ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2010. No. 4(100)
ELEKTRONIKA IR ELEKTROTECHNIKA

MEDICINE TECHNOLOGY
T 115
MEDICINOS TECHNOLOGIJA

ECG Data Analysis Using the Convolution of Mealy and Moore Automata

A. Martusevičienė, Z. Navickas
Department of Applied Mathematics, Kaunas University of Technology,
Studentu str. 50, LT-51368 Kaunas, Lithuania, phone: +370 662 79672, e-mail: asta_asta@yahoo.com
A. Vainoras
Institute of Cardiology, Kaunas University of Medicine,
Sukileliu av. 17, LT-3007, Kaunas, Lithuania, phone + 370 687 92521, e-mail: alfonsas.vainoras@med.kmu.lt

Introduction

ECG is one of the most common signals used in medical practice due to its noninvasive nature and the information it contains. Several systems and various automated approaches have been developed that use computer technology to provide ECG diagnosis [1]. These systems detect abnormalities and other features in the ECG signal and produce a decision which helps the physician when performing diagnosis. ECG decision support system can serve as a diagnostic tool for specific cardiac anomalies such as myocardial ischaemia and arrhythmia.

Practically all these systems are based on single or aggregate mathematical models [2], which often combine sub-systems, based on IF-THEN rules, fuzzy logic, genetic algorithms, Bayesian and neural networks, etc. There are two main types of decision support systems: knowledge-based and non knowledge-based systems. These systems also include parametric algorithms, for example, logistic regression, Fisher linear discriminant and non-parametric models as k nearest neighbor.

In this paper we propose a knowledge-based decision system, which is based on a variable, mathematically described model of Mealy and Moore automata, combined with two iterative mathematical algorithms – Hankel matrix and discriminant calculation.

The aim of both these algorithms is to detect changes in complexity of ECG parameter sequences performing real time calculation of it. If complexity is out of its physiological bounds – performed procedure is suspended. Mealy and Moore automata convolution in similar context was previously proposed only for modeling the long lasting functional state of healthiness dynamics [3] and for mobile ECG and motion activity monitoring [4]. Moore and Mealy automata convolution was also effectively used in the modeling of service and telecommunication systems[5].

Mealy and Moore automata convolution

While performing complex calculations with many system parameters, mathematical formalization and automation is needed. In order to achieve this goal we use a special formation (convolution) of automata (Mealy and Moore), see Fig.1. In such formation the output signal of one automaton becomes the input signal of the other automaton. Outputs, inputs and states of automata in Mealy and Moore convolution form special time series, which also can be analysed. Proposed automata convolution has an advantage: different (fractal) levels of the analysed dynamic system can be described involving one Mealy and Moore automata convolution into the other convolution, see Fig.1. Time moments of events should be effectively synchronized in such formations.

ECG decision support system is interpreted as an automata convolution. Moore automaton surjection f_r describes knowledge base. It includes a register of physiologic norms, remarks of physician etc. Moore automaton state set W depicts status of a patient including foretime. Mealy automaton state set Z describes the process of ECG parameters measurement of a patient. Mealy automaton output (Moore automaton input) signal set Y describes estimates of health according to current ECG flow. These estimates are calculated in inner subautomata convolution. Moore automaton output (Mealy automaton input) signal set X describes instructions sent to Mealy automaton. Moore subautomaton surjection f_r' describes iterative algorithms of ECG analysis, which are H-rank algorithm and special discriminant algorithm [6].

It is important to notice that automata state and signal sets are infinite. In this case we extended automata for modeling.

The convolution operates in such a way: the data stream of ECG is obtained by Mealy subautomaton and processed by Moore subautomaton. When enough data is collected in Moore subautomaton for algorithms to deliver analysis estimates, these estimates are passed to Moore automaton for automatic evaluation and also for a physician to observe. So, Moore automaton has two main functions: to evaluate the analysis data itself and to serve the operator with variuos types of alert signals.

