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Short communication

Modeling of data acquisition systems using the queueing theory

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ABSTRACT

This paper describes the features of a data acquisition system modeling based on queueing theory method. The main elements of the studied data acquisition system structure are sample hold amplifiers and dual-slope analogue digital converters. In case of the threshold control of technological facilities parameters, alarm signals in the system input are presented as a flow of customers with the Poisson intensity distribution. A converting time of these alarms in analogue digital converters depends on signal levels and is described by an exponential distribution. In this case we present the data acquisition system as the Markov model of the multichannel queueing system with a limited queue. This modeling method may help the data acquisition system structure to adapt to characteristics of input signals and features of communication lines in an output of system.

1. Introduction

The continually growing flow of information provided by systems that are used to control technological processes, monitor environmental conditions, test industrial facilities and support scientific research presents increasing challenges in terms of equipment and maintenance costs, as well as timing of information delivery [9,14]. Data acquisition systems (DAS), comprising a set of hardware for sampling, conversion, storage and primary processing of input analogue signals received from sensors installed, for example, at industrial facilities, offer an approach towards the optimisation of information flows [19,20]. Enhanced efficiency of information processing can be achieved by data compression given an accurate DAS functional model. This model is to be based on a detailed analysis of input information and should take into account required output indices and DAS configuration features. DAS input is connected to measuring channels, including sensors, DAS output is connected to communication channels via discrete switch.

Initial attempts to compress data files involved an identification of redundant information by adaptive signal sampling over time intervals [10]. Taking this approach, the selection of the most informative signal samples can be performed provided the approximation error reaches a threshold value. However, the elimination of redundant samples leads to nonuniform sampling intervals and, therefore, to nonuniform communication channels. Moreover, such data compression can only be realised by a DAS equipped with a sensor activity analyser. It is obvious that the DAS structure becomes too involved, since each sensor needs its own analogue digital converter (ADC).

A method for the adaptive commutation of signal sources was developed by Takayama and Kariya [16]. According to this approach, a converter receives a signal only from that sensor whose current approximation error is maximal during sampling. For this method to be implemented, one ADC per all sensors is generally sufficient. However, this approach has a number of disadvantages. Firstly, the system efficiency is largely dependent on how accurately the approximation error for the signal functions in each channel is calculated. Secondly, the ordinariness requirement is violated when the sampling frequency is reduced. Finally, the communication channel is loaded nonuniformly at the exit from the DAS.

This paper proposes a DAS model having an optimal amount of structural elements based on queuing theory. The flow of customers in the queuing system is represented by the signals from those controlled parameters that cross a threshold level. We introduce a Markov model of DAS based on a multichannel queuing system [3,15]. In this model, ADCs represent service centres and

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sample hold amplifiers (SHA) represent queuing nodes. We suggest using a dual-slope integrating ADC, whose reliable qualities are described in Ref. [7]. The optimal number of DAS elements is calculated taking capacity requirements and queuing time into account [2,4]. The model provides a sufficiently high compression of the input information avoiding significant hardware costs.

2. Description of DAS modeling method

The purpose of this chapter is to describe a sequence of DAS modeling using queuing theory. Proposed DAS is intended to process telemetry alarms in industrial sensor networks. Such signals u_i are generated in random moments when controlled parameter x crosses a threshold level x_{Π} (Fig. 1).

Alarm signals, transmitted by sensors of facilities to DAS in random moments, are presented as a queue [11]. Customer service is performed as analogue digital conversion [5]. This modeling method was selected in order to determine analytical dependence of technical parameters of DAS elements and queuing system indicators. Modeling results allow optimizing amount of structural elements that provides harmonizing output indexes of system and capacity requirements of communication channels.

Dual-slope integrating ADCs are mostly used in telemetry because of their accuracy and stability [12].

The elements of dual-slope ADC in classical scheme can be distributed in two DAS subsystems: capacitor C, operational amplifier

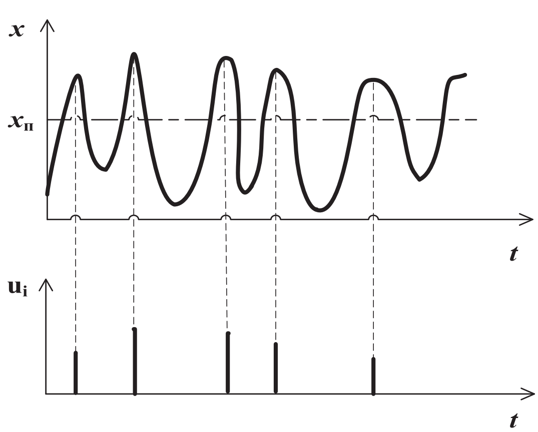

Fig. 1. Alarm forming in DAS input.

and key belong to SHA subsystem, the other elements, including comparator zero (SZ), belong to ADC subsystem (Fig. 2).

