Acta Technica *62* (2017), No. 7A, 1573–1584

Fatigue cracking estimation model of asphalt pavement based on fractal method

Bo Yang[1]

Abstract. In order to improve accuracy of fatigue cracking estimation model of asphalt pavement, this paper proposes a kind of fatigue cracking estimation model of asphalt pavement based on fractal method. Firstly, AI method is adopted in this paper to construct basic form of asphalt pavement fatigue cracking model to effectively predict pavement cracking. Secondly, based on fractional Brownian random field, a kind of new asphalt pavement fatigue cracking estimation feature measurement is proposed through fractal parameters design, and adaptive threshold is calculated according to fractal features of edge to improve estimation accuracy. Finally, the effectiveness of algorithm is verified through simulation experiment.

Key words. Fractal method, Asphalt pavement, Fatigue cracking, Estimation model

.

1. Introduction

Working environment of asphalt pavement structure mainly includes traffic load environment and natural environment. In recent years, road traffic load and traffic flow have increased day by day, and traffic load environment is characterized by large traffic volume and heavy axle load. The effect of natural environment on road structure is that road structure parameters change with humidity and temperature change. Under combined action of load environment and natural environment, asphalt pavement usability has been damped sharply, and its service life has been reduced substantially, which seriously affects use function and service quality of road structure, and fatigue cracking has become one of main diseases of asphalt pavement.

At present, researchers from each country have conducted related research on effect of environment on asphalt pavement fatigue life and asphalt mixture fatigue performance. In literature [3], the effect of overload on asphalt pavement service

---

[1] Liuzhou Railway Vocational Technical College, College of building technology, Liuzhou, Guanxi, 545616

life was researched when taking flexural-tensile stress of asphalt layer and semi-rigid base bottom as design index; in literature [4], the influence coefficient (function) of natural environmental factors of asphalt pavement field fatigue equation was suggested, which provided possibility when effect of different natural environment areas was considered in pavement fatigue analysis, but the shortcoming of the research lied in that environment coefficient of Beijing was assumed as 1, and calculation was made based on it, which made the calculation result have relatively strong regional limitation; literature [5] adopted theoretical analysis and field measurement method to research effect of load environment on asphalt pavement service life, but the research adopted flexible base pavement structure as research object, which greatly differed with semi-rigid base asphalt pavement structure widely adopted in highway of China at current stage. Chinese scholars have developed a great deal of research on asphalt mixture fatigue performance, but because fatigue test is made by adopting indoor small material test piece, its test environment and condition are not in accord with actual road condition, which causes great difference between indoor fatigue life result and fatigue life of road during actual operation period.

Referring to research experience of each country, this paper analyzes effect of environmental factor on asphalt pavement fatigue life, constructs fatigue cracking estimation model of asphalt pavement considering environmental factor, and makes verification by combining with project case, which provides theoretical basis to reasonably evaluate asphalt pavement structure service life and improve asphalt pavement management level.

2. Establishment of fatigue cracking estimation model

2.1. Fatigue cracking criterion

Base section disease mainly includes track, pit slot and transverse crack, most cracks are poured promptly, and few pit slot and longitudinal crack exist in individual section. According to survey to maintenance department and maintenance record, pavement patching is mainly aimed at pit slot. Pit slot of Shanghai-Nanjing Expressway is maintained and repaired quite promptly, and pit slot disease is generally repaired at the next day, so the Expressway has good surface repair condition, which is specifically as shown in Fig.1.

