A Survey on Biofeedback and Actuation in Wireless Body Area Networks (WBANs)

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***Abstract*—Wireless Body Area Networks (WBAN) has attained increasing popularity as the next generation framework of wearable technologies for human monitoring. Invasive or non-invasive wearable sensors designed in WBAN are worn to gather vital information. Biofeedback is a recent concept where collected data is used to generate actuation signals in WBANs. Applications can be seen in various areas such as sports (e.g. locomotor velocity) or medical (e.g. blood pressure measurement). However since the body is closely regulated, the next generation WBAN technology must be smart enough to react to monitored data. The main aim of the paper is to review the current state of biofeedback and actuation technology on WBANs in terms of its structure, applications, benefits, and control approaches. The emphasis on the specific requirements when applying biofeedback to humans will be highlighted and discussed. Challenges and open research issues will be concluded at the end.**

***Index Terms*—Biofeedback, WBAN, control system, wearable**

I. Introduction

Medical services required by the aging population and pathological groups are increasing annually. The top reasons of death in 2010 are reported to be coronary heart disease (15%), cerebrovascular disease (8%), dementia (7%), and lung cancer (6%) [1]. Statistics show that appropriate proactive treatments and interventions could have prevented these diseases [2]. This suggests that future health care systems will need to be proactively providing medical support, resulting in medical solutions and cost effective treatments.

To fulfill these medical requirements, an integrated wireless body area network (WBAN) is the most promising solution due to its ability to provide continuous monitoring, synchronous measurement and real-time feedback services. A classic WBAN is an autonomous sensor network which can monitor dynamic changes occurring in or on the human body. Biofeedback technologies enabled through WBAN will exempt human involvement because feedback signals will be attained from a control centre after analysing incoming sensor data and will be spontaneously applied to maintain required performance or reject undesired changes. WBAN combined with biofeedback mechanisms promise proactive health monitoring capabilities by enabling mobility, independence and automatic medical support as necessary.

There are generally two types of biofeedback mechanisms. Firstly, natural biofeedback systems exist in the human body regulation processes. A typical example can be seen in blood glucose regulation. Humans by nature have the ability to adjust their insulin and glucagon levels by reading the blood glucose level. It is the body's natural regulation, which can be regarded as a biofeedback control system, that maintains a stable blood glucose level. The second type of biofeedback is artificial biofeedback, which can be supplied in addition to existing natural biofeedback provided by the human body. This artificial biofeedback in the WBAN setting is the subject of this paper. Fig. 1 shows the framework of an artificial biofeedback control system. A WBAN-enabled biofeedback control system includes three main components: portable sensors used to detect physiological symptoms or physical states, a control unit acting as the central processing hub for signal processing, power management, and information storage [3], and feedback controlled actuation to alert users to take actions. The whole interaction process allows the desired performance to be automatically attained by learning and adapting according to the reference input [4]. In a WBAN-enabled biofeedback control system, users will adjust their performance by reacting to feedback signals from an external stimuli, conveyed by the actuators. Biofeedback-oriented WBAN will realise the proactive monitoring features. It provides wearable and transparent services to users at a low cost. This is expected to be the ultimate solution for health care improvement and injury minimization.

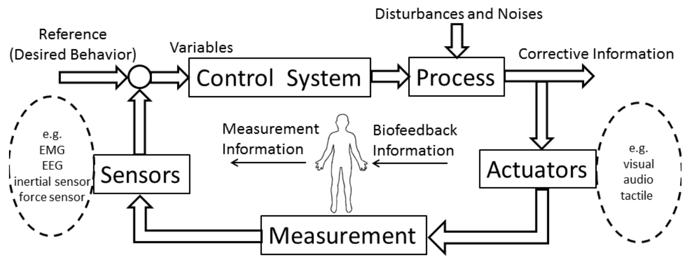

Fig. 1. Artificial biofeedback control framework for WBAN

In addition, biofeedback mechanisms in WBANs could be used in sports for risk elimination or performance enhancement. Example can be found in [5] where accelerometers are placed on motorcycle's front wheel and rider's front and back body to detect collisions and hazards. Some other sports technologies such as Hawk-Eye trajectory tracking [1], advanced stopwatch for swimming stroke characteristics measurement [2], and training set for individuals such as heart rate monitor and GPS-enabled trackers [3] already provide basic feedback. Such technologies could assist our understanding of human sensorimotor mechanisms, or athletes physiological strength

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[1] Hawk-Eye: http://www.hawkeyeinnovations.co.uk/
[2] AutoCoach: https://www.autocoach.com.au/
[3] Polar: http://www.polar.com/au-en

and weakness. Nevertheless, most of these applications are still monitoring-centric or alarm-based. Human-machine interaction is very limited, and information transmission is poor. Involving biofeedback-oriented WBAN in sports will advance the communication between human and machine. It will enable a scientific and interactive self-training approach.

This paper surveys emerging biofeedback control technologies. First of all, characteristics and structure of a feedback control system are introduced in Section II, followed by Section III which introduces miscellaneous applications. Categories of control systems are presented in Section IV. Then specific requirements in merging biofeedback into WBAN are explained in Section V. Lastly, open issues and further research challenges will be discussed in Section VI.