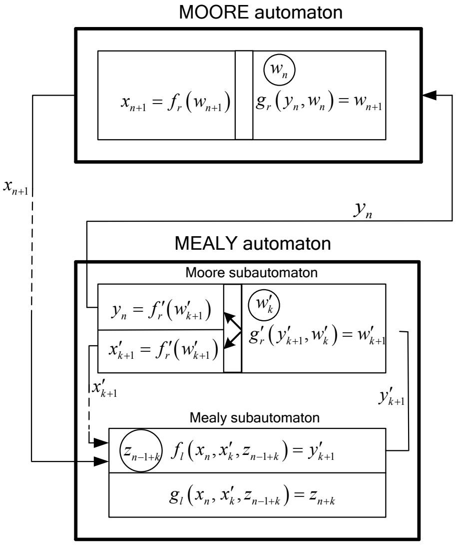

Fig. 1. Mealy and Moore automata convolution

The convolution of automata starts operating after the initial states z_0, w'_0, w_1 are introduced. The implementation of the work of automata is presented in Fig 2.

$$\begin{bmatrix} * \\ * \\ \begin{bmatrix} z_0 \\ * \\ w'_0 \\ * \end{bmatrix} \end{bmatrix} \rightarrow \begin{bmatrix} \begin{matrix} w_1 \\ f_r(w_1) = x_1 \end{matrix} \\ \begin{bmatrix} f_l(x_1, z_0) = y'_1 \\ g_l(x_1, z_0) = z_1 \\ g'_r(y'_1, w'_0) = w'_1 \\ f'_r(w'_1) = x'_2 \end{bmatrix} \rightarrow \begin{bmatrix} f_l(x'_2, z_1) = y'_2 \\ g_l(x'_2, z_1) = z_2 \\ g'_r(y'_2, w'_1) = w'_2 \\ f'_r(w'_2) = x'_3 \end{bmatrix} \rightarrow \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \rightarrow \begin{bmatrix} f_l(x'_n, z_{n-1}) = y'_n \\ g_l(x'_n, z_{n-1}) = z_n \\ g'_r(y'_n, w'_{n-1}) = w'_n \\ f'_r(w'_n) = x'_{n+1} \\ f'_r(w'_n) = y_n \end{bmatrix} \end{bmatrix} \rightarrow$$

$$\rightarrow \begin{bmatrix} \begin{matrix} g_r(y_1, w_1) = w_2 \\ f_r(w_1) = x_1 \end{matrix} \\ \begin{bmatrix} f_l(x_1, z_0) = y'_1 \\ g_l(x_1, z_0) = z_1 \\ g'_r(y'_1, w'_0) = w'_1 \\ f'_r(w'_1) = x'_2 \end{bmatrix} \rightarrow \begin{bmatrix} f_l(x'_2, z_1) = y'_2 \\ g_l(x'_2, z_1) = z_2 \\ g'_r(y'_2, w'_1) = w'_2 \\ f'_r(w'_2) = x'_3 \end{bmatrix} \rightarrow \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \rightarrow \begin{bmatrix} f_l(x'_n, z_{n-1}) = y'_n \\ g_l(x'_n, z_{n-1}) = z_n \\ g'_r(y'_n, w'_{n-1}) = w'_n \\ f'_r(w'_n) = x'_{n+1} \\ f'_r(w'_n) = y_n \end{bmatrix} \end{bmatrix} \rightarrow$$

$$\rightarrow \begin{bmatrix} \begin{matrix} \cdots \\ \cdots \end{matrix} \\ \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \rightarrow \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \rightarrow \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \rightarrow \begin{bmatrix} \cdots \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} \end{bmatrix} \rightarrow \begin{bmatrix} g_r(y_1, w_n) = w_{n+1} \\ f_r(w_{n+1}) = x_{n+1} \\ \end{bmatrix}$$

Fig. 2. The implementation of the work of automata convolution

The presented model is changeable – we can easily add new components (subautomata, states, surjections) to describe the information streams in more details.

