Chapter 4

Human Movement Control

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Additional information is available at the end of the chapter

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Abstract

Control theory is used to design automatic systems, which are able to maintain a desired behaviour despite of the disturbances. It is present in different machines we use every day; in fact, technical systems in our homes and all the industries are hard to imagine today without these concepts. Moreover, the same theories can be used for modelling life processes as a collection of inputs, outputs, plants and control loops. Feedback is one of the main concepts behind control; in particular, several examples of physiological control mechanisms for regulating life aspects can be found in the human anatomy, for example, blood pressure, cholesterol levels, body movements, the equilibrium, etc. Those processes can be damaged by the aging effects, diseases, accidents or when the mechanism has been broken and cannot be recovered naturally; consequently, it will be required external assistance. A relative new field in control theory is related with developing technology for helping with physiological and medicals problems. However, in comparison with machines, those physiological processes are highly nonlinear, with delays and slow responses. Another problem is when human becomes the operators using their capacities of decision making to close the control loop, as they are prone to errors and mistakes. For those reasons, the biomedical system needs to be carefully designed and several aspects have to be considered. This chapter gives a small review of some internal and external control processes within the human body and discusses how to interact with them for designing biomedical devices. Under this design scheme, a practical application of a smart electric wheelchair for assisting persons with strong disabilities is presented. These assistive robotic systems are in close contact with the user, and thus, it is determinant to have a user-friendly relation between the human and the interface. Therefore, intuitive interfaces were included in the design and an intelligent navigation assistant to guarantee a collision-free path.

Keywords: human–machine interaction, control, feedback, biomedical control, sensors, rehabilitation, homeostasis, human anatomy

1. Introduction

Nowadays, it is difficult to imagine a lot of systems working without control, as its application simplifies everyday tasks. It helps to make processes [16] more efficient and faster than those made by hand. Examples are found in different areas: automotive, home appliances, industrial production, financial transactions and medical processes.

Even though control theory was initially developed for physical systems by mathematicians, physicists and engineers, it can be applied to model and explain physiological systems. This does not imply that all the control theories fit exactly into biologic systems, since most of them contain essential nonlinearities. However, an approximate solution can be found for particular cases by looking similarities between linear and nonlinear characteristics [1–4]. It is worth mentioning that from the engineering control perspective, it is searched an optimal result and the system is normally well defined; on the contrary, in physiological control systems, it is searched for an approximate value between boundaries and the system is unknown or hard to define. That is a consequence of the physiological differences between individuals.

Control processes are present in biological systems with their own inputs and outputs. In particular, the human body and the environment are sensed by natural transducers, which provide neural impulses to special areas of the cerebral cortex. After being interpreted by the brain, orders are sent to the muscles to contract and glands to secrete, with the aim to maintain homeostasis. This automatic process controls different mechanisms in the human body, and they will be described in Sections 2.1 and 3.

Human control includes systems with feedback (exteroceptive or proprioceptive), and two categories are considered: indirect or direct. Indirect or automatic means that the individual has no control over a regulatory internal process or the received technology (e.g. implants). On the other hand, direct human interaction with machines, tools, instruments or interfaces requires a series of actions to control the system. These actions start with an initial stimulus to the muscles, joints or tendons; thus, the sensors provide information about the movement that has to be done in order to alter or maintain the stimulus for the next step. In this way, movements follow a sequence that terminates when the task has been accomplished.

It is important to distinguish that in conventional control machines; negative feedback is explicitly subtracted from the reference point. On the other hand, in physiological control systems, negative feedback is embedded in the plant [5] and it is hard to know the set point.

Furthermore, the applied methods in today's systems have evolved from sequential logic to artificial intelligence. In addition, the role of human operators has evolved too, from manually adjusting the system to control supervision. The feedback information, usually displayed in a computer or in an industrial panel, can be interpreted by a human operator or by specialized software to drive the actuators that regulate the process.

In order to motivate the design of new technologies for healthcare, this chapter presents an overview of concepts related with biomedical control. First, it is presented an overview of the nervous systems and some biological processes to understand what happens internally with the body control. Those processes are interpreted as inputs, outputs, blocks, feedback loops, and transfer functions. Then, it is explained how humans act as operators and their limitations; and therefore, what considerations should be done to interact with devices. Finally, with all these in mind, a case study of assistive technology is presented.