II. Biofeedback Systems in WBAN

WBANs equipped with artificial biofeedback capabilities consist of three major components i.e., sensor, actuator, and control centre. In this section, the function of each component will be described.

A. Components of a WBAN with biofeedback

1) Sensors: Sensor development can be regarded as the initiator of biofeedback-enabled WBAN. Sensors transduce physical or chemical information to analog or digital signals, allowing further recognition and analysis. Sensors supply the input of a biofeedback control systems. Wearable sensors offer a quantitative understanding of human physical and physiological characteristics. Typically, inertial sensors and force sensors have found extensive use in sports area, especially in terms of athletes' skills acquisition both in dynamic states (e.g. posture control [6]) and static cases (e.g. balance maintenance capability [7]). Force sensors measuring external pressure usually mounted in exoskeleton devices [8] or fingertip-mounted devices [9], while inertial sensors normally contain three main components: accelerometer [10], gyroscope [11], and magnetometer [12]. In addition, heart rate monitors originally used in medical treatments have been exported to sports and health care areas in recent years. Wearable heart rate monitoring devices are able to warn trainees of their physical response to training intensities and stress [13], or to send heath status of the elderly to their doctors [14]. Energy expenditure can be measured via direct oxygen consumption/carbon dioxide production[15], or indirect heat-flow detections [13]. Besides, kinect-based high-resolution depth and color (RGB) image sensor developed by Microsoft [4] has been found used in human activity recognition, gesture classification [16], as well as tele-robot kinematic and dynamic level control [17] other than its conventional applications in Xbox and Microsoft Windows.

2) Actuators: Actuators initiate the artificial feedback mechanism. They indicate a control subject how to progress its state from the current one to the desired one. Typical actuator applications are presented in Table. I. Audio feedback devices are commonly used for improper performance warning (e.g. risk postures [18], gait diagnosis [19]), and visual feedback

[4]Microsoft Kinect: https://developer.microsoft.com/en-us/windows/kinect

TABLE I
CATEGORIES OF ACTUATORS

Category		Applications
Audio		[18, 19]
Visual		[20, 21]
Tactile Devices	Vibro-tactile (Force-Haptic)	[22, 23]
	Electro-tactile	[24, 25]
	Visuo-tactile (Visual-Haptic)	[26, 27]
	Thermal	[28, 29]

emphasises the illustration of current performance and desired objectives (e.g. 3D shoulder position detection [20], swimmers performance measurement[21]). Both methods provide immediate feedback information to the control subjects. While visual feedback has the advantages of direct expression and diversity of presentation (e.g. graphs, virtual reality), audio feedback is viable in cases where the presentation of visual information is limited or constrained.

There are four subcategories of tactile feedback devices:

- Vibro-tactile feedback devices are critically meaningful in cases where visual or audio information are blocked. It can deliver various distributed stimuli with robust sensations [13]. Other than its conventional applications such as imbalance risk indication [22], it can also be employed in activities on a daily-basis such as gesture control in violin training [23]. There are plenty of on-the-market vibro-tactile devices designed for delivering reliable feedback information to end users. Nevertheless, a 4mm diameter vibration motor, for instance, will need to be powered by a 3.6V source and consume 30mAh [30]. High power consumption is the main drawback of this type of feedback devices.
- Electro-tactile devices deliver control signals via a current injection, which comes from surface electrodes to human skin acting as a prickly sensation. Its applications have been found in hand gesture control [24] and posture control [25]. Electro-tactile feedback devices could consume energy as low as 1μw/pixel [31], which makes it perfectly suitable for wearable WBAN systems. However, the process of generating electro feedback signals will produce heat. Inappropriate applications may cause skin burn and long-term skin irritation is a concern. Therefore, more research on user comfort, individuality of user acceptability, and threshold of safe electro current are required.
- Visual-Haptic feedback devices are designed according to human subtle senses. It is a combination of visual and haptic feedback mechanisms where haptic signals could assist the acceptance of visual information. In practice, visual-haptic feedback can be applied in touchscreen applications [26] or surgical skills acquisitions (improving motor control capabilities) [27]. This is a more effective approach compared with cases that use either visual or haptic feedback solely because it reduces user's perceived task difficulty. However, information fusion still faces great technical challenges and technological limitations.

