

Systematic test on the effectiveness of MEMS nano-sensing technology in monitoring heart rate of Wushu exercise

Shuo Guan*

Wushu and dance department, Shenyang sport university, Shenyang 110102, Liaoning, China

(Received September 17, 2022, Revised November 20, 2022, Accepted November 22, 2022)

Abstract. Exercise is beneficial to the body in some ways. It is vital for people who have heart problems to perform exercise according to their condition. This paper describes how an Android platform can provide early warnings of fatigue during wushu exercise using Photoplethysmography (PPG) signals. Using the data from a micro-electro-mechanical system (MEMS) gyroscope to detect heart rate, this study contributes an algorithm to determine a user's fatigue during wushu exercise. It sends vibration messages to the user's smartphone device when the heart rate exceeds the limit or is too fast during exercise. The heart rate monitoring system in the app records heart rate data in real-time while exercising. A simple pulse sensor and Android app can be used to monitor heart rate. This plug-in sensor measures heart rate based on photoplethysmography (PPG) signals during exercise. Pulse sensors can be easily inserted into the fingertip of the user. An embedded microcontroller detects the heart rate by connecting a pulse sensor transmitted via Bluetooth to the smartphone. In order to measure the impact of physical activity on heart rate, Wushu System tests are conducted using various factors, such as age, exercise speed, and duration. During testing, the Android app was found to detect heart rate with an accuracy of 95.3% and to warn the user when their heart rate rises to an abnormal level.

Keywords: heart rate monitoring; MEMS; photoplethysmography; PPG; Wushu exercise

1. Introduction

Integrated devices and systems comprised of mechanical and electrical elements are called micro-electromechanical systems (MEMS) (Hamidi *et al.* 2015, Allahkarami *et al.* 2017, Ehyaei *et al.* 2017, Akbas 2018a, b, Arefi and Zenkour 2018, Aydogdu *et al.* 2018, Bensaid *et al.* 2018, Navi *et al.* 2019, Ebrahimi *et al.* 2020, Gafour *et al.* 2020, Matouk *et al.* 2020). Microelectromechanical systems are used in the integrated circuit industry to develop miniature sensors and actuators (Ashraf *et al.* 2011). Batch processing of integrated circuits (ICs) allows them to be made in sizes ranging from a few micrometers to a few millimeters (Walsh 2004). They were initially used for electrical and mechanical systems, but today they are also used for magnetic, optical, biological, and fluidic systems (Koester *et al.* 1996). As the name implies, MEMS can be described as objects that move or can deform, which originates in the United States (Aditya Khatokar *et al.* 2021). Microsystems technology (MST) or microstructures technology (MST) are used to describe this technology in Europe. Micromachining is the process of making these devices (Guisbiers and Wautelet 2007). If MEMS are involved in mechanisms and motion, they are called micromachines in Japan and Asia (Ma *et al.* 2021, Zhao *et al.* 2021, Zheng *et al.* 2021). With the invention of the silicon micromachined disposable blood pressure sensors in the early 1970s, MEMS devices entered the medical field for the first time (Benson *et al.*

1993). As a result, MEMS devices currently hold a dominant position in this market and rapidly extend into other areas of medicine (Zhang *et al.* 2016). A compound growth rate of 11.4% is seen for medical applications of MEMS devices over the next decade (Hernandez and Cretu 2018). Because nanomaterials have good properties, such as high aspect ratios, large surface areas, and nano-size effects, they are being extensively studied as semiconductor sensors (Sun *et al.* 2018). Due to their small size, low power consumption, and ease of integration, MEMS-based semiconductor sensors are becoming increasingly popular for environmental monitoring and Internet of Things applications (Galli *et al.* 2022). Sensing materials become more difficult to construct on micro-sensors as the sensor size shrinks to the micro-/sub micro level, especially for micro-scale MEMS sensors (Rico-González *et al.* 2020). As long-term use of micro-sensors is crucial, paying attention to the uniformity and stability of the constructed sensing materials is also essential (Seshadri *et al.* 2019). Technology has enabled the evolution of fields such as disease prevention and patient health maintenance monitoring systems (Kaisti *et al.* 2019). Human cardiovascular health is directly related to heart rate, a significant health parameter (Algamili *et al.* 2021). In addition to physical workload, physiological factors, work stress, and concentration, other variables affect heart rate. In order to monitor athletes' cardiac activity, new methods are needed because of the disadvantages of cardiac monitoring systems (Angermann *et al.* 2018). Commercially available sensors can be used to create a heart monitoring system due to advances in microelectromechanical systems (MEMS) (Lv and Kumar 2020, Xu *et al.* 2022, Liu *et al.* 2023a, b). Exercise is essential for the body's health and well-being,