To effectively predict pavement cracking, this paper adopts AI method fatigue model recommended in NCHRP 1-37A as basic form of fatigue cracking, which is as shown in formula (1).

$$N = 18.4 \times 10^{4.84\left(\frac{V_b}{V_b+V_a}-0.69\right)} \times 0.00432 \left(\frac{1}{\varepsilon_t}\right)^{3.291} \left(\frac{\beta}{E}\right)^{0.854} . \tag{1}$$

Where, N is the number of times of load action under fatigue rupture; ε_t is tensile strain value of asphalt layer bottom; E is dynamic resilient modulus of asphalt material; β is coefficient predicate = 0.006 89476; V_a is asphalt mixture voidage; V_b is effective asphalt volume fraction. On the one hand, because Chinese current

Fig. 1. Pavement cracking

asphalt pavement design specification specifies that static resilient modulus shall be adopted as pavement design parameters, and on the other hand, test method and standard for dynamic resilient modulus of asphalt mixture have not been introduced in China yet, so in consideration of above reasons, this paper adopts static resilient modulus as parameters in fatigue cracking criterion, and mean value ratio of dynamic and static resilient modulus is 3.14, asphalt mixture voidage is assumed as 5% and effective asphalt volume fraction is 11%. Substitute above parameter values into formula (1), to obtain fatigue cracking criterion determined in this paper, which is as shown in formula (2):

$$N = 0.0004272 \left(\frac{1}{\varepsilon_t}\right)^{3.291} \left(\frac{\beta}{E'}\right)^{0.854} . \tag{2}$$

Where, E' is dynamic resilient modulus of asphalt material.

2.2. Estimation model form

Because flexural-tensile strain of asphalt layer bottom is adopted as key parameter of asphalt pavement fatigue cracking, any factor affecting flexural-tensile strain of asphalt layer bottom will affect asphalt pavement fatigue performance. This paper adopts asphalt layer condition parameter, base condition parameter, subgrade condition parameter, and load matrix parameter as core estimation variables of fatigue cracking estimation model of asphalt pavement considering environmental factor, and then fatigue cracking estimation model is:

$$N_f = f\left(F_1, F_2, F_3, N\left(L\right)\right) . \tag{3}$$

In the formula, N_f is fatigue cracking estimation model considering environmental factor; F_1 is asphalt layer condition parameter, related to asphalt layer modulus; F_2 is base condition parameter, related to base modulus; F_3 is subgrade condition parameter, related to subgrade modulus; $N\left(L\right)$ is load matrix parameter, related to load L.

According to mechanical response calculation result of asphalt pavement structure, axle load increase and asphalt layer modulus increase will cause increase of strain level of asphalt layer bottom, thus lowering asphalt pavement fatigue life, which shows that asphalt pavement fatigue life has negative correlation with axle load and asphalt layer modulus. With the increase of base modulus and subgrade modulus, flexural-tensile strain of asphalt layer bottom will be lowered, to improve asphalt pavement fatigue life, which shows that asphalt pavement fatigue life has positive correlation with base modulus and subgrade modulus. Fatigue performance estimation model constructed in this paper shall meet constraint condition listed in formula (4), i.e.

$$\frac{\partial N_f}{\partial E_{AC}} < 0, \frac{\partial N_f}{\partial E_B} > 0, \frac{\partial N_f}{\partial E_R} > 0, \frac{\partial N_f}{\partial L} < 0\,. \tag{4}$$

3. Fractional Brownian random field and fractal feature extraction of asphalt pavement fatigue cracking estimation

3.1. Fractional Brownian random field

Mandelbrot firstly proposed to describe a kind of random process phenomenon having statistics self-similarity through fractional Brownian motion, and use fractional Brownian motion to describe random field of spatial distribution to obtain fractional Brownian random field (FBRF) [20]. Related concepts are simply described as follows:

Definition 1 Assumed that H meets $0 < H < 1$, and $b0$ is any real number, if random function meets:

$$\begin{aligned} B_H(0,\omega) =& b_0\,, \\ B_H(t,\omega) =& [1/\tilde{A}(H+0.5)]\{\int_{-\infty}^{0} [(t-s)^{H-0.5} - (-s)^{H-0.5}]dB(s,\omega) \\ &+ \int_0^t (t-s)^{H-0.5} dB(s,\omega)\}\,. \end{aligned}$$

Then $BH(t)$ is called as fractional Brownian motion (FBM), where H is Hurst index, $b0$ is initial value, ω is sample space Ω, and it is general Brownian motion when $H = 1/2$.