Analog switch (AS-1) provides connection of sensors with output voltage U_x (threshold amplitude) to free SHA. Capacitor of this SHA charges during fixed for all sensors time t_1, connecting to level comparator. Analog switch AS-2 connects output of SHA with charged capacitor to input of SZ of free converter with simultaneous connection of the second SHA input to common negative reference voltage source $-U_{dis}$. In the phase of the capacitor discharge count pulses are formed with a constant speed during the time t_{dis} in the amount, proportional to the input voltage.

Operation of switches can be controlled by Field-Programmable Gate Array (FPGA).

Here GCP is the generator of the counting pulses, DS is the discrete switch.SHA can have several modes according to a voltage in the capacitor:

1) without voltage
2) capacitor charge by the input signal voltage
3) standby mode (voltage storage)
4) capacitor discharge by free ADC.

Distribution of functions of SHA and ADC provides fast process of the signal without overcomplicating DAS structure.

Main idea is to model DAS as the queuing system with n measuring channels represented by ADCs and the queue limited by m SHAs [6]. The service time t_{serv} corresponds to the time of capacitor discharge t_{dis}. As reported previously, the time t_{dis} of telemetry alarm signals is proportional to amplitude of threshold level of controlled parameters and has exponential Poisson distribution. Therefore, DAS is classified as a classical M/M/n/m Markov model [8,22].

A failure probability of customer service is determined if all n ADCs and m SHAs are occupied [1,17]:

$$p_{n+m} = \left[\left(\frac{\lambda}{\mu}\right)^{n+m} / n^m n!\right] p_0, \tag{1}$$

where λ is the average arrival rate; $\mu = 1/\bar{t}_{dis}$ is the average service rate of a single service; $\bar{t}_{dis}$ is the average time of capacitor discharge by free ADC;

$$p_0 = \left(\sum_{j=0}^{n} \frac{\lambda^j}{\mu^j j!} + \frac{(\lambda/\mu)^{n+1}}{n \cdot n!} \cdot \frac{[1-(\lambda/\mu n)^m]}{(1-\lambda/\mu n)}\right)^{-1} \tag{2}$$

is the probability that the server is idle.

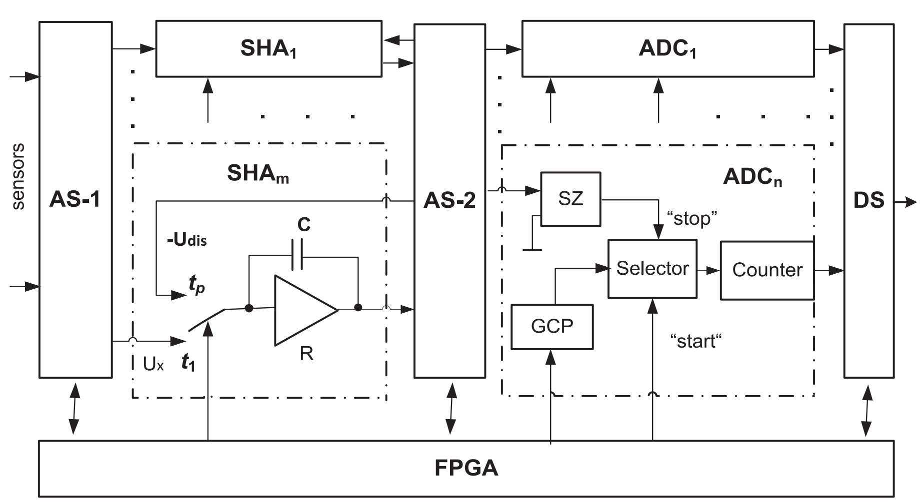

Fig. 2. Decomposition of dual-slope ADC scheme in multichannel DAS structure.

Table 1
Arrival rates λ_{mn} [s^{-1}] at failure probability $p_{nm} = 0.001$ and the service rate μ = 100 [s^{-1}].

