Real-time Biofeedback Systems: Architectures, Processing, and Communication

Anton Kos, Anton Umek, and Sašo Tomažič
Faculty of Electrical Engineering, University of Ljubljana, Slovenia
anton.kos@fe.uni-lj.si, anton.umek@fe.uni-lj.si

***Abstract*— Ubiquitous computing and wearable devices are offering new approaches in sports. Real-time biofeedback systems and applications can be used to speed-up the proper movement learning process. Movements must be processed in real time, what can pose a problem to small, light-weight, wearable devices with limited processing and communication capabilities, and battery power. We study two architectures of real-time biofeedback systems: local and distributed. The emphasis is on their properties when used in various biofeedback usage scenarios. Special focus is given on feedback loop delays and its real-time operation. A multi-user signal processing in football match is given as an example of high performance application that needs high speed communication and high performance computing. With growing number of biofeedback applications in sport, their complexity will grow, requiring new approaches in communication and motion processing.**

I. Introduction

Science and engineering offer new knowledge, expertise, and tools for achieving a competitive advantage in sports. The combination of wearable devices and ubiquitous computing are opening new dimensions in many areas of sport. One such example is the application of biomechanical *biofeedback systems*. One of the most common uses of biomechanical biofeedback is motor learning [2]-[3], which is based on repetition [1]. The primary focus of this paper is *real-time biomechanical biofeedback system* that can reduce the frequency of improper movement executions and speed up the process of learning the proper movement pattern.

The operation of biomechanical biofeedback systems largely depends on parameters of human motion and its analysis algorithms. Biomechanical biofeedback is based on sensing body rotation angles, posture orientation, body translations, and body speed. These parameters are generally calculated from raw data that represent measured physical quantities. Important parameters of human motion should therefore be adequately acquired by the chosen capture system (sensors). Sensors of the motion capture system should have: (a) sufficiently large dynamic ranges for the measured motion quantity, (b) sufficiently high sampling frequency that covers all frequencies contained in the motion, (c) sufficiently high accuracy and/or precision. The processing devices should have sufficient computational power for the chosen analysis algorithms. In biofeedback systems with real-time processing all computational operations must be done within one sampling period. When sampling frequencies are high, this demand can be quite restricting, especially for local processing devices attached to the user.

II. Challenges in Real-Time Biofeedback

Real-time biofeedback can only be incorporated successfully when: (a) human reactions are performed in-movement, i.e., inside the time frame of the executed movement pattern, and (b) the biofeedback system operates in real-time with minimal delay. An ideal real-time biomechanical biofeedback system is an autonomous, wearable, lightweight system with large enough number of sensors to capture all the important motion parameters. Sensor signals exhibit high enough sampling frequency and accuracy. Processing is done instantly and the feedback modality is chosen in a way that it is not interfering with the principal modality of the motion.

The main challenges in real system implementation are often contradictory. For example, under the constraints of technology, the ideals of being wearable and lightweight contradict the ideals of autonomy and processing power.

One important challenge is related to the sampling frequency. Achieving high sampling frequency is generally not a problem, but it leads to large amounts of sensor data that needs to be first transferred to the processing device and then analyzed. Problems that may occur are available bandwidth of the communication channels and the computational power of the processing device. The later is especially a problem in real-time biofeedback systems. Here it should be noted that higher sampling frequency yields shorter sampling time T_s, thus allowing less time for the complete computation cycle needed for each sensor signal sample.

Communication channel bandwidth, range and delays are another set of potential problems. Low power wearable devices usually have low channel bandwidth, and limited communication range. In packet based technologies the delay is linearly proportional to packet length and inversely proportional to bandwidth. Longer packets and/or lower bandwidth cause higher delays.

III. Biomechanical Biofeedback Systems

The architecture of the biomechanical biofeedback system includes sensor(s), a processing device, actuator, and communication channels. Together with a user they form a biofeedback loop. The architecture can be shelled out from Figure 1 or Figure 2

Sensors are essential components of the system, which should be designed to work with one or multiple sensor devices. Sensors capture body movements and are attached to the user. They are the source of signals and data used by the processing device. Inertial sensor based systems are very common. It should be emphasized that inertial sensor based motion tracking systems are generally mobile and have no limitation in covering space. Modern inertial sensors are miniature low-power devices integrated into wearable sensor devices. The *processing device* receives sensor signals, analyses them, and, when necessary, generates and sends feedback signals to the actuator (biofeedback device). Processing device is any device capable of performing computation on sensor signals. The computation can be performed in two basic modes: (a) during the movement; this mode requires processing in real time, (b) after the movement; this mode allows post-processing. The processing device can be located locally, on the user, performing *local processing* or remotely, away from the user, performing *remote processing*. The *actuator* uses human senses to communicate feedback information to the user. The most commonly used senses are hearing, sight, and touch. *Communication channels* enable communication between the independent biofeedback system elements. Although wireless communication technologies are most commonly used, wired technologies can also be used in practice.