Definition 2 Assumed that $BH(t)$ is a Gaussian random field, and for $0< H <1$, if any t and Δt meet:

$$\Pr((B_H(t+\Delta t) - B_H(t))/\left\|\Delta t\right\|^H < y) = F(y)\,. \tag{5}$$

Then $BH(t)$ is called as isotropous FBRF, where $F(y)$ is distribution function of zero-mean Gaussian random variable, $Pr(\cdot)$ is probability measure and $||\cdot||$ represents norm. Fractional Brownian random field $BH(t)$ has following properties:

$$\begin{aligned} &E\left|B_H(t+\Delta t) - B_H(t)\right| = E\left|B_H(t+1) - B_H(t)\right| \left\|\Delta t\right\|^H\,, \\ &E\left|B_H(t+\Delta t) - B_H(t)\right|^2 = E\left|B_H(t+1) - B_H(t)\right|^2 \left\|\Delta t\right\|^{2H}\,. \end{aligned} \tag{6}$$

According to above properties, first-order and second-order absolute moment of FBRF increment are isotropous. According to formula (5) and (6), Hurst index decides a fractional Brownian motion, and fractal dimension of asphalt pavement fatigue cracking surface can be obtained as follows according to Hurst index:

$$D = D_T + 1 - H\,. \tag{7}$$

In the formula, D_T is topology dimension of asphalt pavement fatigue cracking surface. Dimension is an important characteristic quantity of geometric object, being amount of independent coordinate required by position of a point in geometric object. Dimension can be fraction in fractal theory, and we can describe and measure fractal characteristic through fractal dimension. In reality, Richardson law is generally used to estimate fractal dimension:

$$A(\varepsilon) = K\varepsilon^{d-D}\,. \tag{8}$$

In the formula, $\varepsilon = 1, 2, 3\ldots$ is scale factor, $A(\varepsilon)$ is measured characteristic value under dimension ε, D is fractal dimension, d is topology dimension and K is fractal coefficient. For ideal uniform asphalt pavement fatigue cracking of 2-dimensional gray level, $A(\varepsilon)$ is superficial area measure of asphalt pavement fatigue cracking, and topology dimension is 2, and then:

$$A(\varepsilon) = K\varepsilon^{2-D} \tag{9}$$

People pay much attention to fractal dimension, and point out that fractal dimension is a kind of measurement on irregularity degree of asphalt pavement fatigue cracking surface, and reflects roughness of asphalt pavement fatigue cracking gray surface. But because fractal dimension cannot be calculated easily in direct mode, another fractal dimension will be discussed based on above existing formula to obtain new fractal feature.

3.2. Fractal feature extraction of asphalt pavement fatigue cracking estimation

Consider coefficient K in formula (3-5). For an ideal flat fractal surface, its fractal dimension D is 2, and coefficient K is superficial area of gray surface. Give an ideal fractal surface, K is a constant, and if asphalt pavement fatigue cracking consists of surfaces with different texture, or if non-fractal object is implanted to fractal surface, such as manmade object existing in natural scene, K will not be a constant again, but function of dimension ε, which reflects change of surface area under dimension change; take different dimensions, and according to formula (3-5):

$$K = [A(\varepsilon_1) - A(\varepsilon_2)]/(\varepsilon_1^{2-D} - \varepsilon_2^{2-D})\,. \tag{10}$$

In the formula, $\varepsilon 1$ and$\varepsilon 2$ are different dimensions, which shows that value K reflects spatial change rate of superficial area of asphalt pavement fatigue cracking with dimension change. Take the logarithm of both ends of formula (3-5), followings can be obtained:

$$\log A(\varepsilon) = (2 - D)\log \varepsilon + \log K\,. \tag{11}$$

Formula (11) represents a straight line under log$A(\varepsilon)$—logε coordinate system, log$K$ is intercept of the straight line in y-axis log$A(\varepsilon)$, and K is equal to gray surface area under the dimension. It can be seen that coefficient K actually is a fractal parameter similar to area, called as area measurement. For smooth surface, area measurement is relatively small, and fluctuant surface has relatively great area measurement. Therefore, similar to fractal dimension, area measurement reflects roughness of asphalt pavement fatigue cracking surface, i.e. "fluctuating quantity" of asphalt pavement fatigue cracking gray surface. Experiment shows that area measurement can embody characteristics of different surfaces better in many aspects. For 2-dimensional digital asphalt pavement fatigue cracking, fractal dimension $2< D <3$, and value range of area measurement K is positive real number, so it has better distinction degree to surfaces with different properties.