*Corresponding author, Ph.D.,
E-mail: systkd@163.com

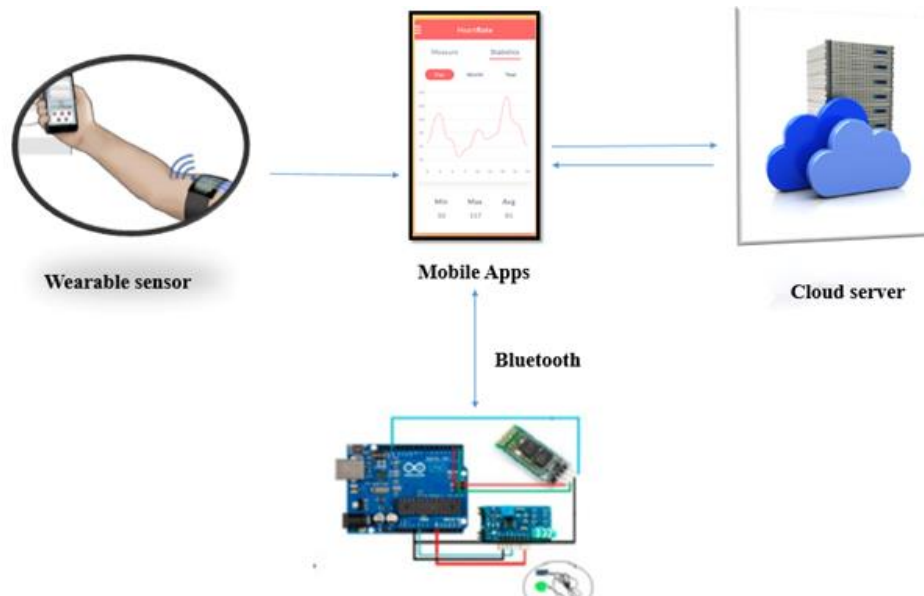


Fig. 1 Design of the system

including the heart (Chen *et al.* 2021, Esparham *et al.* 2021, Raj *et al.* 2021, Shahram Ghaedi Faramoushjan Hossein Jalalifar 2021, Cai *et al.* 2021, Maheswaran *et al.* 2022, Shariq *et al.* 2022). The exercises should be coordinated with heart health care for individuals with heart problems (Hensen 2017, Hu *et al.* 2022). Monitoring heart rate during exercise can reduce the risk of a heart attack, which can be fatal (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016a, b, c, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017). Wearable sensor technology makes heart rate monitoring portable and real-time when doing daily activities, including wushu exercise (Feng *et al.* 2017, Vega-Martinez *et al.* 2018). A continuous monitoring tool for heart rate during wushu exercise is needed because manual methods cannot be used to calculate heart rate during exercise (Alsultan Abdulmajeed 2021, Dai *et al.* 2021, Alimoradlu and Zamani 2022, Behdinin and Moradi-Dastjerdi 2022, Thakur *et al.* 2022, Zhao *et al.* 2022). Due to the number of muscles involved and the energy needed, Wushu exercises require much more oxygen (Ha *et al.* 2013). The lungs need to work hard in Wushu exercises to process oxygen and for the heart to beat rapidly to pump blood throughout the body and carry oxygen to the tissues (Ehyaei *et al.* 2017, Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017, Shafiei and Kazemi 2017, Shafiei *et al.* 2017). The heart and lungs cannot suddenly slow down as it still needs oxygen after exercising (Khan *et al.* 2021). During Wushu exercise, the blood vessels experience pressure that causes the heart rate to differ from that at rest, resulting in an abnormal heart rate (Chooruang and Mangkalakeeree 2016). Wushu increases the heart rate according to the level of activity performed, while at rest, it is between 60-100 BPM (beats per minute) (Atmane Hassen *et al.* 2015, Attia *et al.* 2015, Bennai *et al.* 2015, Chaht Fouzia *et al.* 2015, Kar Vishesh and Panda Subrata 2015, Houari Mohammed Sid *et al.* 2016, Bellifa *et al.* 2017, Avcar 2019, Zarga *et al.* 2019). It is necessary to control the heart rate during wushu exercise because there is a limit to the heart rate (Gomez- Clapers and Casanella

2012, Haroun *et al.* 2021). In some studies, heart rate has been measured during physical activity. However, these studies have not yet explored fatigue as a warning sign (Jiménez Morgan and Molina Mora 2017). With the help of photoplethysmography signals, this study will develop an early warning system for predicting fatigue in sports activities in real-time (Chattopadhyay and Chowdhury 2017). With each heartbeat, blood is circulated throughout the body, changing the amount of blood inside the finger arteries (Nguyen *et al.* 2020). A user can easily insert a pulse sensor into his or her fingertip. An embedded microcontroller uses a pulse sensor connected to a smartphone via Bluetooth to detect the heart rate (Yuvaraj *et al.* 2021). The report recommends the use of accelerometers and PPG signals. This system controls the heart rate during exercise (Patel 2018). Apps for Android smartphones warn users to reduce physical activity if their heart rate is abnormal (Bassiachvili *et al.* 2008).

2. Materials and methods

The research design for this project is based on experimental research methods. In this experiment, Wushu sports are the subject matter. The development process of a system involves four steps: 1) an analysis of system requirements, 2) the design of system models, 3) a design of a sensor device for detecting heartbeats, and 4) the design of the test (Liu *et al.* 2022, Dang *et al.* 2023, Hu *et al.* 2023, Yang *et al.* 2023).

2.1 An analysis of system requirements

As part of the overall system development process, the system needs analysis to ensure that the system requirements are met. A system's functional needs are derived from this process (Shafiei and She 2018, Shafiei *et al.* 2019, Shafiei *et al.* 2020). As part of the functionality of this system,

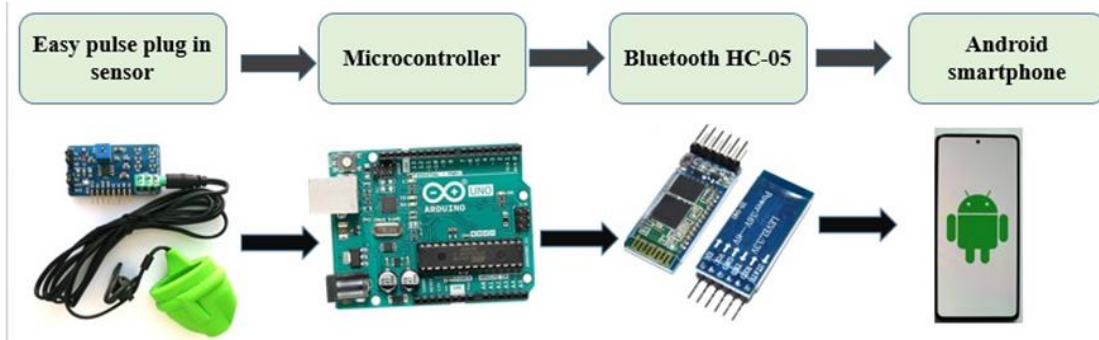


Fig. 2 Block diagram design of the wearable device

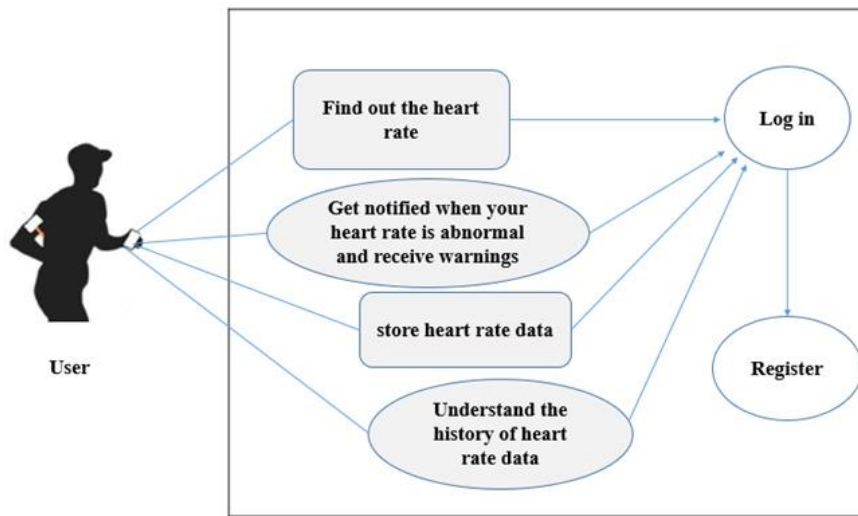


Fig. 3 Use a case diagram

users will be able to find out the number of heartbeats while exercising, receive alerts and notifications if their heart rate is abnormal, save their heart rate data, and view their heart rate history. Fig. 1 illustrates the use case diagram for the system.

2.2 The design of system models

By designing the system model, one can get a general idea about what will be built (Omidi *et al.* 2013, Mousavi *et al.* 2017). There are two parts to this system, an initial wearable device sensor is placed on the fingertips of the user as part of this system. Second, a smartphone displays the user's heart rate and calculates the level of fatigue. Fig. 2 illustrates the general design of the system used in this research. Users will receive alerts and notifications in case of an abnormal heart rate. Additionally, the heart rate activity history during a run can be retrieved from a web server by sending the data displayed on the screen.

2.3 A design of a sensor device for detecting heartbeats

It detects heart rate using a PPG signal generated by an easy pulse plug-in sensor. Health information is provided by this sensor, which rests at the user's fingertips. An Arduino

microcontroller, sensors, easy pulse plug-in, Bluetooth, and power supply are in a separate box on the user's arm (Hou *et al.* 2021, Huang *et al.* 2021, Xu *et al.* 2021, Wang *et al.* 2022). The Arduino UNO is a microcontroller that converts digital signals obtained from analog signals. Using Bluetooth technology, the smartphone application displays the heart rate data based on the signal received. See Fig. 3 for the design of the wearable device.

