampling and quantization is performed when the signal is inactive. However, LCS ADCs suffer from noises around the threshold voltage, which may introduce insertion/deletion errors [6]. Moreover, the LCS ADCs is difficult to catch the peak of the waveforms unless they use small voltage gaps between reference voltages. This may increase the number of sampling events, and cause a high circuit complexity and power cost of the system.

To address this issue, recent advances in level-crossing ADCs focus on adjusting the reference voltage with the input signal, which forms sloped reference voltages [7], as shown in Fig. 1. Such systems trigger a sampling event when the input signal greatly changes its slope in a short time so that turning points can be recorded including peaks of the waveforms. Combined with a fixed sampling clock and implemented inside of a SAR ADC, the event is only triggered at a turning point and a precise multi-bit quantization is performed at the turning point. Such slope level-crossing sampling or predictive level-crossing sampling has solved most of the issues in level-crossing sampling ADCs. The output of the predictive level-crossing sampling ADC contains both timing and amplitude information of the turning points. By adjusting the voltage gap between the threshold voltages, the system creates a trade-off between data throughput and reconstruction accuracy, which is beneficial for low-power biosensors. However, the system relies on a pre-determined voltage gap between the input voltage and the reference voltage, which may suffer from different amplitude of noise and the sparsity of the signal. An automatic adjustment of the reference voltage gap becomes necessary to implement such a method in real applications.

In this work, we propose an automatic reference voltage gap

adjustment circuit based on digital feedback of a counter. The method stabilizes the data throughput by a target event rate of the level-crossing ADCs. It brings the benefit of a stable data throughput in a non-uniform sampling system. The detailed methods, simulation results, and analysis are described in the following sections.

II. CIRCUIT AND SYSTEM DESIGN

Predictive Level-Crossing Sampling senses the analog input waveform by using prior digitized sampling points to generate a prediction of current sampling values. It then determines whether to digitize the current sampling point based on a comparison between the current sampling and its prediction. The system only digitizes the selected turning points in the analog waveform. A digital prediction error Δ is introduced and applied to the predicted digital value to establish upper and lower thresholds for comparison. These thresholds are then converted into analog values for comparison with the current analog sampling value. The prediction is considered accurate when the sampled input analog value is between the upper and lower thresholds while the predictive digital value is used for the future prediction and no quantization is performed for the current sampling. Otherwise, digitization is required for unsuccessful predictions of the input sampling point, which is identified as the selected sampling point. These are usually the turning points in the analog waveform. Timing information between selected sampling points is recorded as timestamps. The output of the Predictive Level Crossing Sampling contains both the amplitude of turning points and the timestamps between them. This data enables the reconstruction of the input analog waveform using methods such as piecewise linear reconstruction or other advanced techniques.

The predictive level-crossing sampling method combines advantages between Nyquist sampling and Level Crossing sampling approaches. Compared to conventional level-crossing sampling, this method records multi-bit accurate digital data of amplitude with digital data of time-stamps between sampling events, which reduces the potential insertion/deletion of pulses and drift errors. Compared with the conventional Nyquist sampling method employing a fixed clock, dynamic predictive sensing separates the sampling and quantization processes, performing quantization only at the turning points of the input analog signal. This method brings advantages in reducing data throughput when the input signal is sparse or predominantly linear. The error threshold brings an additional trade-off between data throughput and the accuracy of the reconstructed signal. Moreover, it reduces power consumption by skipping the quantization steps for successful prediction.

One of the major problems in this system is that the threshold of the predictive error has to be manually adjusted, which is usually a fixed value for the system in a specific application. This reduces the flexibility of the system for different applications. For example, the output data throughput is variable due to non-uniform sampling. The event rate is directly related to the input signal sparsity. Therefore, the output event rate changes with the signal sparsity. This increases the complexity of the following data storage and

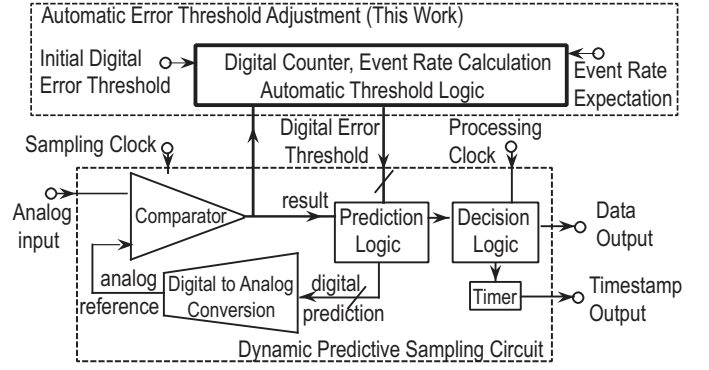


Fig. 2. Block diagram of the proposed automatic threshold adjustment circuits for near-constant event rate control.

processing circuits since it is difficult to estimate the incoming data size from time to time. To solve this problem, in this work, we introduced a digital feedback system to automatically adjust the threshold. As shown in Fig. 2, a digital counter is included in the system counting the number of events during a certain amount of time, which is the event rate. If the event rate is higher than an upper threshold value, the threshold voltage value is then increased digitally to lower the event rate. Similarly, if the event rate is too low, the threshold voltage will be decreased to increase the event rate. Therefore, the system can generate events around a near-constant event rate.