State and signal sets of automata convolution

Mealy automaton state set Z describes the process of ECG parameters measurement of a patient:

$$Z = \mathrm{N}, \quad \mathrm{N} = \{0, 1, 2, \ldots\}. \tag{1}$$

Input signal of Moore subautomaton is:

$$Y' = \left\{ \begin{bmatrix} DQRS^{(1)} & DJTp^{(1)} & RR^{(1)} & \cdots & X_m^{(1)} \\ DQRS^{(2)} & DJTp^{(2)} & RR^{(2)} & \cdots & X_m^{(2)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ DQRS^{(n)} & DJTp^{(n)} & RR^{(n)} & \cdots & X_m^{(n)} \end{bmatrix}_{n \times m}^{k} \right\}, \tag{2}$$

$k = 1, 2, 3, \ldots.$

Here m denotes the number of measured parameters, n – the number of measurements of stage k. For current system $m = 3$ and $n = 1$. Matrix y' is filled with input data row by row. Each column of it contains the same type of information.

Moore automaton (subautomaton) output and Mealy automaton (subautomaton) input signal set describes instructions sent to Mealy automaton:

$$X' = X = \{0, 1\}. \tag{3}$$

Here 0 stops the work of automata convolution, 1 – continues the convolution.

Mealy automaton output signal set is as follows:

$$Y = \left\{ \begin{bmatrix} CDQRS^{(1)} & CDJTp^{(1)} & CRR^{(1)} & \cdots & CX_m^{(1)} \\ CDQRS^{(2)} & CDJTp^{(2)} & CRR^{(2)} & \cdots & CX_m^{(2)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ CDQRS^{(n)} & CDJTp^{(n)} & CRR^{(n)} & \cdots & CX_m^{(n)} \end{bmatrix}_{n \times m}^{k} \right\}, \tag{4}$$

$k = 1, 2, 3, \ldots.$

here m denotes the number of measured parameters; n – the number of estimates (applied algorithms). In our current system $m = 3$ and $n = 2$. First line of the matrix represents estimates of H-rank algorithm, the second line represents estimates of discriminant algorithm [6].

Moore automaton state set W depicts status of a patient including foretime

$$W = \begin{bmatrix} w_1^{(1)} & w_2^{(1)} & w_3^{(1)} & \cdots & w_m^{(1)} \\ w_1^{(2)} & w_2^{(2)} & w_3^{(2)} & \cdots & w_m^{(2)} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ w_1^{(n)} & w_2^{(n)} & w_3^{(n)} & \cdots & w_m^{(n)} \end{bmatrix}_{n \times m} \tag{5}$$

is a decision matrix, where m denotes the number of measured parameters and n represents evaluation states of computed estimates. In current system decision matrix is yet not conclusively formed.

Mathematical formalization of decision support system by automata convolution

In this section we supply formal mathematical description of the automata model.

Signal of output y'_n of Mealy subautomaton is a composite function of parameters of the specific ECG derivation:

$$f_l = [f_{l0}, f_{l1}, f_{l2}];$$

$$\begin{aligned} f_{l0}&: \begin{cases} DQRS_i^{der},\ i = z_i', & if \quad x_i \vee x_i = 1, \\ Inf, & else; \end{cases} \\ f_{l1}&: \begin{cases} DJTp_i^{der},\ i = z_i', & if \quad x_i \vee x_i = 1, \\ Inf, & else; \end{cases} \\ f_{l2}&: \begin{cases} RR_i^{der},\ i = z_i', & if \quad x_i \vee x_i = 1, \\ Inf, & else. \end{cases} \end{aligned} \tag{6}$$

Function, describing the state of Mealy subautomaton, shows the number of ECG cycles already obtained:

$$g_l: \quad z_{i+1} = \begin{cases} z_i + 1, & if \quad x_i \vee x_i' = 1, \\ z_i, & else. \end{cases} \tag{7}$$

It's value changes only after output signal of Mealy automaton is transmitted.