2.4 The design of the test

A total of ten subjects are used in this experiment, six men and four women between the ages of 20 and 30. This research study focusing on adults, not professional athletes, uses this age range. Among the ten subjects, each user ran five runs. An experiment was conducted using heart rate data. During the Wushu exercise, the subject's heart rate was measured at rest and during exercise. The speed at which the subject performs exercises may vary depending on the subject's desire, so the exercises should not be conducted at a constant speed. The purpose of this speed is to facilitate the retrieval of information for the subject since exercising at the given speed would be difficult (Tang *et al.* 2021, Xiao *et al.* 2022, Luo *et al.* 2023). Due to this, each user's ability and age can be determined by the speed of the exercises. During runtime, a warning message can be

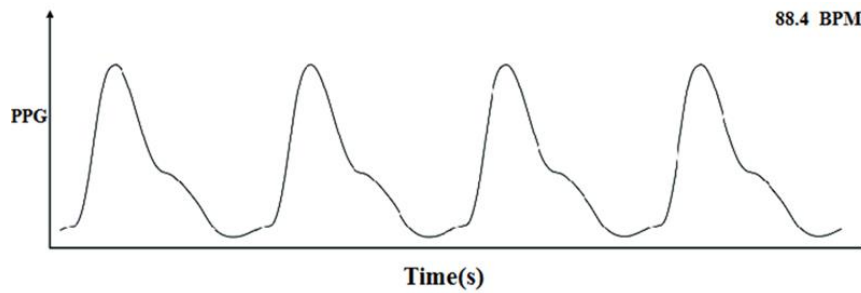


Fig. 4 Output PPG signals on the easy pulse sensor

Table 1 Experimental results

Subject	Age (years)	Total number of tests	The duration of the exercise	The highest heart rate when exercising	The success of alert notifications		
					Yes	No	Accuracy (%)
1	20	5	0:14:19	155	5	0	100
2	20	5	0:15:20	146	3	0	100
3	20	5	0:16:55	157	5	0	100
4	22	5	0:18:35	163	5	0	100
5	23	5	0:17:36	167	3	0	100
6	24	5	0:16:52	159	4	0	100
7	25	5	0:18:13	168	4	0	100
8	28	5	0:17:23	149	5	0	100
9	28	5	0:14:49	151	5	0	100
10	30	5	0:15:37	156	3	0	100

displayed. During an exercise program, when a warning is sent at a particular speed, the subject's heart rate will increase at a different rate depending on the speed of the warning message. A database containing the average and the highest heart rates will be available for the subject to review during the second round of evaluation. The program also records the user's heart rate and the time and duration of their exercises (Wang *et al.* 2020, Zhang *et al.* 2020, Cao *et al.* 2022, Lei *et al.* 2022, Tang *et al.* 2022, Zhang *et al.* 2023).

3. Definition of fatigue level

By detecting the changes in blood volume passing through the arteries, a sensor generates electrical signals detected as heart rate. The sensor outputs the signal at the midpoint of the voltage when not in contact with the heart rate source. The sensor changes into reflected light when it touches the pulse source. When the blood volume changes in the vessels that carry blood through the tissue, the signal fluctuates around the reference point. By detecting these fluctuations, the sensor can identify tissues or organs moving through the arteries. A high-pass filter circuit will be used to filter the signal received by the receiver circuit. Through a non-inverting amplifier circuit, the signal is amplified and returned to normal. As seen in Fig. 4, the generated signal graph takes the form of a line graph.

The number of heart beats per minute (BPM) is calculated by dividing 60,000 (in milliseconds) by the pulse rate of

three consecutive IBI peaks (interbeat intervals). When the graph experiences a sharp increase, IBI is the time difference between one point and the next point, with the point value equal to 50% of P (peak) subtracted by T (valley). Eq. (1) is used to calculate heart rate.

$$\text{Heart rate (BPM)} = (60000 / \text{pulse rate}) \quad (1)$$

A time period of the PPG signals waveform is used to calculate the heart rate. Waveforms are identified by identifying three consecutive peaks by changing the slope of the line from positive to negative and identifying that the magnitude of the signal is greater than 80% of all samples combined. Three consecutive PPG signal peaks are used to calculate two heart rates, and their average values are displayed as heart rates. During physical exercise, an algorithm was created to determine the fatigue level experienced by users to calculate the maximum heart rate, multiplying 220 by the user's age. During exercise, the heart rate fluctuates typically between 50% and 80% of the maximum heart rate. Subjects will experience pain if their heart rate exceeds 80% of their maximum heart rate, so physical activity should be limited. It is necessary to reduce physical activity if the subject feels pain in a particular body part at a heart rate of 60%-70% of the maximum heart rate.

4. Result and discussion

With the help of the HC-05 Bluetooth chip, Arduino Uno microcontroller, and easy pulse sensor, are used to

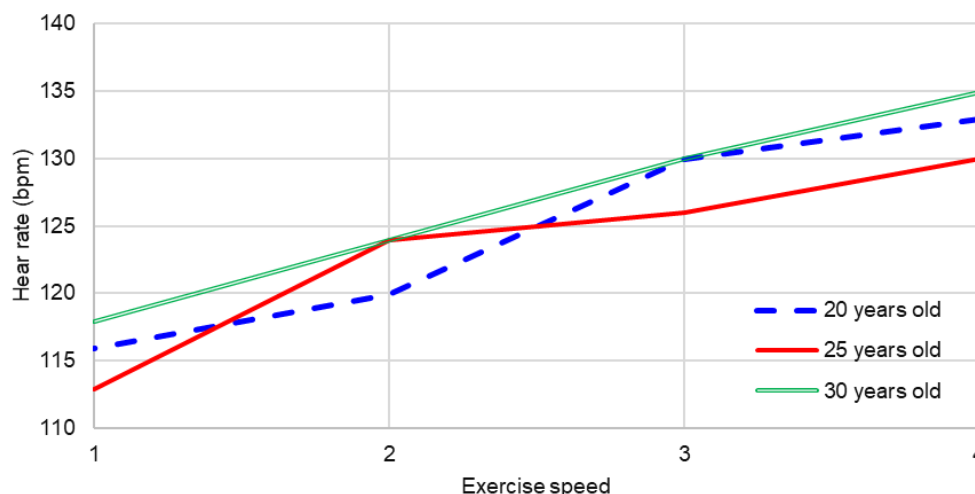


Fig. 5 The test results of exercise speed of heart rate

Table 2 The results of measuring the accuracy of wearable devices

Testing No.	Number of heart rate (BPM)		Accuracy
	1180 skmei watch	Wearable device	
1	72	70	100
2	73	74	95.66
3	71	69	97.22
4	70	66	100
5	74	78	93.4
6	66	71	98.27
7	75	77	92.87
8	77	81	94.35
9	78	75	100
10	75	68	97.25
11	79	80	95.98
12	61	79	98.43
13	65	82	91.86
14	71	69	88.35
15	76	72	90.49
16	85	62	89.67
17	83	78	96.05
18	76	79	96.78
19	78	81	97.94
20	69	75	93.12