A. *Real-time biofeedback system groups*

Real-time biofeedback systems can be divided into two basic groups on the grounds of processing device location. We denote a system with local processing as a personal biofeedback system, and a system with remote processing as a distributed biofeedback system.

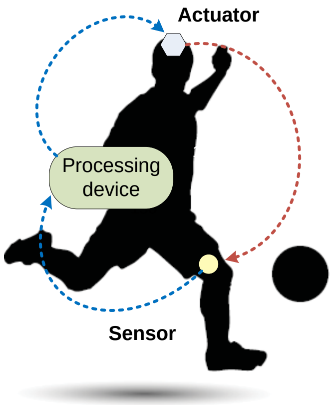

Figure 1. Personal biofeedback system. All devices of the system are attached to the user. Wearable processing device tends to be the most critical element of the system in terms of its computational power and/or battery time.

Personal biofeedback system is compact in the sense that all the system devices are attached to the user of the system and in close vicinity of each other, see Figure 1. Because the distance between devices is short, communication can be performed through low-latency wireless channels or over wired connections. The primary concern of personal biofeedback systems is the available computational power of the processing device. Personal version is completely autonomous. The user is not limited to confined spaces but free to use the system at any time and at any place.

In *distributed biofeedback system* sensor(s) and actuators are attached to the user's body, while the processing device is at some remote location, see Figure 2. The primary concern of distributed biofeedback systems are communication channel ranges, bandwidths, and increased loop delays. Distributed versions, especially the network one, have high computational power. With the local version of the system the user might be limited to a confined space if communication channel technology has short range.

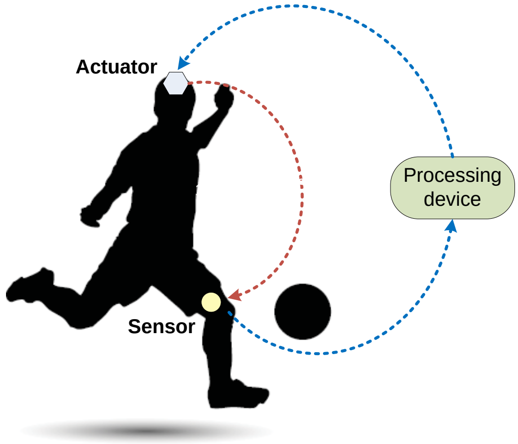

Figure 2. Distributed biofeedback system. Sensor(s) and actuators are attached to the user. The processing device is at the remote location, away from the user. Communication channels tend to be the most critical element of the system in terms of range, bandwidth, and delays or any combination of mentioned.

B. *Local vs. remote processing*

In wearable systems device energy consumption in the biofeedback loop is of the prime concern. One should consider choosing the system with the optimum energy consumption for the given task. According to [5] sensor devices consume many times more energy for radio transmission and memory storage than for local processing. This means that personal version with local processing could be more favorable option than distributed version with remote processing. Energy wise local processing at sensor device is very attractive, but there are some limitations that should be considered [5]:

(a) Algorithms developed in environments such as MATLAB are difficult to port to sensor devices.
(b) Sensor devices use fixed point microcontrollers for signal processing. Floating point operations must be simulated by using fixed point operation. This is slow and induces calculation errors.
(c) Total energy needed for all operations of one cycle could be higher than the energy needed for radio transmission of the raw data of the same cycle.
(d) Data from more than one sensor is processed by a single algorithm instance.
(e) Computational load of the algorithm could be too high to be handled by the sensor device.

When one or more of the abovementioned limitation apply, distributed system with remote processing is a better option. Its advantages are:

(a) The processing device has practically unlimited energy supply, high available processing power, and large amounts of memory storage.