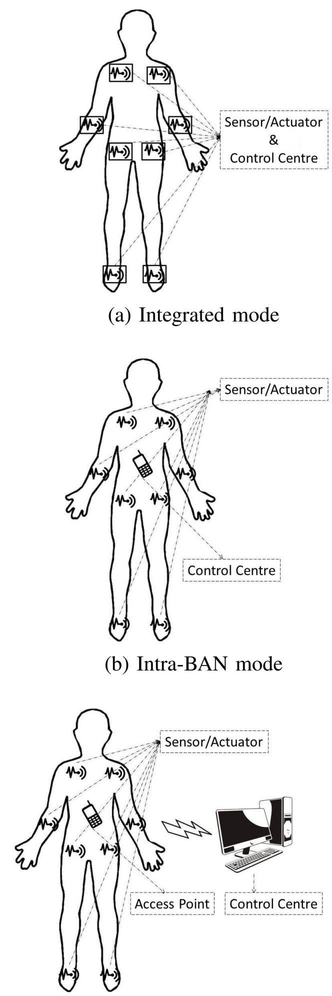
- Thermal feedback devices can include, but not limited to, temperature control systems (e.g. temperature sensors, thermal-electric heating pump and water cooling system) and thermal stimulators [32]. Thermal feedback devices supply temperature information to assist user discrimination of different materials [28]. Besides, intensity of vibro-tactile feedback adding on human skin can also be detected in accordance with the heat they perceived [29]. However, application of thermal feedback is unfortunately restricted due to the lack of devices developed and limited experience in dealing with them [32].

3) Control Functions: Data processing and control algorithms are critical in any control systems. Factors such as limits and natures of control variables or level of accuracy and processing speed [33] will all significantly affect control performance. In addition, some universal regulations will restrict the design of control functions. For instance, there are physical laws (e.g. Newton's law of motion, etc.)[4], disturbances and uncertainties, science of dynamics, and system homogeneity (multi-system interconnection issue)[33]. Different categories of control systems emphasising various operational restrictions will be discussed in Section IV.

B. WBAN Architectures

For the aim of delivering biofeedback, WBAN can be constructed into three main architectures including integrated mode, intra-BAN mode, and inter-BAN mode as depicted in Fig. 2 and explained as following. The selection is critical because it will impact in the feedback intensities, system lifespan, and correspondingly the overall control performance. Trade-offs in selection and WBAN performance in regard of each selection criterion are summarised in Table II.

- Integrated mode fuses sensors, actuators and a control hub in a single node. A typical example application can be found in [34] where an inertial sensor and a microprocessor are jointly placed in a single node and used to collect data of swimmer's body rotation. In some special environment, swimming, for instance, wireless date transmission is limited so integrated WBAN mode is a convenient solution. This structure provides the fastest feedback delivery and response time, while the cost is the high power consumption.
- Intra-BAN mode involves an independent control hub which collects information from different sensors and sends feedbacks to different actuators. Example application can be seen in [6] where sensors (gyroscopes and motion capture markers) are placed on athletes while processing center is isolated. The reason of using intra-BAN structure in this case is to avoid unnecessary distractions from bulky nodes on body. The aim of such arrangement is to lower the complexity and power consumption of each wearable node.
- In inter-BAN mode, incoming sensing data and outgoing feedback commands will all travel through an access point placed on human body, then arrive at a computer control center or the human body respectively. [14] presents an inter-BAN prototype of a modern healthcare system which involves the use of sensors (heart beat rate monitor, body temperature detection, etc.), a base station (PC or mobile phones), Internet, and a web browser. This system is able to gather feedback from doctors and professions in distance. Processing control functions in an isolated computer could maximally allow the complexity of control algorithms and correspondingly provide most accurate feedback information. However, system responsive cycles will be negatively affected due to the long data transmission time.



(a) Integrated mode

(b) Intra-BAN mode

(c) Inter-BAN mode

Fig. 2. Structures of WBAN

TABLE II
PERFORMANCE OF WBAN STRUCTURES

Criteria \ Mode	Integrated	Intra-BAN	Inter-BAN
Node Power Consumption	Highest	Medium	Lowest
Algorithm Complexity	Lowest	Medium	Highest
Response Time	Fastest	Medium	Slowest
Control Accuracy	Lowest	Medium	Highest

III. Biofeedback Control System Applications

Biofeedback control systems have been found broadly used in areas such as biomechanics, health care, and sports. The ability of providing real-time feedback and distance control makes it of great benefit in terms of effectively delivering appropriate treatment and preventing further hazards. Following are some typical biofeedback implementations in different fields.

A. Biomechanics and Human Movement

As the primary tool in understanding human locomotion, biomechanical analysis is able to provide extrinsic feedback (FB) to assist users' performance learning and objective achievements. Such feedback-oriented learning can be further categorised into four horizontal levels: neuromuscular level (L1), kinetic level (L2), kinematic level (L3), and movement outcome level (L4). The division is in accordance with the scope of the control subject: a piece of muscle or nerve (L1), a body part (L2), group of body parts (L3), or the overall locomotor performance (L4) [35]. It should be noted that there is a growing tendency of control complexity along with the rise of control level because of the increasing number of control variables, yet the control specificity and precision decreases. A summary of example applications can be seen in Table. III.

1) LEVEL 1 – Neuromuscular Feedback: Three decades ago, neuromuscular biofeedback mechanism was designed for hemiplegia treatment [44]. It was found that electromyography (EMG) biofeedback with visual and audio cues was beneficial for upper-limb-dysfunctional hemiplegic patients in terms of their ability to self-control their movements. Such technology was then widely applied in muscle rehabilitation therapy in later research. EMG biofeedback was used in computer-game-based recovery training programs so that motion-impaired patients were better motivated. Research results indicated that patients involved in feedback training (10 minutes per session $\times$ twice per week $\times$ 4 weeks) improved their range of movement by 12.75° and muscle tension by a factor of 1, while the ones in non-feedback training had only 1° increase in range of movement and no improvement in muscle tension [36].