create a wearable device. Smartphone applications are developed using Android studio on the Android operating system. The user of the smartphone application will receive a first warning notification and vibrate for two seconds when the heart rate exceeds 70%. A second warning notification will be given when the user's heart rate is more than 80% of the maximum heart rate, and the device will vibrate for four seconds. The general test results were administered this test five times to each of the ten individuals. High-speed exercises increase the heart rate,

and exercising at a fast pace also affects it. Users whom wushu exercise at a faster pace achieve the highest heart rates. Table 1 shows the test results performed five times on ten subjects. The maximum heart rate obtained in this test is 168 beats per minute for a 25-year-old. In this case, a heart rate could be considered dangerous if it is above 85% of the user's cardiac rate, but if one does not experience pain or discomfort, the heartbeat could also be considered harmless. On a 25-year-old user, 168 BPM was obtained during an experiment, and the user did not experience any pain. A total of three cases were collected in the whole experiment to compare heart rate changes when the same speed was given under the same conditions and at the same time. During this test, subjects perform wushu for 15 minutes at various speeds. Speed changes were made at 15, 16, and 18 minutes.

A speed change test indicates that Wushu exercise speeds affect heart rate data. During an 18-minute speed test, a subject's heartbeat tends to increase, and the user receives an alert message. As the user's heart rate decreases at the 15-minute pace, even if the decrease is insignificant, the user's heart rate begins to decrease. In users 25 years of age with a speed of 18 minutes, the heart rate is the highest. According to the diagram in Fig. 5, the Wushu exercise speed test with heart rate produced these results.

Comparing the output of the wearable device with the existing heart rate measuring device was used to test the accuracy of heart rate measurement. SKMei 1180 was used as the available tool. The 1180 skmei is a watch that counts heart rate during wushu exercises. When each device detected a heartbeat, measurements were performed in parallel. Table 2 shows that the wearable device has a 94.33% accuracy in measuring heart rate.

5. Conclusions

This research developed and implemented a heart rate monitoring system for Wushu sports using photoplethysmography signals and MEMS nanosensor technology. According to an experiment with varying speeds, ages, and

performance times, Wushu exercises can affect the heart rate by age and speed. Based on this study's findings, sports performed at a higher speed also increase heart rate. A warning message will appear on the Android smartphone when the heart rate is not average or close to the maximum. It is possible to classify the table's highest heart rate at 168 beats per minute as dangerous and close to the maximum heart rate (which may vary from 85% of the user's heart rate). Nevertheless, if this exercise did not cause the user to feel any pain in any part of his body and he felt it was harmless, it could also be classified as a harmless heartbeat.

Acknowledgement

The study was supported by Shenyang Sport University key construction subjects in 14th five years plan (Direction of sport health promotion).

References

- Aditya Khatokar, J., Vinay, N., Sudhir Bale, A., Nayana, M.A., Harini, R., Suhaas Reddy, V., Soundarya, N., Satheesha, T.Y. and Shivashankar Huddar, A. (2021), "A study on improved methods in Micro-electromechanical systems technology", *Mater. Today Proc.*, **43**, 3784-3790. <https://doi.org/10.1016/j.matpr.2020.10.993>.
- Akbas, S.D. (2018a), "Forced vibration analysis of cracked functionally graded microbeams", *Adv. Nano Res.*, **6**(1), 39. <http://doi.org/10.12989/anr.2018.6.1.039>.
- Akbaş, Ş.D. (2018b), "Bending of a cracked functionally graded nanobeam", *Adv. Nano Res.*, **6**(3), 219. <http://doi.org/10.12989/anr.2018.6.3.219>.
- Algamili, A.S., Khir, M.H.M., Dennis, J.O., Ahmed, A.Y., Alabsi, S.S., Ba Hashwan, S.S. and Junaid, M.M. (2021), "A review of actuation and sensing mechanisms in MEMS-based sensor devices", *Nanos. Res. Lett.*, **16**(1), 16. <https://doi.org/10.1186/s11671-021-03481-7>.
- Alimoradlu, K. and Zamani, A. (2022), "Hydrophobicity in nanocatalysis", *Adv. Nano Res.*, **12**(1), 49-63. <http://doi.org/10.12989/ANR.2022.12.1.049>.
- Allahkarami, F., Nikkiah-Bahrami, M. and Saryazdi, M.G. (2017), "Damping and vibration analysis of viscoelastic curved microbeam reinforced with FG-CNTs resting on viscoelastic medium using strain gradient theory and DQM", *Steel Compos. Struct.*, **25**(2), 141-155. <https://doi.org/10.12989/scs.2017.25.2.141>.