The signal of output of Moore subautomaton:

$$f_r' = [f_{r0}', f_{r1}', f_{r2}'];$$

$$\begin{aligned} f_{r0}'&: \begin{cases} 0 \wedge C(DQRS_i^{der}), & if\ comp([DQRS]_i^{der}) = 1, \\ 1, & if \quad comp([DQRS]_i^{der}) = 0; \end{cases} \\ f_{r1}'&: \begin{cases} 0 \wedge C(DJTp_i^{der}), & if\ comp([DJTp]_i^{der}) = 1, \\ 1, & if \quad comp([DQRS]_i^{der}) = 0; \end{cases} \\ f_{r2}'&: \begin{cases} 0 \wedge C(RR_i^{der}), & if\ comp([RR]_i^{der}) = 1, \\ 1, & if \quad comp([RR]_i^{der}) = 0. \end{cases} \end{aligned} \tag{8}$$

Composite function, describing the state of Moore subautomaton:

$$g_r' = [g_{r0}', g_{r1}', g_{r2}'];$$

$$\begin{aligned} g_{r0}'&: \begin{cases} [DQRS]_i^{der} = [DQRS]_{i-1}^{der} \# DQRS_i^{der}, & if\ y_i' = DQRS_i^{der}; \\ [DQRS]_i^{der} = [Inf], & if \quad y_i' = Inf, \end{cases} \\ g_{r1}'&: \begin{cases} [DJTp]_i^{der} = [DJTp]_{i-1}^{der} \# DJTp_i^{der}, & if \quad y_i' = DJTp_i^{der}; \\ [DJTp]_i^{der} = [Inf], & if \quad y_i' = Inf, \end{cases} \\ g_{r2}'&: \begin{cases} [RR]_i^{der} = [RR]_{i-1}^{der} \# RR_i^{der}, & if\ y_i' = RR_i^{der}; \\ [RR]_i^{der} = [Inf], & if \quad y_i' = Inf, \end{cases} \end{aligned} \tag{9}$$

here the symbol "#" denotes the concatenation operation; symbol *Inf* defines the empty set.

Composite function, describing the state of Moore automaton:

$$g_r = [g_{r0}, g_{r1}, g_{r2}];$$

$$\begin{aligned} g_{r0}&: \begin{cases} [C(DQRS)]_i^{der} = [C(DQRS)]_{i-1}^{der} \# DQRS_i^{der}, & if\ y_i = C(DQRS)_i^{der}; \\ [C(DQRS)]_i^{der} = [C(DQRS)]_i^{der}, & if\ y_i = Inf, \end{cases} \\ g_{r1}&: \begin{cases} [C(DJTp)]_i^{der} = [C(DJTp)]_{i-1}^{der} \# DJTp_i^{der}, & if\ y_i = C(DJTp)_i^{der}; \\ [C(DJTp)]_i^{der} = [C(DJTp)]_i^{der}, & if\ y_i = Inf, \end{cases} \\ g_{r2}&: \begin{cases} [C(RR)]_i^{der} = [C(RR)]_{i-1}^{der} \# RR_i^{der}, & if\ y_i = C(RR)_i^{der}; \\ [C(RR)]_i^{der} = [C(RR)]_i^{der}, & if\ y_i = Inf. \end{cases} \end{aligned} \tag{10}$$

The signal of output of Moore automaton:

$$f_r: \begin{cases} x_i = 1, \quad if \quad [C(DQRS)]_i^{der} \le threshold1, \\ \qquad\qquad\quad [C(DJTp)]_i^{der} \le threshold2, \\ \qquad\qquad\quad [C(RR)]_i^{der} \le threshold3, \\ x_i = 0, \quad else. \end{cases} \tag{11}$$