SHAs	ADCs								
	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	n = 7	n = 8	n = 9
m = 0	0.1	0.5	20	45	80	120	160	210	260
m = 1	3.5	18	45	75	120	165	210	265	310
m = 2	11	35	65	105	150	200	245	295	355
m = 3	19	49	91	130	180	230	280	335	395
m = 4	28	65	112	160	210	260	320	380	440
m = 5	36	80	130	180	230	290	350	420	470
m = 6	41	90	145	200	260	310	380	450	500
m = 7	48	100	155	220	270	345	400	460	530

Table 2
DAS capacity $V = |v_{mn}|$ [bit/s] at $p_{nm} = 0.001$ and $\bar{t}_{dis} = 0.01$ [s]; r = 4; d = 8.

SHAs	ADCs								
	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	n = 7	n = 8	n = 9
m = 0	1	6	240	540	959	1439	1918	2518	3217
m = 1	42	216	540	899	1439	1978	2518	3177	3717
m = 2	132	420	779	1259	1799	**2398**	2938	3537	4256
m = 3	228	588	1091	1559	2158	2758	3357	4017	4736
m = 4	336	779	1343	1918	2518	3117	3837	4556	5276
m = 5	432	959	1559	2158	2758	3477	4197	5036	5635
m = 6	492	1079	1739	**2398**	3117	3717	4556	5396	5995
m = 7	576	1199	1858	2638	3237	4137	4796	5515	6355

A matrix $\Lambda = |\lambda_{mn}|$ (Table 1) shows the average arrival rates according to acceptable values of the failure probability of customer service p_{n+m} and the average service rate of a single service μ, presented in (1), (2). The rows of the matrix are filled by *n* ADCs and the columns are filled by *m* SHAs.

Let us assume that every served customer in the output of the system consists of $(r + d)$ bit elements, where *r* and *d* are numbers of bytes in informational and address parts of telemetry word respectively. Then a capacity should be determined as the following:

$$v = \lambda(1 - p_{n+m})(r + d). \tag{3}$$

Using (3) and λ_{mn} values from the matrix Λ we create a matrix $V = |v_{mn}|$ of capacity values for different amounts of *n* ADC and *m* SHA (Table 2). If the DAS capacity fits with a communication channel capacity ς from the matrix V, we chose a value $v^*_{mn} \in V$, which is closely to communication channel capacity ς. If the DAS capacity is higher than the channel capacity, a part of customers does not reach a receiver. If the DAS capacity is lower than the communication channel capacity, it indicates an inefficient use of the channel. Coordinates of chosen v^*_{mn} location define rational amount of *n* ADCs and *m* SHAs.

Let us present a generalized model for calculating the optimal DAS structure, using (1)(3):

$$\lambda\left\{1 - \left[\left(\frac{\lambda}{\mu}\right)^{n+m} \Big/ n^m n!\right]\left(\sum_{j=0}^{n}\frac{\lambda^j}{\mu^j j!} + \frac{(\lambda/\mu)^{n+1}}{n \cdot n!}\cdot\frac{[1-(\lambda/\mu n)^m]}{(1-\lambda/\mu n)}\right)^{-1}\right\} = \frac{v^*_{mn}}{r+d}. \tag{4}$$

This method allows considering how determined number of electronic elements affects accuracy of signal analogue digital conversion.

If all ADCs are not available, the reservoir capacitor with capacitance *C* has a standby mode during τ≠0. When information is stored too long, a leakage current *I* appears. In this case the capacitor voltage U_x is decreased by value ΔU and the capacitor discharge time is decreased by value $\Delta t_p = t_p - t_p^{/}$. If $\Delta t_p \geqslant \theta/2$, where θ is a count pulse period in dual-slope integrating ADC, errors in conversion appear.

The ratio of voltage drift to time of signal delay in SHA is fixed and is determined as the following:

$$\Delta U/\tau = I/C. \tag{5}$$

Taking (5) and $U_x/(U_x - \Delta U) = t_p/(t_p - \Delta t_p)$ into account we can find customer waiting time in SHA, according to the fixed capacitor charge time t_1 and discharge voltage U_{dis}. That is calculated as follows:

$$\tau = \Delta t_p \frac{U_{dis}/t_1}{I/C}. \tag{6}$$

$L = 2^r$ number of impulses will be calculated for maximum voltage in the SHA input during capacitor discharge time $t_{dis\,max}$, so $\theta = t_{p\,max}/L$, where *L* is a number of quantization levels, *r* is code length of analogue digital conversion. Therefore, available waiting time of signal in SHA should not exceed a value

$$\tau_{lim} = \frac{\theta}{2}\frac{U_{dis}/t_1}{I/C} = \frac{t_{dis\,max}}{2^{r+1}}K, \tag{7}$$

where $\frac{U_{dis}/t_1}{I/C} = K$ is a constant for SHA types.