- Alsultan Abdulmajeed, S. (2021), "Assessment of microstructure and surface effects on vibrational characteristics of public transportation", *Adv. Nano Res.*, **11**(1), 101-113. <http://doi.org/10.12989/ANR.2021.11.1.101>.
- Angermann, C.E., Assmus, B., Anker, S.D., Brachmann, J., Ertl, G., Köhler, F., Rosenkranz, S., Tschöpe, C., Adamson, P.B. and Böhm, M. (2018), "Safety and feasibility of pulmonary artery pressure-guided heart failure therapy: rationale and design of the prospective CardioMEMS Monitoring Study for Heart Failure (MEMS-HF)", *Clin. Res. Cardiol.*, **107**(11), 991-1002. <https://doi.org/10.1007/s00392-018-1281-8>.
- Arefi, M. and Zenkour, A.M. (2018), "Free vibration analysis of a three-layered microbeam based on strain gradient theory and three-unknown shear and normal deformation theory", *Steel Compos. Struct.*, **26**(4), 421-437. <https://doi.org/10.12989/scs.2018.26.4.421>.
- Ashraf, M.W., Tayyaba, S. and Afzulpurkar, N. (2011), "Micro electromechanical systems (MEMS) based microfluidic devices for biomedical applications", *Int. J. Mol. Sci.*, **12**(6), 3648-3704. <https://doi.org/10.3390/ijms12063648>.
- Atmane Hassen, A., Tounsi, A., Bernard, F. and Mahmoud, S.R. (2015), "A computational shear displacement model for vibrational analysis of functionally graded beams with porosities", *Steel Compos. Struct.*, **19**(2), 369-384. <http://doi.org/10.12989/SCS.2015.19.2.369>.
- Attia, A., Tounsi, A., Bedia, E.A.A. and Mahmoud, S.R. (2015), "Free vibration analysis of functionally graded plates with temperature-dependent properties using various four variable refined plate theories", *Steel Compos. Struct.*, **18**(1), 187-212. <http://doi.org/10.12989/SCS.2015.18.1.187>.
- Avcar, M. (2019), "Free vibration of imperfect sigmoid and power law functionally graded beams", *Steel Compos. Struct.*, **30**(6), 603-615. <http://doi.org/10.12989/SCS.2019.30.6.603>.
- Aydogdu, M., Arda, M. and Filiz, S. (2018), "Vibration of axially functionally graded nano rods and beams with a variable nonlocal parameter", *Adv. Nano Res.*, **6**(3), 257. <http://doi.org/10.12989/anr.2018.6.3.257>.
- Bassiachvili, E., Stewart, R., Shavezipur, M. and Nieva, P. (2008). "A MEMS capacitive, passively powered heart rate monitor: Design and analysis", *2008 1st Microsystems and Nanoelectronics Research Conference*, 15-15 Oct. 2008. <https://doi.org/10.1109/MNRC.2008.4683383>.
- Behdinin, K. and Moradi-Dastjerdi, R. (2022), "Thermal buckling resistance of a lightweight lead-free piezoelectric nanocomposite sandwich plate", *Adv. Nano Res.*, **12**(6), 593-603. <http://doi.org/10.12989/ANR.2022.12.6.593>.
- Bellifa, H., Bakora, A., Tounsi, A., Bousahla Abdelmoumen, A. and Mahmoud, S.R. (2017), "An efficient and simple four variable refined plate theory for buckling analysis of functionally graded plates", *Steel Compos. Struct.*, **25**(3), 257-270. <http://doi.org/10.12989/SCS.2017.25.3.257>.
- Bennai, R., Atmane Hassen, A. and Tounsi, A. (2015), "A new higher-order shear and normal deformation theory for functionally graded sandwich beams", *Steel Compos. Struct.*, **19**(3), 521-546. <http://doi.org/10.12989/SCS.2015.19.3.521>.
- Bensaid, I., Bekhadda, A. and Kerboua, B. (2018), "Dynamic analysis of higher order shear-deformable nanobeams resting on elastic foundation based on nonlocal strain gradient theory", *Adv. Nano Res.*, **6**(3), 279. <http://doi.org/10.12989/anr.2018.6.3.279>.
- Benson, B., Sage, A.P. and Cook, G. (1993), "Emerging technology-evaluation methodology: With application to micro-electromechanical systems", *IEEE T. Eng. Manag.*, **40**(2), 114-123. <https://doi.org/10.1109/17.277403>.
- Cai, T., Zandi, Y., Agdas, A. S., Salmi, A., Issakhov, A. and Roco-Videla, A. (2021), "The compressive strength of concrete retrofitted with wind ash and steel slag pozzolans with a water-cement based polymers", *Adv. Concr. Constr.*, **11**(6), 507-519. <https://doi.org/10.12989/ACC.2021.11.6.507>.
- Cao, C., Wang, J., Kwok, D., Cui, F., Zhang, Z., Zhao, D., Li, M.J. and Zou, Q. (2022), "webTWAS: A resource for disease candidate susceptibility genes identified by transcriptome-wide association study", *Nucl. Acids Res.*, **50**(D1), D1123-D1130. <https://doi.org/10.1093/nar/gkab957>.
- Chaht Fouzia, L., Kaci, A., Houari Mohammed Sid, A., Tounsi, A., Beg, O.A. and Mahmoud, S.R. (2015), "Bending and buckling analyses of functionally graded material (FGM) size-dependent nanoscale beams including the thickness stretching effect", *Steel Compos. Struct.*, **18**(2), 425-442. <http://doi.org/10.12989/SCS.2015.18.2.425>.
- Chattopadhyay, M. and Chowdhury, D. (2017), "Design and performance analysis of MEMS capacitive pressure sensor array for measurement of heart rate", *Microsyst. Technol.*, **23**(9), 4203-4209. <https://doi.org/10.1007/s00542-016-2842-2>.
- Chen, T., Crosbie Robert, C., Anandkumarb, A., Melville, C. and