The rougher the asphalt pavement fatigue cracking gray surface is, the stronger the gray change will be, and the greater the area measurement will be. What is noteworthy is that at junction of different smooth surfaces, as previously mentioned, i.e. between gray surfaces with different textures, relative to asphalt pavement fatigue cracking of any kind of texture, gray fluctuation is more obvious, area measurement is larger correspondingly, and these texture junctions are the places where boundary of asphalt pavement fatigue cracking is located, so area measurement can be used to detect edge. As a kind of estimated feature of asphalt pavement fatigue cracking, area measurement is called as estimated fractal feature of asphalt pavement fatigue cracking by us. To calculate estimated fractal feature of asphalt pavement fatigue cracking, "asphalt pavement covering method" is adopted to estimate gray superficial area measure $A(\varepsilon)$ of asphalt pavement fatigue cracking. Pixel gray value of asphalt pavement fatigue cracking constitutes a digital texture surface in depth direction of 2-dimensional asphalt pavement fatigue cracking space, and $A(\varepsilon)$ is the surface area under dimension ε. Considering all pixel points being ε away from surface, it is obvious that points above gray surface constitute a upper surface $U(i,j,\varepsilon)$, while points below it constitute a lower surface $B(i, j, \varepsilon)$. In this way, gray surface is seemingly covered by a "asphalt pavement" with thickness of 2ε. Upper and lower surfaces of asphalt pavement are defined as follows:

$$\begin{aligned} &U(i,j,0) = B(i,j,0) = f(i,j) \\ &U(i,j,\varepsilon) = \max\{U(i,j,\varepsilon-1)+1, \max_{(m,n)\in\alpha}[U(m,n,\varepsilon-1)]\} \\ &B(i,j,\varepsilon) = \min\{B(i,j,\varepsilon-1)-1, \min_{(m,n)\in\alpha}[U(m,n,\varepsilon-1)]\} \end{aligned} \tag{12}$$

In the formula, $f(i,j)$ ($i = 0,1,2\ldots X$; $j = 0,1,2\ldots Y$) is gray function of asphalt pavement fatigue cracking, X is line number of asphalt pavement fatigue cracking, and Y is column number of asphalt pavement fatigue cracking. $\alpha = \{(m,n)/DISTANCE[(m,n),(i,j)] \le d\}$, and when $d = 1$, it represents 4-neighborhood; when $d = 2$, it represents 8-neighborhood. Therefore, volume of asphalt pavement is $V(i,j,\varepsilon)=\sum_{(i,j)\in R}[U(i,j,\varepsilon)-B(i,j,\varepsilon)]$, where R is a valuing rectangular region centering around (i,j) in asphalt pavement fatigue cracking, so gray surface area is:

$$A(i,j,\varepsilon)=V(i,j,\varepsilon)/2\varepsilon\,. \tag{13}$$

Calculate $A(i,j,\varepsilon)$ under different dimensions, utilize dot pair [log $A(i,j,\varepsilon)$, logε], and fit straight line represented by formula (3-7) through least square method, to obtain estimated fractal feature K of asphalt pavement fatigue cracking of point (i,j). Calculate estimated fractal feature K of asphalt pavement fatigue cracking of each point of asphalt pavement fatigue cracking for original asphalt pavement fatigue cracking in figure 3-2(a), to obtain featured asphalt pavement fatigue cracking of K, and its 3-dimensional expression is as shown in figure 3-2(d). It can be seen that value of estimated fractal feature of asphalt pavement fatigue cracking at asphalt pavement fatigue cracking edge is obviously greater than value of non-edge position.