Formula (7) is schematic model of DAS. The available customer waiting time for serving depends on ADC and SHA parameters, which are: ADC code length *r*, capacitance *C* of the capacitor, its charge time t_1 and discharge time $t_{dis\,max}$, leakage current *I* of the capacitor in standby mode.

Values of the customer waiting time for serving $T = |\tau_{mn}|$ can be seen in Table 3. It is based on M/M/n/m queuing system model [13]:

$$\tau = \frac{(\lambda/\mu)^n\{1-(\lambda/\mu n)^m \cdot [1+m(1-\lambda/\mu n)]\}}{\mu \cdot n \cdot n! \cdot (1-\lambda/\mu n)^2} p_0, \tag{8}$$

According to elements of $T = |\tau_{mn}|$ matrix, if $\tau_{mn} < \tau_{lim}$, we can define optimal ratio of *n* ADCs and *m* SHAs, that provides accuracy of signal conversion (Table 3).

Table 3
Waiting time τ_{mn} [ms] at $p_{nm} = 0.001$ и $\bar{t}_{dis} = 10$ [ms].

SHAs	ADCs								
	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	n = 7	n = 8	n = 9
m = 0	0	0	0	0	0	0	0	0	0
m = 1	0.338	0.068	0.032	0.016	0.012	0.009	0.006	0.005	0.004
m = 2	**1.195**	0.29	0.114	0.067	0.045	0.033	0.022	0.016	0.014
m = 3	**2.291**	0.608	0.315	0.159	0.109	0.076	0.053	0.041	0.034
m = 4	**3.798**	**1.133**	0.594	0.345	0.22	0.145	0.115	0.092	0.073
m = 5	**5.4886**	**1.828**	**0.945**	0.54	0.336	0.254	0.194	0.171	0.118
m = 6	**6.805**	**2.451**	**1.343**	**0.816**	0.573	0.36	0.308	0.263	0.18
m = 7	**8.991**	**3.22**	**1.685**	**1.183**	0.692	0.607	0.415	0.311	0.265

In the section that follows, an example of calculation of the optimal number of DAS elements is presented. The preset parameters are communication channel capacity, available service probability and technical system characteristics.

3. Calculation of the optimal number of DAS elements

The principal aim of DAS modeling is towards the development of an integrated DAS structure, i.e. an optimal choice of the ratio of SHAs to ADCs in order to ensure coordination between the DAS and the output channels in terms of their respective transmission capacities. In this study, we used the queuing theory method to model the DAS structure.

In this section, the numerical results of such modeling are presented for those DAS indicators that are used in actual telemetry systems. Table 1 presents the arrival rates $\Lambda = |\lambda_{mn}|$ for different ratios of n ADCs and m SHAs using the failure probability of customer service $p_{nm} = 0.001$ and the average time of capacitor discharge $\bar{t}_{dis} = 0.01$ s from (1), (2).

Every served request is considered as a telemetric word, which contains $r = 4$ bytes of the informational part and $d = 8$ bytes of the address part. Table 2 presents the DAS capacity for different ratios of n ADCs and m SHAs. According to (3), λ values are taken from Table 1.

When the DAS transmission capacity is coordinated with the communication channel capacity of $\varsigma = 2400$ [bit/s], the recommended numbers for SHAs and ADCs are $m = 6$; $n = 4$ and $m = 2$; $n = 6$. Such ratios provide a transmission capacity of $v_{mn} = 2398$ [bit/s]. The final number of system elements can be determined provided that the accuracy demands of signal conversion are taken into account.

Table 3 correlates the average customer waiting times for the respective ADCs and SHAs by substituting λ values taken from Table 1 in (8).

When selecting the maximal capacitor discharge time $t_{dis\,\max}$ 25.6 [ms] and SHA coefficient $K = 1$, the limited waiting time in a SHA is defined according to (7) as follows $\tau_{\lim} = 0.8$ [ms].

The values $\tau_{mn} \geqslant \tau_{\lim}$ for forbidden numbers of SHAs and ADCs are written in bold in Table 3. These ratios produce an unacceptable ADC conversion error. The ratio $m = 6$ and $n = 4$ is also forbidden. Therefore, the DAS capacity matches with the communication channel capacity $(v^*_{mn} = v_{26} \approx \varsigma = 2400\ [\text{bit/s}])$ only if the system contains $m = 2$ SHAs and $n = 6$ ADCs.