- Chan, J. (2021), "Optimized AI controller for reinforced concrete frame structures under earthquake excitation", *Adv. Concr. Constr.*, **11**(1), 1-9. <https://doi.org/10.12989/ACC.2021.11.1.001>.
- Chooruang, K. and Mangkalakeeree, P. (2016), "Wireless heart rate monitoring system using MQTT", *Procedia Comput. Sci.*, **86** 160-163. <https://doi.org/10.1016/j.procs.2016.05.045>.
- Dai, W., Zand, Y., Sadighi, A.A., Selmi, A., Roco-Videla, A., Wakil, K. and Issakhov, A. (2021), "The economic and management use of rhododendron petals in potas-sium-ion nano batteries anode via efficient computer simulation", *Adv. Nano Res.*, **10**(6), 517-529. <http://doi.org/10.12989/ANR.2021.10.6.517>.
- Dang, W., Xiang, L., Liu, S., Yang, B., Liu, M., Yin, Z., Yin, L. and Zheng, W. (2023), "A feature matching method based on the convolutional neural network", *J. Imag. Sci. Technol.*, 1-11. <https://doi.org/10.2352/J.ImagingSci.Technol.2023.67.3.030402>
- Ebrahimi, F., Kokaba, M., Shaghghi, G. and Selvamani, R. (2020), "Dynamic characteristics of hygro-magneto-thermo-electrical nanobeam with non-ideal boundary conditions", *Adv. Nano Res.*, **8**(2), 169-182. <https://doi.org/10.12989/anr.2020.8.2.169>.
- Ebrahimi, F. and Shafiei, N. (2016), "Application of Eringen's nonlocal elasticity theory for vibration analysis of rotating functionally graded nanobeams", *Smart Struct. Syst.*, **17**(5), 837-857. <https://doi.org/10.12989/sss.2016.17.5.837>.
- Ebrahimi, F., Shafiei, N., Kazemi, M. and Mousavi Abdollahi, S.M. (2017), "Thermo-mechanical vibration analysis of rotating nonlocal nanoplates applying generalized differential quadrature method", *Mech. Adv. Mater. Struct.*, **24**(15), 1257-1273. <https://doi.org/10.1080/15376494.2016.1227499>.
- Ehyaie, J., Akbarshahi, A. and Shafiei, N. (2017), "Influence of porosity and axial preload on vibration behavior of rotating FG nanobeam", *Adv. Nano Res.*, **5**(2), 141. <http://doi.org/10.12989/anr.2017.5.2.141>.
- Esparham, A., Moradikhoh Amir, B., Andalib Faeze, K. and Avanaki Mohammad, J. (2021), "Strength characteristics of granulated ground blast furnace slag-based geopolymer concrete", *Adv. Concr. Constr.*, **11**(3), 219-229. <https://doi.org/10.12989/ACC.2021.11.3.219>.
- Feng, X., Dong, M., Levy, P. and Xu, Y. (2017). "Non-contact Home Health Monitoring Based on Low-Cost High-Performance Accelerometers", *2017 IEEE/ACM International Conference on Connected Health: Applications, Systems and Engineering Technologies (CHASE)*, 17-19 July 2017. <https://doi.org/10.1109/CHASE.2017.119>.
- Gafour, Y., Hamidi, A., Benahmed, A., Zidour, M. and Bensattalah, T. (2020), "Porosity-dependent free vibration analysis of FG nanobeam using non-local shear deformation and energy principle", *Adv. Nano Res.*, **8**(1), 37-47. <https://doi.org/10.12989/anr.2020.8.1.037>.
- Galli, A., Montree, R.J.H., Que, S., Peri, E. and Vullings, R. (2022), "An overview of the sensors for heart rate monitoring used in extramural applications", *Sensors*, **22**(11). <https://doi.org/10.3390/s22114035>.
- Ghadiri, M., Shafiei, N. and Alavi, H. (2017a), "Vibration analysis of a rotating nanoplate using nonlocal elasticity theory", *J. Solid Mech.*, **9**(2), 319-337.
- Ghadiri, M., Shafiei, N. and Babaei, R. (2017b), "Vibration of a rotary FG plate with consideration of thermal and Coriolis effects", *Steel Compos. Struct.*, **25**(2), 197-207. <https://doi.org/10.12989/SCS.2017.25.2.197>.
- Gomez-Clapers, J. and Casanella, R. (2012), "A fast and easy-to-use ECG acquisition and heart rate monitoring system using a wireless steering wheel", *IEEE Sensors J.*, **12**(3), 610-616. <https://doi.org/10.1109/JSEN.2011.2118201>.
- Guisbiers, G. and Wautelet, M. (2007), "Materials selection for micro-electromechanical systems", *Mater. Des.*, **28**(1), 246-248. <https://doi.org/10.1016/j.matdes.2005.05.012>.
- Ha, D.W., Park, H.S., Choi, S.W. and Kim, Y. (2013), "A wireless MEMS-based inclinometer sensor node for structural health monitoring", *Sensors*, **13**(12), 16090-16104. <https://doi.org/10.3390/s131216090>.
- Hamidi, A., Houari, M.S.A., Mahmoud, S. and Tounsi, A. (2015), "A sinusoidal plate theory with 5-unknowns and stretching effect for thermomechanical bending of functionally graded sandwich plates", *Steel Compos. Struct.*, **18**(1), 235-253. <https://doi.org/10.12989/scs.2015.18.1.235>.
- Haroun, A., Le, X., Gao, S., Dong, B., He, T., Zhang, Z., Wen, F., Xu, S. and Lee, C. (2021), "Progress in micro/nano sensors and nanoenergy for future AIoT-based smart home applications", *Nano Exp.*, **2**(2), 022005. <https://doi.org/10.1088/2632-959x/abf3d4>.
- Hensen, S.J. (2017), "Measuring physical activity with heart rate monitors", *Am. J. Publ. Health*, **107**(12), e24. <https://doi.org/10.2105/ajph.2017.304121>.
- Hernandez, J.E. and Cretu, E. (2018). "Simple heart rate monitoring system with a MEMS gyroscope for sleep studies", *2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, 1-3 Nov. 2018. <https://doi.org/10.1109/IEMCON.2018.8614753>.
- Hou, F., Wu, S., Moradi, Z. and Shafiei, N. (2021), "The computational modeling for the static analysis of axially functionally graded micro-cylindrical imperfect beam applying the computer simulation", *Eng. Comput.*, 1-19. <https://doi.org/10.1007/s00366-021-01456-x>.
- Houari Mohammed Sid, A., Tounsi, A., Bessaim, A. and Mahmoud, S.R. (2016), "A new simple three-unknown sinusoidal shear deformation theory for functionally graded plates", *Steel Compos. Struct.*, **22**(2), 257-276. <http://doi.org/10.12989/SCS.2016.22.2.257>.
- Hu, J., Zhang, T., Chen, Y., Xu, P., Zheng, D. and Li, X. (2022), "Area-Selective, In-Situ Growth of Pd-Modified ZnO Nanowires on MEMS Hydrogen Sensors", *Nanomaterials*, **12**(6). <https://doi.org/10.3390/nano12061001>.
- Hu, Z., Ren, L., Wei, G., Qian, Z., Liang, W., Chen, W., Lu, X., Ren, L. and Wang, K. (2023), "Energy flow and functional behavior of individual muscles at different speeds during human walking", *IEEE T Neural Syst. Rehabil. Eng.*, **31**, 294-303. <https://doi.org/10.1109/TNSRE.2022.3221986>.
- Huang, X., Zhang, Y., Moradi, Z. and Shafiei, N. (2021), "Computer simulation via a couple of homotopy perturbation methods and the generalized differential quadrature method for nonlinear vibration of functionally graded non-uniform micro-tube", *Eng. Comput.*, 1-18. <https://doi.org/10.1007/s00366-021-01395-7>.
- Jiménez Morgan, S. and Molina Mora, J.A. (2017), "Effect of heart rate variability biofeedback on sport performance, a systematic review", *Appl. Psychophysiol. Biofeedback*, **42**(3), 235-245. <https://doi.org/10.1007/s10484-017-9364-2>.
- Kaisti, M., Panula, T., Leppänen, J., Punkkinen, R., Jafari Tadi, M., Vasankari, T., Jaakkola, S., Kiviniemi, T., Airaksinen, J., Kostiaainen, P., Meriheinä, U., Koivisto, T. and Pänkäälä, M. (2019), "Clinical assessment of a non-invasive wearable MEMS pressure sensor array for monitoring of arterial pulse waveform, heart rate and detection of atrial fibrillation", *npj Digital Med.*, **2**(1), 39. <https://doi.org/10.1038/s41746-019-0117-x>.
- Kar Vishesh, R. and Panda Subrata, K. (2015), "Nonlinear flexural vibration of shear deformable functionally graded spherical shell panel", *Steel Compos. Struct.*, **18**(3), 693-709. <http://doi.org/10.12989/SCS.2015.18.3.693>.
- Khan, M.S., Tariq, M.O., Nawaz, M. and Ahmed, J. (2021), "MEMS sensors for diagnostics and treatment in the fight against COVID-19 and other pandemics", *IEEE Access*, **9**,