3.3. Computer simulation realization

Computer simulation steps are as follows:

(1) For a pair of $N\times N$asphalt pavement fatigue cracking, following line-by-line and column-by-column scanning sequence, and taking rectangular window $R(M\times M)$ as disposal area, we calculate estimated fractal feature $K(i,\,j)$ of asphalt pavement fatigue cracking of central pixel of rectangular window, so as to obtain asphalt pavement fatigue cracking of estimated fractal feature of asphalt pavement fatigue cracking;

(2) Calculate adaptive threshold T, make binarization processing to asphalt pavement fatigue cracking, and detect edge. There are several noteworthy problems in above algorithm:

① Ideal fractal picture has scale invariance, and fractal parameters meet self-similarity in all dimensions. But in reality, there is no true fractal; asphalt pavement fatigue cracking only presents fractal self-similarity in a small-dimension scope, so in the process of calculating estimated fractal feature of asphalt pavement fatigue cracking, dimension ε is valued as $1\leq\varepsilon\leq 9$;

② Dimension of local disposal area R is closely concerned with accuracy and speed of asphalt pavement fatigue cracking estimation. The larger the area selected is, the lower the detection edge accuracy will be, and the lower the speed will be. Therefore, in algorithm realization process, relatively small local disposal area shall be selected. For different asphalt pavement fatigue cracking, value range of estimated fractal feature of asphalt pavement fatigue cracking is different, so when binarization processing is made to asphalt pavement fatigue cracking to extract edge, fixed threshold cannot be adopted, and this paper adopts following formula to calculate required threshold:

$$T=\min K(i,j)+a*[\max K(i,j)-\min K(i,j)]\,. \tag{14}$$

Where, a is constant, $0<a<1$, and generally speaking, relatively ideal effect can be achieved when value of a is between 0.75 and 0.85. For more accurate threshold, numerous asphalt pavement fatigue cracking obtained with different thresholds shall be compared visually to select the one with the best effect.

4. Experimental analysis

This paper selects pavement fatigue cracking of Suzhou Section and Wuxi Section of Shanghai-Nanjing Expressway to make evaluation analysis, and adopts repeated loading permanent deformation test (flow number) to evaluate related performance of current Shanghai-Nanjing Expressway pavement asphalt mixture. 69kpa confining pressure, 1200KPa axial pressure and 55°C test temperature are adopted in test. Summary result on FN test of track section and non-track section is as shown in following Table 1 and Fig.2-3. It is clear that value of Flow Number obtained by section having track is lower than the value obtained by non-track section, which describes applicability of adopting repeated loading permanent deformation test to evaluate capability of pavement core sample to resist track in a certain degree.

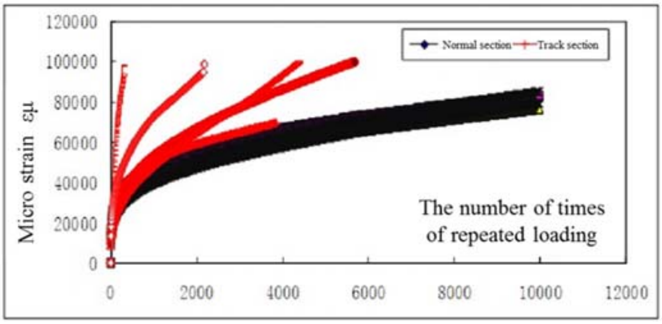

Fig. 2. Summary figure on repeated loading permanent deformation test result of suzhou section

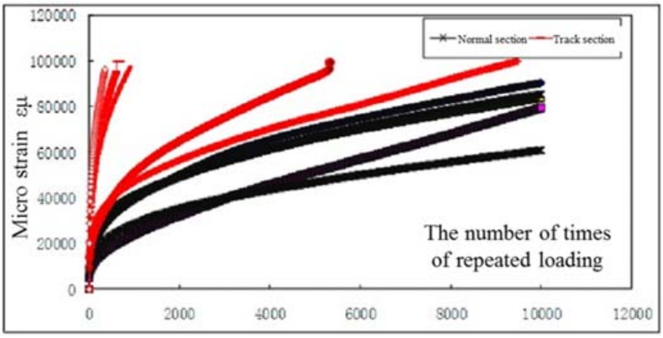

Fig. 3. Summary figure on repeated loading permanent deformation test result of wuxi section