Results

Model functionality is simulated in MATLAB and C++ environments. In this section we will provide the work and results of Moore automaton surjection f_r. Surjection f_r forms a special complexity profile, evaluates it and supplies to the physician. Complexity profile is a synchronous real-time calculation of complexity for three ECG parameters of different fractal levels, which differ significantly in measure scale: duration of QRS complex – DQRS (300 ms), an interval from J point till the end of wave T – DJTp (100 ms) and an interval between R wave amplitudes – RR (1000 ms). RR parameter belongs to the fractal level of a patient and indicates the state of the whole organism. DJTp parameter belongs to the fractal level of a heart and describes its activity. DQRS parameter is duration of spread of arousal in a heart. It belongs to the inner fractal level of a heart.

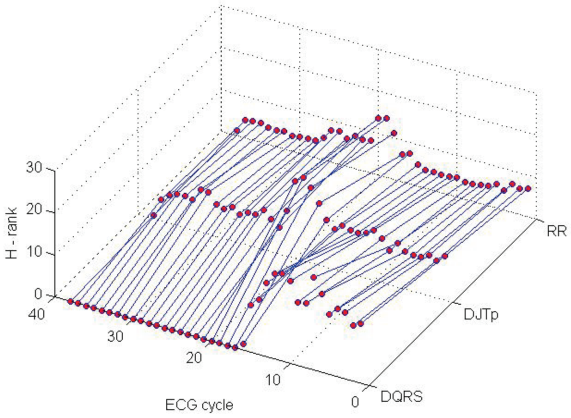

Fig. 3. Complexity profile

For instance, load level of veloergometric test, heart operation procedure or intensive physical activity influence complexity profile, which is a register of patients' status in different fractal levels. Nevertheless, H-rank and discriminant (dsk) should stay within established and depending on null-level ε physiological bounds that is to be evaluated. Software provides real-time monitoring of signal complexity and forms warning alert if H-rank or discriminant coefficient is out of their established bounds.

Complexity profile is also supplied in convenient visualization (Fig.3). In comparison with H-rank, complexity profile formed by discriminant coefficients is also provided for more accurate diagnosis, see Fig.4.

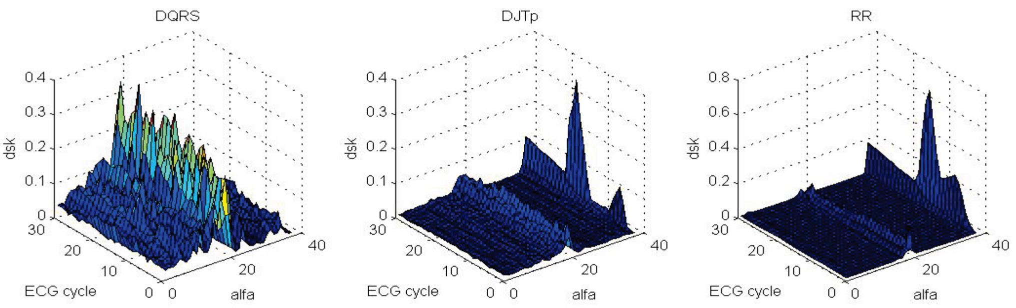

Fig. 4. Complexity profile provided by discriminant coefficient

Conclusions

In this paper an improved model of Mealy and Moore automata convolution for decision support system was proposed. Formal description of the model for real time ECG data stream observation was provided. Two ECG analysis algorithms were included to the model for complexity monitor of heart process dynamics. The results of convolution are depicted in the last section. As the proposed model is changeable, it is to be extended for more detailed analysis of various information streams.

Acknowledgements

The study was supported by Agency for International Science and Technology Development Programs in Lithuania, project ITEA2 08018 GUARANTEE.