- 61123-61149. <https://doi.org/10.1109/ACCESS.2021.3073958>.
- Koester, D.A., Markus, K.W. and Walters, M.D. (1996), "MEMS: Small machines for the microelectronics age", *Computer*, **29**(1), 93-94. <https://doi.org/10.1109/2.481497>.
- Lei, X., Li, Z., Zhong, Y., Li, S., Chen, J., Ke, Y., Lv, S., Huang, L., Pan, Q., Zhao, L., Yang, X., Chen, Z., Deng, Q. and Yu, X. (2022), "Gli1 promotes epithelial-mesenchymal transition and metastasis of non-small cell lung carcinoma by regulating snail transcriptional activity and stability", *Acta Pharm. Sinica B*, **12**(10), 3877-3890. <https://doi.org/10.1016/j.apsb.2022.05.024>.
- Liu, A.A., Zhai, Y., Xu, N., Nie, W., Li, W. and Zhang, Y. (2022), "Region-aware image captioning via interaction learning", *IEEE T. Circ. Syst. Video Technol.*, **32**(6), 3685-3696. <https://doi.org/10.1109/TCSVT.2021.3107035>.
- Liu, B., Peng, Y., Jin, Z., Wu, X., Gu, H., Wei, D., Zhu, Y. and Zhuang, S. (2023a), "Terahertz ultrasensitive biosensor based on wide-area and intense light-matter interaction supported by QBIC", *Chem. Eng. J.*, **462**, 142347. <https://doi.org/10.1016/j.cej.2023.142347>.
- Liu, M., Zhang, X., Yang, B., Yin, Z., Liu, S., Yin, L. and Zheng, W. (2023b), "Three-dimensional modeling of heart soft tissue motion", *Appl. Sci.*, **13**(4), 2493. <https://doi.org/10.3390/app13042493>.
- Luo, G., Xie, J., Liu, J., Zhang, Q., Luo, Y., Li, M., Zhou, W., Chen, K., Li, Z., Yang, P., Zhao, L., Siong Teh, K., Wang, X., Dong, L., Maeda, R. and Jiang, Z. (2023), "Highly conductive, stretchable, durable, breathable electrodes based on electrospun polyurethane mats superficially decorated with carbon nanotubes for multifunctional wearable electronics", *Chem. Eng. J.*, **451**, 138549. <https://doi.org/10.1016/j.cej.2022.138549>.
- Lv, Z. and Kumar, N. (2020), "Software defined solutions for sensors in 6G/IoE", *Comput. Commun.*, **153**, 42-47. <https://doi.org/10.1016/j.comcom.2020.01.060>.
- Ma, Z., Zheng, W., Chen, X. and Yin, L. (2021), "Joint embedding VQA model based on dynamic word vector", *PeerJ Comput. Sci.*, **7**, e3553. <https://doi.org/10.7717/peerj-cs.353>.
- Maheswaran, J., Chellapandian, M. and Kumar, V. (2022), "Behavior of GGBS concrete with pond ash as a partial replacement for sand", *Adv. Concr. Constr.*, **13**(3), 233-242. <https://doi.org/10.12989/ACC.2022.13.3.233>.
- Matouk, H., Bousahla, A.A., Heireche, H., Bourada, F., Bedia, E., Tounsi, A., Mahmoud, S., Tounsi, A. and Benrahou, K. (2020), "Investigation on hygro-thermal vibration of P-FG and symmetric S-FG nanobeam using integral Timoshenko beam theory", *Adv. Nano Res.*, **8**(4), 293-305. <https://doi.org/10.12989/anr.2020.8.4.293>.
- Mirjavadi, S.S., Rabby, S., Shafiei, N., Afshari, B.M. and Kazemi, M. (2017), "On size-dependent free vibration and thermal buckling of axially functionally graded nanobeams in thermal environment", *Appl. Phys. A*, **123**(5), 315. <https://doi.org/10.1007/s00339-017-0918-1>.
- Mousavi, S.M., Shafiei, N. and Davvand, A. (2017), "Numerical simulation of subsonic turbulent flow over NACA0012 airfoil: Evaluation of turbulence models", *Sigma J. Eng. Natural Sci.*, **35**(1), 133-155.
- Navi, B.R., Mohammadimehr, M. and Arani, A.G. (2019), "Active control of three-phase CNT/resin/fiber piezoelectric polymeric nanocomposite porous sandwich microbeam based on sinusoidal shear deformation theory", *Steel Compos. Struct.*, **32**(6), 753-767. <https://doi.org/10.12989/scs.2019.32.6.753>.
- Nguyen, T.-V., Mizuki, Y., Tsukagoshi, T., Takahata, T., Ichiki, M. and Shimoyama, I. (2020), "MEMS-based pulse wave sensor utilizing a piezoresistive cantilever", *Sensors*, **20**(4). <https://doi.org/10.3390/s20041052>.
- Omid, S., Oskooee, M.B. and Shafiei, N. (2013), "Finite element analysis of an ultra-fine grained Titanium dental implant covered by different thicknesses of hydroxyapatite layer", *Indian J. Dent.*, **4**(1), 1-4. <https://doi.org/10.1016/j.ijd.2012.10.002>.
- Patel, N. (2018), "Heart attack detection and heart rate monitoring using IoT", *Int. J. Innov. Adv. Comput. Sci.*, **7**(4), 611-615.
- Raj, A., Sathyan, D. and Mini, K.M. (2021), "Performance evaluation of natural fiber reinforced high volume fly ash foam concrete cladding", *Adv. Concr. Constr.*, **11**(2), 151-161. <https://doi.org/10.12989/ACC.2021.11.2.151>.
- Rico-González, M., Los Arcos, A., Rojas-Valverde, D., Clemente, F.M. and Pino-Ortega, J. (2020), "A survey to assess the quality of the data obtained by radio-frequency technologies and microelectromechanical systems to measure external workload and collective behavior variables in team sports", *Sensors*, **20**(8). <https://doi.org/10.3390/s20082271>.
- Seshadri, D.R., Li, R.T., Voos, J.E., Rowbottom, J.R., Alfes, C.M., Zorman, C.A. and Drummond, C.K. (2019), "Wearable sensors for monitoring the physiological and biochemical profile of the athlete", *npj Digital Med.*, **2**(1), 72. <https://doi.org/10.1038/s41746-019-0150-9>.
- Shafiei, N., Ghadiri, M. and Mahinzare, M. (2019), "Flapwise bending vibration analysis of rotary tapered functionally graded nanobeam in thermal environment", *Mech. Adv. Mater. Struct.*, **26**(2), 139-155. <https://doi.org/10.1080/15376494.2017.1365982>.
- Shafiei, N., Hamisi, M. and Ghadiri, M. (2020), "Vibration analysis of rotary tapered axially functionally graded Timoshenko nanobeam in thermal environment", *J. Solid Mech.*, **12**(1), 16-32.
- Shafiei, N. and Kazemi, M. (2017), "Nonlinear buckling of functionally graded nano-/micro-scaled porous beams", *Compos. Struct.*, **178**, 483-492. <https://doi.org/10.1016/j.compstruct.2017.07.045>.
- Shafiei, N., Kazemi, M. and Ghadiri, M. (2016a), "Nonlinear vibration of axially functionally graded tapered microbeams", *Int. J. Eng. Sci.*, **102**, 12-26. <https://doi.org/10.1016/j.ijengsci.2016.02.007>.
- Shafiei, N., Kazemi, M. and Ghadiri, M. (2016b), "On size-dependent vibration of rotary axially functionally graded microbeam", *Int. J. Eng. Sci.*, **101**, 29-44. <https://doi.org/10.1016/j.ijengsci.2015.12.008>.
- Shafiei, N., Mirjavadi, S.S., Afshari, B.M., Rabby, S. and Hamouda, A.M.S. (2017), "Nonlinear thermal buckling of axially functionally graded micro and nanobeams", *Compos. Struct.*, **168** 428-439. <https://doi.org/10.1016/j.compstruct.2017.02.048>.
- Shafiei, N., Mousavi, A. and Ghadiri, M. (2016c), "On size-dependent nonlinear vibration of porous and imperfect functionally graded tapered microbeams", *Int. J. Eng. Sci.*, **106**, 42-56. <https://doi.org/10.1016/j.ijengsci.2016.05.007>.
- Shafiei, N. and She, G.-L. (2018), "On vibration of functionally graded nano-tubes in the thermal environment", *Int. J. Eng. Sci.*, **133**, 84-98. <https://doi.org/10.1016/j.ijengsci.2018.08.004>.
- Shahram Ghaedi Faramoushjan Hossein Jalalifar, R.K. (2021), "Mathematical modelling and numerical study for buckling study in concrete beams containing carbon nanotubes", *Adv. Concr. Constr.*, **11**(6), 521-529. <https://doi.org/10.12989/ACC.2021.11.6.521>.
- Shariq, M., Pal, S., Chaubey, R. and Masood, A. (2022), "An experimental and analytical study into the strength of hooked-end steel fiber reinforced HVFA concrete", *Adv. Concr. Constr.*, **13**(1), 35-43. <https://doi.org/10.12989/ACC.2022.13.1.035>.
- Shivanian, E., Ghadiri, M. and Shafiei, N. (2017), "Influence of size effect on flapwise vibration behavior of rotary microbeam and its analysis through spectral meshless radial point interpolation", *Appl. Phys. A*, **123**(5), 329. <https://doi.org/10.1007/s00339-017-0955-9>.
- Sun, Y., Dong, Y., Gao, R., Chu, Y., Zhang, M., Qian, X. and