A conventional DAS with $m = k = 4$ and $m = k = 5$ elements supports a transmission capacity of $v_{44} = 1918$ [bit/s]. This is $v_{26}/v_{44} = 1.23$ times lower than that of our DAS structure, i.e. $v_{55} = 2758$ [bit/s], which is not acceptable due to exceeding the channel capacity. Moreover, as shown in Table 1, the maximum permissible average arrival rate of our DAS structure is $\lambda_{26}/\lambda_{44} = 1.23$ times higher than that of a conventional DAS, which allows the number of sensors to be increased.

4. Discussion

Current telemetry systems are characterised by a large number of measured parameters derived from sensors located far from their respective control objects. The resultant losses during conversion and transmission by real channels mean that the problem of data acquisition cannot be solved by traditional methods [18,21,23].

In this paper, the problem of coordination between the DAS and communication channel is described. In order to reduce

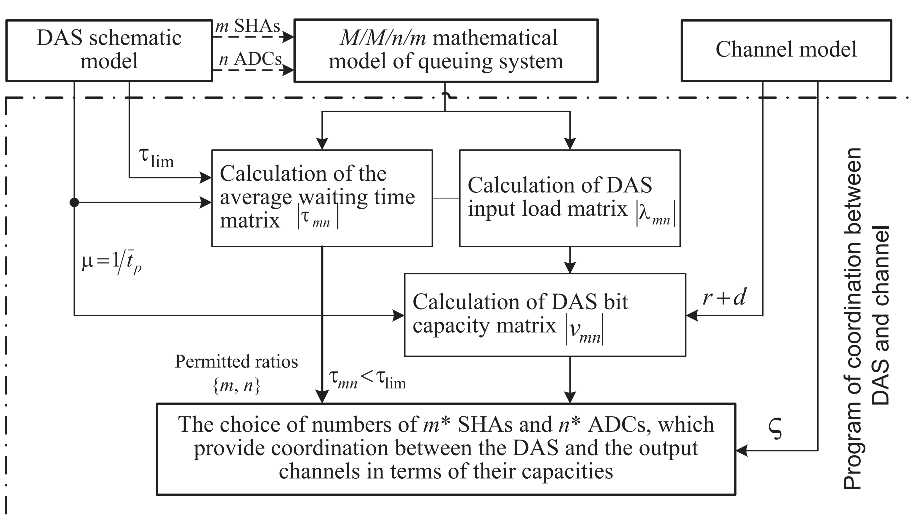

Fig. 3. DAS and channel coordination scheme.

signal-serving losses in a DAS having a small number of ADCs and SHAs, it is necessary to decrease the number of measured parameters. If the DAS structure is overfilled and the arrival rate is high, but communication channel capacity is low, some served signals will be lost. A model DAS structure that optimises coordination between the system and output channels in terms of their bit transmission capacities is described. In order to create the DAS model, mathematical methods derived from queuing theory, particularly the M/M/n/m Markov model, are used.

Fig. 3 presents a generalisation of derived results in terms of a DAS and communication channel coordination schematic, considered in terms of their capacities. The schematic DAS model is presented in (5)(7); the mathematical DAS model is presented in terms of a queuing system in (1), (2) and (8). A recommended bit width r of binary coding and channel capacity ς is defined from the channel model.

The results of our study show coordination between DAS and communication channel to be effective using an optimised ADC/SHA ratio. In this model, in contrast to methods described in other studies in which a DAS with a fixed number of elements is coordinated with the channels by changing the number of sensors, the arrival rate of sensors remains constant. The proposed method allows DAS capacity dependence to be defined not only on input load and number of elements, but also on schematic parameters, operating modes and bit width of binary code of digital signal. The results support the concept of a DAS with a variable number of elements such as the queuing system, in which ADCs represent service centres and SHAs represent queuing nodes. In this model, the arrival rate is defined by the number of sensors and the dynamics of changes in controlled parameters. Queuing system output indices, such as customer service failure probability and system capacity, depend on arrival rate, number of elements and conversion time in the ADC.

An important result of the schematic modeling (7) is the limited customer waiting time $\tau_{\lim}$ in the SHA, the exceeding of which generates an analogue-digital conversion error. The dependence of $\tau_{\lim}$ on technological parameters of DAS elements and the binary coding bit width in the ADC has been established. The ratio $\tau_{mn} < \tau_{\lim}$ limits the available choice range {m,n} of the system structure.

Our research is bounded by the study of a schema of a dual-slope ADC, such as is widely used when measuring engineering processes. Future research will focus on DAS modeling using other types of ADCs and dynamic DAS commutation to channels having different capacities.

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