References

1. **Kawamoto K., Houlihan C., Balas A., Lobach D.** Improving clinical practice using clinical decision support systems: a systematic review of trials to identify features critical to success // British Medical Journal (BMJ), 2005. – Vol. 330 – P.765–768.
2. **Beliakov G., Warren J.** Appropriate Choice of Aggregation Operators in Fuzzy Decision Support Systems // IEEE, 2001. – Vol. 9, no. 6 – P.773–783.
3. **Berškienė K., Lukoševičius A., Navickas Z., Vainoras A.** Modeling of long lasting functional state of healthiness dynamics // Electronics and Electrical Engineering. – Kaunas: Technologija, 2006. – No. 7(71). – P.73–76.
4. **Korsakas S., Lauznis J., Vainoras A., Markovitch Z., Gargasas L., Markovitcha I., Navickas Z., Ruseckas R.** The mobile ECG and Motion Activity Monitoring System for Home Care Patients // Computers in Cardiology, 2006. – IEEE, 2006. – P.833–836.
5. **Žvironienė A., Navickas Z., Rindzevičius R.** Telecommunication systems analysis using the convolution of Moore and Mealy automata // Electronics and Electrical Engineering. – Kaunas: Technologija, 2005. – No. 3(59). – P. 64–69.
6. **Šmidtaitė R., Navickas Z., Vainoras A., Bikulčienė L, Poškaitis V.** Evaluation of Coherence of T wave in Different Leads // Electronics and Electrical Engineering. – Kaunas: Technologija, 2009. – No. 5(93). – P.113–116.

Received 2010 02 15

A. Martusevičienė, Z. Navickas, A.Vainoras. ECG Data Analysis Using the Convolution of Mealy and Moore Automata // Electronics and Electrical Engineering. – Kaunas: Technologija, 2010. – No. 4(100). – P. 103–106.

Clinical decision support systems are interactive computer programs. Most advanced of these systems are based on mathematical models. In this paper model of convolution of Mealy and Moore automata for real time ECG data analysis is introduced. The proposed model helps to effectively organize the feedback between current patient functional state and applied influence. Mathematical formalization of the system is also provided. Ill. 4, bibl. 6 (in English; abstracts in English, Russian and Lithuanian).

А. Мартусевичиене, З. Навицкас, А. Ваинорас. Использование свертки автоматов Миля и Мура для анализа данных ЭКГ // Электроника и электротехника. – Каунас: Технология, 2010. – № 4(100). – С. 103–106.

В настоящее время нередко клинические системы принятия решений являются интерактивными компьютерными программами. Наиболее передовые из этих систем построены как правило на основе математических моделей. В этой работе для анализа данных ЭКГ реального времени применяется в качестве математического моделя свертика автоматов Миля и Мура. Предложенная модель позволяет эффективно организовать обратную связь между текущего функционального состояния пациента и прикладного влияния на этого пациента. Также предлагается математическая формализация системы. Ил. 4, библ. 6 (на английском языке; рефераты на английском, русском и литовском яз.).

A. Martusevičienė, Z. Navickas, A. Vainoras. EKG duomenų analizė naudojant Milio ir Muro automatų sąsūką // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 4(100). – P. 103–106.

Klinikinių sprendimų priėmimo sistemos sistemos yra interaktyvios kompiuterinės programos. Moderniausios sistemos yra grindžiamos matematiniais modeliais. Šiame straipsnyje pasiūlytas Milio ir Muro automatų sąsūkos modelis realaus laiko EKG signalo duomenų analizei atlikti. Kadangi pasiūlytasis modelis yra adaptyvus, jis gali būti taikomas platesnei klinikinės informacijos srautų analizei. Modelis taip pat padeda efektyviai organizuoti grįžtamąjį ryšį tarp esamos paciento funkcinės būklės ir jam taikomo poveikio. Taip pat yra pateikta matematinė sistemos formalizacija. Il. 4, bibl. 6 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).