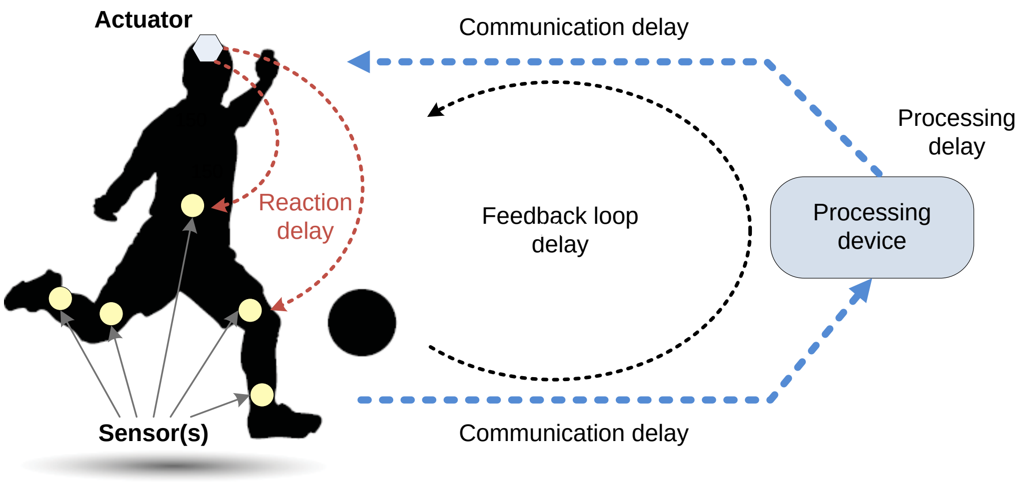

Figure 3. Real-time biofeedback system operation and delays. User movement (action) is captured by sensor(s) and their signals are sent to the processing device for analysis. Analysis results are sent to actuators, which use one of the human modalities to communicate the feedback to the user, who tries to react on it. The biofeedback system devices can control only the feedback loop delay, defined as a sum of all communication and processing delays of sensor(s), processing device(s), actuator(s) and communication paths.

(b) The processing is flexible in the terms of software environments usage, algorithm changes, algorithm complexity, choice of technology, choice of computing paradigm, etc.
(c) High performance computing (HPC) solutions can be used when the amounts of data increases and/or computational complexity rises.

C. Delays and processing times in the biofeedback loop

The delays in the real-time biofeedback system are illustrated in Figure 3. There are two basic points of view on delays in real-time biofeedback systems: (a) user's point of view and (b) system's point of view.

From the user's perspective the feedback delay occurs during the movement execution. This is the delay that occurs between the start of the user's action and the time the user reacts to the feedback signal. It is the sum of the feedback loop delay and the reaction delay and should be as low as possible. The feedback loop delay consists of system devices processing delays and communication delays between them. The processing delays of sensors and actuators are considered to be negligibly low comparing to communication delays and processing delay of the processing unit; therefore we consider them to be zero. The feedback loop delay should be a small portion of the human reaction delay, which depends on the modality (visual, auditory, haptic) used for the feedback. For example, reaction delays for visual feedback are around 250 ms for amateurs and around 150 ms for professional athletes [6].

Communication and processing delays within the feedback loop depend on the parameters of the equipment and technologies used. Some of the most important parameters are: sensor sampling frequency, processing unit computational power, communication channel throughput, and communication protocol delay. The feedback loop delay t_F is the sum of communication delays t_{c1} and t_{c2}, processing delay t_p, sensor sampling time t_s and actuator sampling time t_a:

$$t_F = t_s + t_{c1} + t_p + t_{c2} + t_a \quad (1)$$

In general the biofeedback system operates in cycles that are equal to sensor sampling time. If we want to ensure the real time operation of the system, processing time should not exceed sensor sampling time $t_p \le t_s$.

IV. COMMUNICATION

Motion capture systems can produce large quantities of sensor data that are being transmitted through communication channels of a biofeedback system. When real-time transmission is required, the capture system forms a stream of data frames with sensor's sampling frequency. In real-time biofeedback systems two main transmission parameters are important; bit rate and delay. While bit rate depends on the technology used, delay t_{delay} depends on signal propagation time t_{prop}, frame transmission time t_{tran}, and link layer protocol t_{MAC} or medium access control protocol (MAC).

$$t_{delay} = t_{prop} + t_{tran} + t_{MAC} \quad (2)$$

At constant channel bit rate R, the transmission delay is linearly dependent on frame length L.

$$t_{tran} = \frac{L}{R} \quad (3)$$

Propagation time on different transmission media is 3.3 to 5 nanoseconds per meter and is sufficiently small to be neglected. MAC delays vary considerably with channel load, from a few tens microseconds to seconds. In lightly to moderately loaded channel MAC delays are below 1 ms. In most cases that leaves the transmission delay as the main delay factor.