2) LEVEL 2 – Kinetic Feedback: Kinetic feedback focuses on a particular part of human body, e.g. a leg or an arm. For this aim, inertial measurement units (IMUs) and force sensitive resistors (FSRs) are essential. IMU applications can be frequently found in trunk tilt measurement. Control subjects such as the elder or bilateral-vestibular-lost patients are at risk of falling due to the lost of their natural control of posture. IMUs together with audio feedback can act as an alternative sensory input. For example, Wireless Vibrotactile Feedback (VTTF) [22] was an efficient training manner where feedback was generated when an excess of safe threshold was detected. Patients in this study had a maximum of 25% gait parameter improvement because of decreased mediolateral sway and increased locomotor. FSRs are usually used in gait measurement or step count [39]. Combined with telecommunication tools, a tele-rehabilitation system can be built for post-stroke recovery.

3) LEVEL 3 – Kinematic Feedback: Feedback in this level contains integrated systematic information. It relates to multiple parts of human body which makes it an interactive and dynamic model. In this level, electromagnetic tracking devices can be applied to provide interventional-image-based visual feedback for respiratory motion detection [45] or shoulder position measurement [20].

4) LEVEL 4 – Movement Outcome Feedback: "Knowledge" of locomotion is defined as the highest level control emphasis [35]. Overall movement consequences are fedback in this level applications. [42, 43] concluded that feedback has more profound influence in movement effect enhancement than movement conduction. Also, learning the effect is more effective than learning each movement. That is to say, movement effects can be regarded as the motivation of locomotor performance. This is the ultimate goal of human locomotion control.

B. Health Care

Biofeedback applications in clinical therapies are also popular. It can be seen in wearable respiratory systems. Sensing equipment such as ECG (electrocardiograph) heart rate monitoring belt or respiratory inductance plethysmograph monitoring belt is widely applied in self-training process and rhythm-follow practice. It was stated that wearable respiratory device was able to successfully detect 83% long-term respiration rhythms in six hours, and feedback training achieved approximately 17% improvement in LF (low frequency)/HF (high frequency) ratio, which was the representative of heart rate variability [46]. Wearable respiratory feedback is effective in boosting the regulations of sympathetic and parasympathetic nerve systems.

Similarly, dementia patients' psychosocial and cognitive status can be assessed by EEG (for brain activity detection) and near-infrared spectroscopy (blood hemoglobin measurement and correspondingly active brain area identification) [47]. Hypertension can be monitored via pulse and breathing patterns and blood pressure can be well controlled by asking patients to follow the instructive inhale and exhale guidance [48]. Blood glucose is measured with a in-body subcutaneous sensor in hospital [49], while wearable options (e.g. Glucowatch Biographer Wristwatch coming with electrode, glucose oxidase, and biosensor unit [49]) is more convenient for home settings. Visual feedback is available in all above-mentioned medical applications.

C. Sports

Applying wearable technologies in sports focus mainly on kinematic performance enhancement, psychological capability assistance, and fitness maintenance. Examples are listed as following.

1) Athletes' Kinematic Analysis: As the rapid development of micro-electro-mechanical-systems(MEMS), wearable technologies can be found in diverse applications such as running– runners' spatial-temporal stride measurements using three-dimensional (3D) accelerometer [50]; snowboarding– insufficient knee flexion, inappropriate upper body rotation, and incorrect weight distribution can be detected with IMUs,

TABLE III
BIOFEEDBACK APPLICATIONS IN BIOMECHANICS AND HUMAN MOVEMENT

Level	Sensors	Actuators	Objectives	Effects	References
L1	EMG, bioconditioner, sensor tracker	audio, visual, visual-haptic	muscle rehabilitation	FB training increases range of movement by 11.75° more than non-FB training	[36]
			sense rehabilitation	$\frac{2}{9}$ dystonia and $\frac{5}{9}$ normal children reduced proximal muscle activity, $\frac{7}{9}$ dystonia and $\frac{8}{9}$ normal children reached the goal with distal muscle	[37]
			disease identification	chronic low back pain patients demonstrate lower value of flexion relaxation ration compared with healthy group	[38]
L2	pressure sensor, accelerometer, gyroscope, magnetometer	audio, visual, vibro-tactile	posture rehabilitation	FB reduces mechanical energy expenditure	[18]
			post-stroke recovery	step-counting system is able to count 100 fast/ slow steps with average error lower than 0.6%	[39]
			pre-risk indication	FB training changes gait parameters by maximum 25%	[22]
L3	electromagnetic tracking system	visual	position measurement and motion detection	”image-guided intervention procedure” is comparable to traditional sensor tracking with 94% correlation	[20]
			dynamic tumours treatment	2% per 2mm gamma-failure rate is reduced from 59.7% to 3% (500ms latency, two-dimension target motion) with high-precision dynamic tracking	[40]
L1&L2&L3	EMG, IMUs, force sensor, 3D Motion Capture	visual	injury prevention	integrated bioFB in neuromuscular training is feasible and able to boost training outcome	[41]
L4	stabilometer	visual, kinesthetic	FB on motion pattern VS. motion effect	FB provides an external focus of attention; FB on motion effect could improve the accuracy	[42]
			FB frequency	100% and 33% FB have equal effect on motion effect; reduced frequency is more beneficial on motion pattern	[43]
			FB on post-experiment effect	FB benefits the delayed retention test results	[42]