Table 1. Repeated loading permanent deformation test result

Section	Does it be track section?	FN value/ the number of times	Average	Remarks
Wuxi Section	Yes	7362	5364	Individual track section has large test piece deformation, the number of times on deformation of data flow cannot be read by program, and its test result is summarized jointly, which is as shown in figure.
	Yes	3349		
	Yes	5381		
	No	9464	9438	
	No	9653		
	No	9198		
Suzhou Section	Yes	9964	7764	
	Yes	3412		
	Yes	9916		
	No	6640	8770	
	No	9976		
	No	9694		

According to the figure, when the number of times of repeated loading action is lower than or equal to 6000, track deformation of different degree will appear in pavement. Therefore, it is suggested that F_n of repeated loading permanent deformation test can be set to be greater than or equal to 6000 preliminarily as auxiliary verification index to evaluate high-temperature performance of asphalt mixture.

Fig.4-5 gives deflection response of pavement structure 1 and 2 under 0.7MPa, 0.84MPa and 1.0MPa load effect respectively. The figure gives deflection value calculated according to the 20°C of compressive resilient modulus. It can be seen that with the increase of load, pavement deflection will increase greatly. Dynamic modulus calculation result shows that pavement deflection presents periodical change with time. Under different load effect, deflection at 6 or 7 o'clock in the morning is relatively small, but deflection at 3 or 4 o'clock in the afternoon is relatively great. Deflection response of pavement structure 1 and 2 is relatively close.

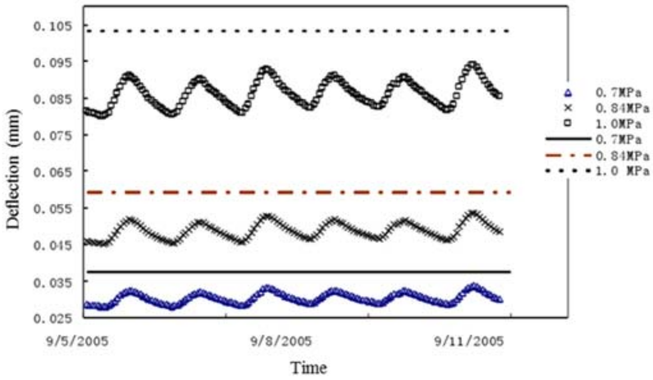

Fig. 4. Pavement deflection of structure 1

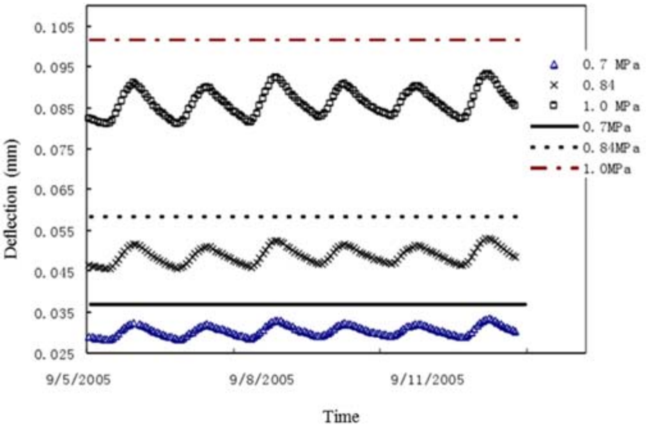

Fig. 5. Pavement deflection of structure 2

5. Conclusion

This paper proposes a kind of fatigue cracking estimation model of asphalt pavement based on fractal method, presents the new asphalt pavement fatigue cracking estimation feature measurement through fractal parameters design adopting AI method to construct basic form of asphalt pavement fatigue cracking model, based on fractional Brownian random field, and calculates adaptive threshold according to fractal features of edge to improve estimation accuracy. Finally, the effectiveness of algorithm is analyzed and verified through experiment in evaluation to pavement fatigue cracking of Suzhou Section and Wuxi Section of Shanghai-Nanjing Expressway.