Personal biofeedback systems can use wires or body sensor network (BSN) technologies that have bit rates from a few tens of kilobits per second up to 10 Mbit/s [5]. Considering the projected sampling frequency of 1000 Hz, that yields the maximal possible frame size in each sampling period in the range of a few tens of bits (a few bytes) up to 10,000 bits (1250 bytes). The range of BSN is typically a few meters.

Distributed biofeedback systems use various wireless technologies with bit rates from a few hundreds of kilobits per second up to few hundreds of Mbit/s [7]. Considering the projected sampling frequency of 1000 Hz, that yields the maximal possible frame size in each sampling period in the range of a few hundreds of bits up to 100,000 bits. The range of considered wireless technologies is between 100 m (WLAN) and a few kilometres (3G/4G).

V. Real-time processing

In real-time biofeedback systems the processing device is receiving a stream of data frames with inter-arrival times equal to sensors' sampling time. To assure real-time operation of the system, the processing time of any received frame should not exceed the sampling time. This depends on many factors: computational power of the processing device, sampling time, amount of data in one streamed frame, number of algorithms to be performed on the data frame, complexity of algorithms, etc.

In section III we have studied the trade-offs between the local and remote processing of biofeedback signals. While many examples of biofeedback applications, that do not require a lot of processing, exist, enough opposite examples can be found. One example is a real-time biofeedback system for a football match. Parameters in the capture side of the system are: 22 active players and 3 judges, 10 to 20 inertial sensors per player, 1000 Hz sampling rate, up to 13 DoF data. The data rate produced is between 92 Mbit/s. and 200 Mbit/s. Such data rates can presently be handled only by the most recent IEEE 802.11 technologies that promise bit rates in Gbit/s range.

The presented example clearly implies powerful processing device and high speed communication channels. Algorithms that are regularly performed on a streamed sensor signals are [8]-[10]: statistical analysis, temporal signal parameters extraction, correlation, convolution, spectrum analysis, orientation calculation, matrix multiplication, etc. Processes include: motion tracking, time-frequency analysis, identification, classification, clustering, etc. Algorithms and processes can be applied in parallel or consecutively.

Delay is the primary parameter defining the concurrency of a biofeedback system, as viewed from the user's perspective. The feedback delay, which is the sum of all delays of the technical part of the biofeedback system (sensors, processing device, actuator, communication channels), should not exceed a small portion of the user's reaction delay. To present two exemplary calculations for movements with high dynamics and movements with low dynamics. Let us set the maximal feedback delay at 20% of user's reaction delay. Considering that the reaction delay is around 150 ms [6], the maximal feedback delay is at most 30 ms. the two examples are:

High dynamic movement: biofeedback system sampling frequency should be high, for example 1000 Hz. Samples of captured motion are occurring every millisecond, accordingly the processing device must calculate one result every millisecond. The processing device receives a new frame of sensor data every millisecond and it has 1 ms to perform all the calculations, leaving 29 ms for the communication path delays. The implementation of high dynamic real-time biofeedback systems is feasible, if the processing device has enough processing power, the communication delays should not be a problem. The use of the *distributed version* of the biofeedback system is more likely.

Low dynamic movement: biofeedback system sampling frequency can be set relatively low, for example at 40 Hz. Samples of captured motion are occurring at 25 ms intervals, accordingly the processing device must calculate one result every 25 ms, leaving only 5 ms for the communication delays. The implementation of real-time biofeedback systems is feasible, if the communication delays are low, the processing power should not be a problem. The use of the *local version* of the biofeedback system is more likely.

VI. Conclusion

Science and advanced technology with connection to ubiquitous computing are opening new dimensions in many areas of sport. Real-time biofeedback systems are one such example. To assure the operation in real time, the technical equipment must be capable of real-time processing with low delay within the biofeedback loop. Challenges are present in all phases of real-time biomechanical biofeedback systems; at motion capture, at motion data transmission, and at processing. With growing number of biofeedback applications in sport and other areas, their complexity and computational demands will grow, possibly requiring new approaches in communication and processing paradigms.

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