TABLE IV
MEMS IN SPORTS KINEMATIC ANALYSIS

Feedback Effect	Sports	Data Collection	Feedback Information	References
Remote Monitor	Run	accelerometer	spatial-temporal characteristics	[50]
	Ski	IMU force sensing resistors, infrared distance sensor	centrifugal force during movement	[51]
	Football	position tracking system	players’ strains, actions, and potentials	[52]
	Snowboard	IMU, capacitive sensor, temperature sensor, navigation switch, bend sensors, pressure sensors	common mistake warnings	[12]
	Golf	IMU, camera system	motion patterns during swing	[53]
Skill Assessment and Acquisition	Tennis	gyroscope, motion capture system	contribution distribution: 54% upper arm rotation, 31% wrist rotation, and 10% shoulder rotation	[6]
	Motorcycle	gyroscope, motion capture system	position estimation; positive correlation between rotation and displacement trajectory and rider’s skills	[54]
	Swimming	IMU, GPS	lap time, stroke characteristics, velocity, and temporal phase detection	[55–57]
Simulate Challenges	Cycle	power meter	power consumption	[58]

bend sensors, and force sensors; and golf– using IMUs in swing motion remodelling [53].

Skills acquisition and assessment can also be achieved with biofeedback systems. Position tracking is a technology which has been broadly involved in many ball games for game monitoring and player performance observation [52]. Gyroscope and optical-markers-based motion-capturing system are applied in motorcycler posture estimation [54] and tennis serve training [6]. IMUs in swimming supply immediate data such as lap time, stroke characteristics, velocity, and temporal phases with ease. In all examples, feedback information is recorded for further athletes selection or coaching purpose.

In addition, there are some specific designs for each particular sport type. In cycling, average power output can be measured using embedded strain gauges (cyclists’ energy consumption = $power \times time$) [58]. Cyclists’ aerodynamic and body position analysis can be visually fedback using computed tomography [59], radiography [60], or magnetic resonance [61]. Applications of biofeedback in sports kinematic analysis are summarised in Table. IV.

2) Athletes’ Psychological Assessment: Athletes’ psychological health is directly related to their competitive abilities.

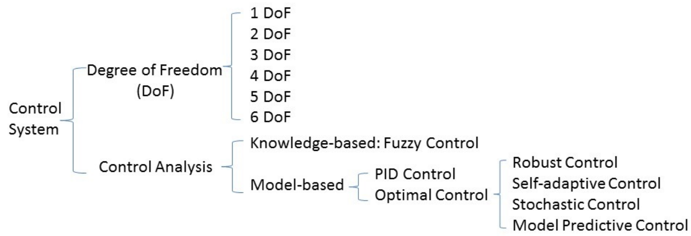


Fig. 3. Category of control systems

Emotional or nervous moods will inevitably debilitate their intrinsic performance. The research conducted in 1980 firstly revealed that EMG and heart rate feedback could to a certain extent reduce football and basketball players' muscle tension and correspondingly improve their competitiveness [62]. Nowadays, more reliable biofeedback control systems have been developed for psychological training. It has been shown that electrodermal response (EDR) biofeedback, peak achievement training (PAT), and EEG sensory-motor-rhythm (SMR) training can all assist elite skiers with their mood management and activation control [63]. Results also indicated some potential improvements in athletes attention and concentration maintenance due to the lower anxiety level. Biofeedback has proven to be a promising technique in maximizing athletes competition performance.

3) Fitness Maintenance: Wearable biofeedback devices are also developed by many commercial industries for fitness maintenance, which makes biofeedback training an accessible routine. Typically, GPS activity trackers are used for distance and velocity recording (e.g. Garmin[1], TomTom[2]). Heart rate monitoring can be added to basic activity trackers to trace exercise intensity (e.g. Fitbit[3], Polar[4]). Textile pressure sensors are mounted into shoes to optimize walking cadence and foot kinematics (e.g. Sensoria Smart Sock[5]). Kinematic sensors possess a wide range of applications such as step/ strike counting, pace measurement, and impact G force detection (e.g. RunScribe[6]). All the above-mentioned equipment come with visual feedback allowing users to access their statistics or images on devices.

IV. Categories of Feedback Control System

After reviewing some typical biofeedback applications, the core of biofeedback systems, design of control centres, will be discussed in this section. Fig. 3 illustrates different ways to categorise control systems.