Fig. 2 presents the circuit block diagram of a Proposed Predictive level-crossing sampling System. The circuit contains an analog comparator, a digital-to-analog converter (DAC), prediction logic, decision logic, and a digital timer. It operates similarly with successive approximation register (SAR) ADC. The analog segment of the circuit (comparator and DAC) is synchronized by a sampling clock while the digital segment is driven by a processing clock operating faster than the sampling clock, particularly during SAR digitization. The analog input signal is consistently compared with the analog reference value from the DAC based on the sampling clock. The results are processed by the prediction and decision logic circuits to calculate the digital prediction for the DAC. The prediction logic incorporates the digital error Δ to compute upper and lower prediction thresholds. If the prediction fails, the circuit switches to a SAR logic for digitization. Consequently, the digitized sampling becomes the data output, and the timer resets for recording the timestamp between the current and subsequent selected sampling points. The automatic threshold adjustment circuits take the comparison results from the comparator to calculate the event rate based on the sampling clock and adjust the digital error threshold value according to the initial digital error threshold value, the target event rate, and the current event rate.

In conventional level-crossing sampling [8], the adjustment of threshold voltage must be recorded for reconstructing the original waveform since the system only generates the pulse sequence and records the event timing. Without the actual threshold voltage, the original input signal cannot be reconstructed. This increases the system complexity for storing temporary threshold voltage value data. This problem is not an

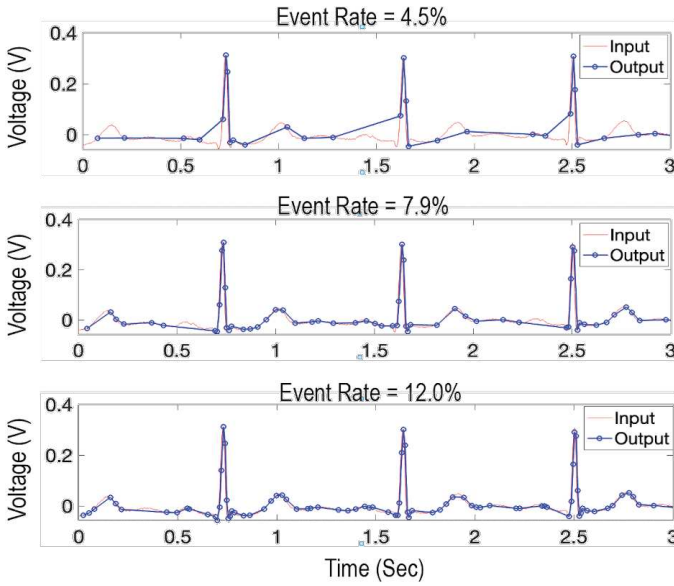


Fig. 3. Simulation result of the automatic threshold adjustment at different event rates for ECG signal sensing. An optimal event rate of 12% is selected for less data throughput while not missing the critical fiducial points.

issue in the proposed predictive level crossing sampling since the proposed method records the exact digital value of each selected sampling point. The system does not need to know the threshold voltage value for reconstructing the original waveform. Therefore, the proposed system with automatic threshold adjustment creates a non-uniform sampling but relatively uniform data throughput system without compromising system complexity. The additional circuit cost is the digital counter and digital feedback control of the threshold voltage data, which is negligible for the overall data converter.

III. SIMULATION AND IMPLEMENTATION RESULTS

A time-domain simulation waveform of the ECG signal sensing using the proposed method is shown in Fig. 3. The input waveform is a 3-second ECG signal from the MIT-BIH database with an original sampling rate of 250 Samples/second. The proposed method selects only a few turning points from the original waveform. An event rate is defined as the number of the selected sampling points over the total number of sampling points in a fixed timing window. The event rate is controlled at 4.5%, 7.9%, and 12% respectively for one-second window in each case using the automatic threshold adjustment method. The selected turning points and the reconstructed waveform are shown in Fig. 3 to compare with the raw input waveform. In order to perform arrhythmic heartbeat classification, the fiducial points such as the onset, peak, and end-point of P/QRS/T waves must be recorded. Therefore, an event rate of 12% system can meet the requirement while providing the minimum data throughput. A higher event rate may generate too much unnecessary data while a lower event rate may miss critical information from the analog waveform.

The primary advantage of applying automatic threshold adjustment in predictive level-crossing sampling is stabilizing

the data throughput. After setting the target event rate, the system can estimate the output data rate without considering the input signal sparsity or manually adjusting the threshold voltage level, which depends on the input signal amplitude. The user only needs to perform a preliminary study for a specific application to determine the estimated event rate for the system without considering the threshold voltage for the predictive level crossing sampling ADC. Therefore, the proposed automatic threshold adjustment circuits alleviate the primary challenge of threshold voltage determination in the system implementation for biomedical data acquisition.

IV. CONCLUSION

This paper proposes a new method for adjusting the voltage threshold for predictive level-crossing sampling in the application of biomedical data acquisition. The predictive level-crossing sampling system can reduce data throughput by selecting only the key turning points in the input waveform for quantization. The proposed method stabilizes the output data rate for non-uniform sampled waveforms for sparse signals. The proposed method only adds a digital counter and a digital control logic to the predictive level-crossing sampling system. The proposed method requires a target event rate for specific applications instead of manually adjusting a voltage threshold. A study of ECG signal recording is performed and an optimized event rate of 12% is identified to balance the accuracy and data throughput without requiring specific voltage threshold information for the system. The proposed method has great potential in implementing predictive level crossing sampling in biomedical data acquisition systems.

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