References

[1] N. Arunkumar, K. K. Ram, V. Venkataraman: *Automatic detection of epileptic seizures using permutation entropy, Tsallis entropy and Kolmogorov complexity.* Journal of Medical Imaging and Health Informatics *6* (2016), No. 2, 526–531.

[2] Y. Y. Zhang, A.,Algburi, N. Wang, V. Kholodovych, D. O. Oh, M. Chikindas, and K. E.. Uhrich: *Self-assembled Cationic Amphiphiles as Antimicrobial Peptides Mimics: Role of Hydrophobicity, Linkage Type, and Assembly State*, Nanomedicine: Nanotechnology, Biology and Medicine *13* (2017), No. 2, 343–352.

[3] X. Du, S. Zhen, Z. Peng, C. Zhao ,Y. Zhang ,W. Zhe, X. Li, G. Liu, X. Li: *Acetoacetate induces hepatocytes apoptosis by the ROS-mediated MAPKs pathway in ketotic cows.* Journal of Cellular Physiology (2017) No./,232, 3296–3308.

[4] Y. Y. Zhang, Q. Li, W. J. Welsh, P. V. Moghe, and K. E. Uhrich: (2016) *Micellar and Structural Stability of Nanoscale Amphiphilic Polymers: Implications for Anti-atherosclerotic Bioactivity*, Biomaterials, 84, 230-240.

[5] L. R. Stephygraph, N. Arunkumar, V. Venkatraman: *Wireless mobile robot control through human machine interface using brain signals*, 2015 International Conference on Smart Technologies and Management for Computing, Communication, Con-

trols, Energy and Materials, ICSTM 2015 - Proceedings, art. no. 7225484 (2015), 596–603.

[6] Z. Lv, A. Halawani, S. Feng, H. Li, &S. U. Réhman:*Multimodal hand and foot gesture interaction for handheld devices.* ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM) *11* (2014), No. 1s, 10.

[7] Y. Z. Chen, F. J. Tang, Y. Bao, Y. Tang, G. Chen:*A Fe-C coated long period fiber grating sensor for corrosion induced mass loss measurement.* Optics letters *41* (2016), 2306–2309.

[8] N. Arunkumar, S. Jayalalitha, S. Dinesh, A. Venugopal, D. Sekar:*Sample entropy based ayurvedic pulse diagnosis for diabetics.* IEEE-International Conference on Advances in Engineering, Science and Management, ICAESM-2012, art. no. 6215973 (2012) , 61–62.

[9] Y. Song, N. Li, J. Gu, S. Fu, Z. Peng, C. Zhao, Y. Zhang, X. Li, Z. Wang, X. Li: *β-Hydroxybutyrate induces bovine hepatocyte apoptosis via an ROS-p38 signaling pathway.* Journal of Dairy Science *99* (2016), No. 11, 9184–9198.

[10] N. Arunkumar, K. K. Ram, V. Venkataraman: *Automatic detection of epileptic seizures using permutation entropy, Tsallis entropy and Kolmogorov complexity.* Journal of Medical Imaging and Health Informatics *6* (2016), No. 2, 526–531.

[11] R. Hamza, K. Muhammad, N. Arunkumar, G. R. González: *Hash based Encryption for Keyframes of Diagnostic Hysteroscopy*, IEEE Access, https://doi.org/10.1109/ACCESS.2017.2762405 (2017).

[12] J. W. Chan, Y. Y. Zhang, and K. E. Uhrich: *Amphiphilic Macromolecule Self-Assembled Monolayers Suppress Smooth Muscle Cell Proliferation*, Bioconjugate Chemistry *26* (2015), No. 7, 1359–1369.

Received May 7, 2017