A. Degree of Freedom

It is viable to categorise control systems in accordance with system degree of freedom (DoF). This is to integrate control inputs based on the variability of system measurements collected by multiple sensors. For example, 1 DoF robot can support angular position of human elbow [64]. It can be upgraded to a 2 DoF system for a point-to-point elbow and shoulder movement control [65]. A 3 DoF manipulator with steerable base, arm and forearm is capable of conducting accurate position reaching [66]. 4 DoF (shoulder horizontal and vertical extension and flexion, elbow extension and flexion, and forearm pronation and supination) arm control model is developed for human locomotion rehabilitation [67]. Similarly, 5 DoF virtual reality (VR) robot (2 controllable shoulders, 2 controllable wrists and 1 controllable elbow) is designed for same effort [68].

6 DoF is the maximum degrees of freedom for a rigid body moving in 3D space due to the limited number of operable variables: 3D locational displacements including up/ down, left/ right, forward/ backward, and roll angle (flexion and extension), pitch angle (abduction and adduction), and yaw angle (pronation and supination). 6 DoF system explains how a human performs each physical action. Every movement at each body position can be resolved into six sub-movements in each translation or orientation. Most human body control systems are designed with 6 DoF such as [69] which collected 3D acceleration and 3D angular rotation to describe a swimmer's postures.

B. Control Methods

Control systems can also be defined according to approaches adopted for various control situations. In this article, six representative analytical control methods are presented.

1) Knowledge-based control method: Knowledge-based controllers define the control rules linguistically instead of statistically. Following is a typical example of knowledge-based controller.

- Fuzzy control: Fuzzy control method is primarily applied to systems with higher degree of complexity and highly variable, or systems whose mathematical models are hard to derive. It will implement pre-stored expert knowledge (database and fuzzy rules) to execute control functions with the aim of reducing processing and maintenance time [70]. System conversions and execution of control functions can be seen in Fig. 4 [71]. Basic fuzzy control operations include system normalization, system fuzzification, fuzzy control functions based on pre-designed rules, system defuzzification, and system denormalization. This method has been applied in the design of balanced standing and turning control of a two-wheel robot vehicle [72]. It is also envisaged to predict human thinking as described in [73]. Fuzzy control approach is suitable for situations where system mathematical models or dynamic characteristics are too complicated to be described precisely. It uses linguistic rules in the control process to secure robustness and fault tolerance properties. Since the control system accuracy is largely dependent on the design of fuzzy rules, system precision and sensitivity could be of serious concerns.

[1]Garmin: http://www.garmin.com/
[2]TomTom: http://www.tomtom.com
[3]Fitbit: http://www.fitbit.com/
[4]Polar: http://www.polar.com/
[5]Sensoria: http://www.sensoriafitness.com/
[6]RunScribe: http://www.runscribe.com/

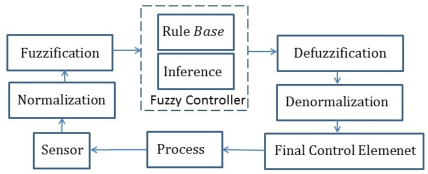


Fig. 4. Block diagram of fuzzy control

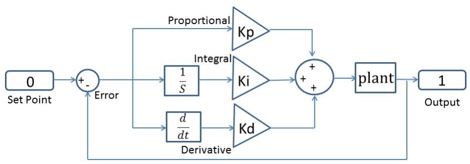


Fig. 5. Block diagram of PID control

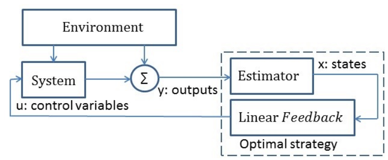


Fig. 6. Block diagram of linear optimal control

2) Model-based control method: Model-based control refers to the implicit or explicit use of system or process models in the control design. Following are some well-studied approaches.