- Wang, X. (2018), "Wearable pulse wave monitoring system based on MEMS sensors", *Micromachines*, **9**(2). <https://doi.org/10.3390/mi9020090>.
- Tang, F., Niu, B., Zong, G., Zhao, X. and Xu, N. (2022), "Periodic event-triggered adaptive tracking control design for nonlinear discrete-time systems via reinforcement learning", *Neural Netw.*, **154**, 43-55. <https://doi.org/10.1016/j.neunet.2022.06.039>.
- Tang, Y., Liu, S., Deng, Y., Zhang, Y., Yin, L. and Zheng, W. (2021), "An improved method for soft tissue modeling", *Biomed. Signal Pr. Control*, **65**, 102367. <https://doi.org/10.1016/j.bspc.2020.102367>.
- Thakur, P., Chahar, D. and Thakur, A. (2022), "Visible light assisted photocatalytic degradation of methylene blue dye using Ni doped Co-Zn nanoferrites", *Adv. Nano Res.*, **12**(4), 415-426. <http://doi.org/10.12989/ANR.2022.12.4.415>.
- Vega-Martinez, G., Ramos-Becerril, F.J., Mirabent-Amor, D., Franco-Sánchez, J.G., Vera-Hernández, A., Alvarado-Serrano, C. and Leija-Salas, L. (2018). "Analysis of heart rate variability and its application in sports medicine: A review", *2018 Global Medical Engineering Physics Exchanges/Pan American Health Care Exchanges (GMEPE/PAHCE)*, 19-24 March 2018. <https://doi.org/10.1109/GMEPE-PAHCE.2018.8400756>.
- Walsh, S.T. (2004), "Roadmapping a disruptive technology: A case study: The emerging microsystems and top-down nanosystems industry", *Technol. Forecast. Soc. Change*, **71**(1), 161-185. <https://doi.org/10.1016/j.techfore.2003.10.003>.
- Wang, J., Jiang, X., Zhao, L., Zuo, S., Chen, X., Zhang, L., Lin, Z., Zhao, X., Qin, Y., Zhou, X. and Yu, X.Y. (2020), "Lineage reprogramming of fibroblasts into induced cardiac progenitor cells by CRISPR/Cas9-based transcriptional activators", *Acta Pharm. Sinica B*, **10**(2), 313-326. <https://doi.org/10.1016/j.apsb.2019.09.003>.
- Wang, P., Gao, Z., Pan, F., Moradi, Z., Mahmoudi, T. and Khadimallah, M.A. (2022), "A couple of GDQM and iteration techniques for the linear and nonlinear buckling of bi-directional functionally graded nanotubes based on the nonlocal strain gradient theory and high-order beam theory", *Eng. Anal. Bound. Elem.*, **143**, 124-136. <https://doi.org/10.1016/j.enganabound.2022.06.007>.
- Xiao, X., Mu, B., Cao, G., Yang, Y. and Wang, M. (2022), "Flexible battery-free wireless electronic system for food monitoring", *J. Sci. Adv. Mater. Devices*, **7**(2), 100430. <https://doi.org/10.1016/j.jsamd.2022.100430>.
- Xu, W., Pan, G., Moradi, Z. and Shafiei, N. (2021), "Nonlinear forced vibration analysis of functionally graded non-uniform cylindrical microbeams applying the semi-analytical solution", *Compos. Struct.*, 114395. <https://doi.org/10.1016/j.compstruct.2021.114395>.
- Xu, Y., Zhang, Y., Yang, H., Yin, W., Zeng, L., Fang, S., Liu, S.-Y., Dai, Z., Zou, X. and Pan, Y. (2022), "Two-dimensional coordination polymer-based nanosensor for sensitive and reliable nucleic acids detection in living cells", *Chin. Chem. Lett.*, **33**(2), 968-972. <https://doi.org/10.1016/j.ccllet.2021.07.041>.
- Yang, H., Huang, H., Liu, X., Li, Z., Li, J., Zhang, D., Chen, Y. and Liu, J. (2023), "Sensing mechanism of an Au-TiO₂-Ag nanograting based on Fano resonance effects", *Appl. Opt.*, **62**(17), 4431-4438. <https://doi.org/10.1364/AO.491732>.
- Yuvaraj, T., Bindushri, Chandana, G.S., Shetty, D. and Sanil, H. (2021), "Development of prototype heart pulse rate monitoring system", *Int. J. Res. Eng. Sci. Manag.*, **4**(7), 172-174.
- Zarga, D., Tounsi, A., Bousahla Abdelmoumen, A., Bourada, F. and Mahmoud, S.R. (2019), "Thermomechanical bending study for functionally graded sandwich plates using a simple quasi-3D shear deformation theory", *Steel Compos. Struct.*, **32**(3), 389-410. <http://doi.org/10.12989/SCS.2019.32.3.389>.
- Zhang, G., Liu, M., Guo, N. and Zhang, W. (2016), "Design of the MEMS piezoresistive electronic heart sound sensor", *Sensors*, **16**(11). <https://doi.org/10.3390/s16111728>.
- Zhang, H., Zhao, X., Wang, H., Niu, B. and Xu, N. (2023), "Adaptive tracking control for output-constrained switched MIMO pure-feedback nonlinear systems with input saturation", *J. Syst. Sci. Complex.*, **36**(3), 960-984. <https://doi.org/10.1007/s11424-023-1455-y>.
- Zhang, L., Deng, S., Zhang, Y., Peng, Q., Li, H., Wang, P., Fu, X., Lei, X., Qin, A. and Yu, X. (2020), "Homotypic targeting delivery of siRNA with artificial cancer cells", *Adv. Healthcare Mater.*, **9**(9), 1900772. <https://doi.org/10.1002/adhm.201900772>.
- Zhao, F., Song, L., Peng, Z., Yang, J., Luan, G., Chu, C., Ding, J., Feng, S., Jing, Y. and Xie, Z. (2021), "Night-time light remote sensing mapping: Construction and analysis of ethnic minority development index", *Remote Sens.*, **13**(11), 2129. <https://doi.org/10.3390/rs13112129>.
- Zhao, K., Chen, Y., Yu, F., Jian, W., Zheng, M. and Zeng, H. (2022), "A biodegradable magnesium alloy sample induced rat osteochondral defect repair through Wnt/ β -catenin signaling pathway", *Adv. Nano Res.*, **12**(3), 301-317. <http://doi.org/10.12989/ANR.2022.12.3.301>.
- Zheng, W., Liu, X. and Yin, L. (2021), "Research on image classification method based on improved multi-scale relational network", *PeerJ Comput. Sci.*, **7**, e613. <https://doi.org/10.7717/peerj-cs.613>.

JL