- PID control
  This is the most basic and traditional control method. The block diagram of a PID controller is shown in Fig. 5. It can be seen that there are three parameters, Kp (proportional), Ki(integral), and Kd (differential), that can be tuned for system performance. Recently, fuzzy logic controller [74] or rule-based adaptive controller [75] has been employed to assist PID parameter setting. PID controllers have been found in some non-linear artificial manipulator applications [76].
  The most obvious advantage of PID controller is that its theory is simple, mature and applicable for most control situations. However, for big or complicated process, such as those involved in WBAN, PID controllers may not stabilise the systems because of the presence of large time delays, system inertia, and high-order system dynamics.
- Optimal control
  Fig. 6 shows the basic structure of an linear optimal control system. Control strategies with various emphasis can be applied. Commonly adopted strategies are described in the following.
  a) Robust Control: This method is used to deal with system uncertainties and disturbances [77]. The robust controller is best understood in terms of its frequency domain characteristics. Unlike self-adaptive controllers which respond to changes in system dynamics by adjusting their control parameters, robust controllers will maintain their control capabilities without any parameter adjustment. However, it can only cope with uncertainties within certain range due to its fixed parameter setting. A classic application of robust controller can be found in [78] where a servo manipulator is designed to handle dynamic interactions in diverse environment.
  b) Self-adaptive Control: The term ”Self-adaptive” indicates the essence of this method that controller parameters are set up on the basis of continuous learning of plant behaviours, which makes it good at handling system uncertainties, especially time-varying ones. A typical illustration is shown in Fig. 7 [79]. The controller has three inputs: system set point, feedback signals, and parameter adjustment information calculated from performance objective. The most obvious drawback of this controller is that control system performance cannot be guaranteed. The superiority of a self-adaptive controller is significantly affected by the structured uncertainty of system models. Its application in learning of reaching movement control was reported in [80].
  c) Stochastic Control: This method is mostly used in situations where the system and the disturbances are modelled in terms of their statistical properties [81]. In real time systems, stochastic control method provides a way to deal with random delays [82]. Stochastic controller is performance-oriented and is designed on the basis of probabilistic nature of the unknowns. Its weakness is its poor robustness against the error in the probabilistic model. Some human locomotion control research, such as walking analysis in [83] or walking posture control in [84], have applied this method.
  d) Model Predictive Control (MPC): In MPC theory, the next state of the system under control is calculated by computer programs prior to its occurrence. That is to say, computer algorithms will constantly predict control plant’s response to the designed algorithms [85]. This can be done by importing model information (such as a mathematical model), system constraints and cost functions into the problem solving controller as it is depicted in Fig. 8 [86]. MPC approach can overcome most system constraints such as non-linearity in inputs and outputs of control models. Outstanding control performance and strong robustness can be achieved. However, performance and robustness largely depend on the precision of control models, especially the accuracy of delay estimation. MPC control method has been used for diabetes treatment in terms of flexibly adjusting meal glucose according to blood sugar predictions [87].

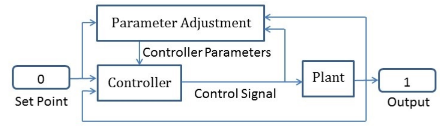


Fig. 7. Block diagram of self-adaptive control

V. Biofeedback Requirements for WBAN

A high level system integration is critical in biofeedback-enabled WBAN. Fig. 9 demonstrates an overview of design

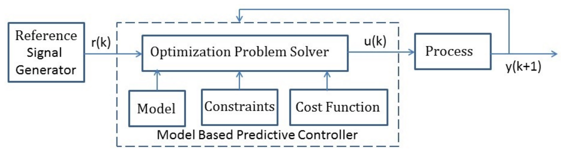


Fig. 8. Block diagram of predictive control

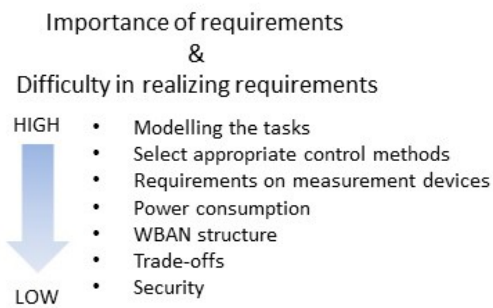


Fig. 9. Biofeedback Control System Design Requirements

requirements.

WBAN design includes four main stages: system modelling, system identification, signal processing, and control function integration [88]. Mathematical models are required to effectively represent real world control problems. System identification includes the recognition of inputs, outputs, and their potential relationships. Human locomotion is dynamic and complex. Kinematic parameters such as dynamic state, static state, and various environment impacts will all be considered. In the meantime, variables such as interferences, noises (e.g. body temperature, limb shaking, skin moisture, electromagnetic radiation, etc.), and disturbances should also be noted. To avoid the corruption with desired motion signals, highly accurate denoising mechanisms will be critical. Additionally, design of control functions including number of DoF and analytical methods as described in Section IV will significantly affect system performance. Customised design in accordance with each control subject's characteristics as well as the balance of all the trade-off factors will be key to success.

A typical trade-off here appears to be the feedback gain selection. It is universally acknowledged that high gain is beneficial in altering control subject's behaviours. However, high gain meanwhile results in excessive control actions. Moreover, high gain may increase system sensitivity to noises or lead to system instability [33]. Therefore, an appropriate feedback gain is essential in feedback design.

It should be noticed that suitable measurement units are also critical, especially when implementing in WBAN. According to [33], requirements on sensor selection include:

- Reliability: acceptable working range and data transmission capability
- Accuracy: data should be accurate enough to represent a real-world situation
- Responsiveness: flexible to rapid change and response
- Noise Immunity: no serious influence by noises
- Linearity: ability to compensate non-linear effects
- Non-intrusiveness: no impacts on control subjects

Particularly, network lifetime and power consumption is one of the main concerns in WBAN. To avoid unexpected suspension due to battery outage, either battery capacity needs to be improved or system power consumption should be minimised. It is required that battery maintenance should follow the balance between minimum interference, minimum tissue heating, minimum required transmission power and minimum failure [89–92]. Moreover, to reduce mutual effects between human body and WBAN (e.g. tissue energy absorption, electronic and magnetic radiation), low transmission duty cycles should also be added when requiring low transmission power [92].

Finally, data security is another concern. Data security include:

- CIA
  - Data confidentiality authorised users, groups, or organisations could have access to certain data depending on their authorisation level;
  - Data integrity: the entire set of user data should be maintained accurate and consistent;
  - Data availability: all the authorised users, groups, or organisations should be able to access data whenever they require.
- Data authentication: user end, control centre and online database should store user credentials for secure data communication.
- Data refreshing: active data should be kept updated according to requirements of analysis organisations.

All of these security aspects are set up to protect user privacy and information security. Distinguishable management plans for various applications are expected. For instance, users may like to share their training achievements to the whole online society, but they could only be willing to discuss their examinations or recovery progress with their attending doctors. That is to say, certain throughput, error rate, transmission bandwidth, delay, and security level should be maintained for individual requirements, even if it may sacrifice system performance or power consumption.

VI. Challenges in Biofeedback Control System Design

Applying wearable biofeedback control system to human body is still in the initial stage of research. Various research challenges (Fig. 10) need to be surmounted before this technology becomes common place. These challenges are elaborated on in the following.

Firstly, the effect of artificial biofeedback on humans is not fully understood. How will humans interact with control devices (sensors/ actuators) so that maximum desired performance can be achieved, how will power consumption be minimised without compromising system reliability, and how will the control algorithms deal with human mobility and the changing environment are still some of the challenging issues.

Secondly, selecting a suitable control algorithm is challenging due to the lack of knowledge on how to describe the problem in traditional control settings. The control methods introduced in Section IV have mainly been applied in industrial scenarios where plant systems have been accurately

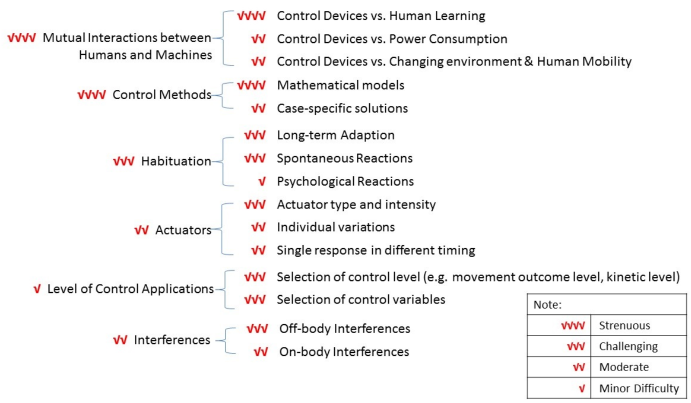


Fig. 10. Biofeedback Control System Design Challenges in terms of Difficulty to Achieve

modelled. At present, it is still not fully understood how the human body systems, e.g. locomotor, can be modelled in the traditional control sense. Since the control of human body is extremely complex and human subject variations result in diverse reactions to a single stimulation, conventional control solutions may be oversimplified. For instance, the controller for swimming rotation control and for surfing control could be entirely different even though the goal of restricting motion is the same. This characteristic of WBAN biofeedback control system will bring great opportunities for discovering new and creative solutions with acceptable adaptability for each human control subject.

The effect of applying biofeedback-enabled WBAN on human body is another unknown due to diverse psychological reactions (e.g. learning capability, adaptability). Ideally, users are expected to spontaneously adapt to biofeedback rapidly and precisely. By doing so, each control cycle is reduced and control effectiveness can be improved. Nevertheless, human reactions on external stimulations are diverse. The conjecture that artificial feedback mechanisms are able to be learnt and sustained after training needs to be proved.

In addition, the application of optimal actuation mechanism for providing biofeedback is still an open research issue. When applying control algorithms to subject groups, system performance can be over-dependent on control subjects' reactions to actuator type and intensity. This is challenging, firstly because of the way in which different subjects may perceive and respond to the actuation and secondly because an individual may respond differently to the same actuation applied at different times. This problem may be mitigated if precise models of the system i.e. human body, could be obtained so that the effect of the biofeedback could be predicted.

The biomechanics of human movement control as discussed in Section. III can be divided into four levels depending on the selection of control variables. The selection regarding control specificity and available complexity of control algorithms brings flexility for diverse control applications, yet the choice is pivotal for control performance. It is crucial to select the correct control variables that are sensitive to the application of feedback and can respond appropriately to external demands.

Finally, the deployment of artificial biofeedback technology should not encumber the user. This is challenging if on-body interference occurs when multiple sensing and actuation nodes in the WBAN are positioned on the human body and they adversely interact with each other. External interferences are brought by other electronic systems operating within certain range. Both types are unavoidable but could be minimized through use of filters or new sensors and actuators.

VII. Conclusion

In this paper, a review of ongoing biofeedback research in WBAN is presented. Typical applications of biofeedback system and their merits were highlighted and discussed. Additionally, the various applicable control methods available for feedback implementation were discussed followed by definition of the requirements. Biofeedback control systems will allow for constant monitoring and measurement, and will be able to provide instantaneous feedback. This feedback will potentially allow humans to efficiently self manage their health leading to more cost effective and proactive health care.

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