2. Nervous system

The human body is a complex machine that poses many sub-systems interacting each other and a main control to make efficient this interaction: the nervous system. For an effective control, the nervous system takes inputs from all the sensors in the body. The sensors send information by nerve impulses that travel to the brain through the spinal cord. Then, according to the nature of the stimulus, there is a reaction sent to the effectors: contractions in the muscles and secretions in glands. Examples of the interaction between the nervous and other systems can be seen in **Table 1**.

System	**Muscular action**	**System reaction**
Skeletal system	Receptors send sensory input from bones and joints to brain	Protect sense organs. Store Ca^2 for muscle function
Respiratory system	Regulate breathing rate	Provide Oxygen. Gets rid of CO_2 produce by neurons
Muscular system	Controls muscle contractions. Receive information of muscles	Move eyes. Permit speech. Creates facial expressions
Cardiovascular system	Controls nerves that regulate the heart. Controls dilatation of blood vessels. m	Blood vessels deliver nutrients and oxygen. Remove waste
Digestive system	Control contractions for digestive track movements	Provide nutrients for grow, maintenance and repair
Urinary system	Control muscle contraction that permits urination	Eliminates creatinine. Kidneys maintain levels of Na^+, K^+ and Ca^{2+} needed for nerve conduction
Endocrine system	Innervates certain glands secretion. The hypothalamus is part of these systems	Hormones are involved in the development of the brain
Integumentary system	Nerves regulate size of cutaneous blood vessels. Activate sweat glands and pili muscles	Skin protects the nerves. Helps regulating the temperature. Send information from skin receptors
Reproductive system	Starts puberty. Control erections. Control contraction of the uterus and ducts carrying gametes	Sexual hormones masculinize or feminize the brain. Influence sexual behaviour

Table 1. Nervous system and its interaction with another systems.

The nervous system is described by two main components: the central nervous system (CNS) integrated by the brain and the spinal cord, and the peripheral nervous system (PNS) that includes sensory neurons, ganglia and the nerves connected to the CNS. Both systems work together to capture information from the current state of the body and from the environment. The brain is the main control centre and interprets all the collected information. The communication between the body and the brain is made through the PNS. The PNS is divided into the somatic and the autonomic nervous system. The somatic or voluntary nervous system consists of nerves that connect the spinal cord with muscle effectors and sensory receptors. The autonomic nervous system regulates involuntary processes like the breathing rate or the blood pressure. This classification makes possible to distinguish the characteristics of human control.

2.1. Autonomic physiological control

Before describing these systems, it is necessary to state some of the differences between conventional and physiological control. First, in conventional control, it is intended to design for accomplishing a specific task and fine tune of the parameters is needed for optimal results. In comparison, physiological control is versatile and accomplishes many tasks at the same time. Second, conventional systems are well defined and their state variables may be independent. In contrast, physiological systems are usually unknown and difficult to analyse, as these systems are highly dependent between each other. Furthermore, in conventional control, it is normal that the feedback is directly subtracted from the input, and under this scheme, it is clear the use of the feedback. However, in physiological systems, the feedback is embedded within the plant and it is not clearly observed. Lastly, it is intended that the engineering systems do not change over time; meanwhile, physiological systems are adaptive to the changing environment. A summary of these differences can be seen in **Table 2**.

Conventional control	Physiological control
Designed to accomplish a specific task	Built in versatility
Fine tune for optimal results	Capable of doing several jobs
System is generally known	Unknown and difficult to analyse
Independent	Cross-coupling among different systems
Direct feedback	Adaptive to plant change
Preferred linearity	Highly nonlinear
Explicitly feedback	Feedback embedded in the plant

Table 2. Difference between conventional and physiological.

To develop every day activities, humans need to control the intake and outtake of energy within the system. The body converts the consumed food and the breathed air into the required energy. For this conversion to work, it is necessary a system to takes the food, another one to transform it, another to distribute it and one more to controls all of them. In fact, this conversion is done by the digestive, cardiovascular and respiratory systems; and they are controlled by the nervous system. Although there are many other systems for controlling the processes within the human body (e.g. reproductive, lymphatic, endocrine systems, etc.), they will not be discussed in this chapter due to their specificity.

2.2. Homeostasis

Homeostasis is the maintaining of stable, internal conditions of the human body within specific limits [7–9, 27]. To maintain these conditions, it is required negative and positive feedback. Negative feedback works by detecting changes using sensing mechanism or receptors, and thus, a control centre evaluates the changes and activates mechanisms to correct it. Once the condition has returned to normal, the corrective action is stopped (**Figure 1**).

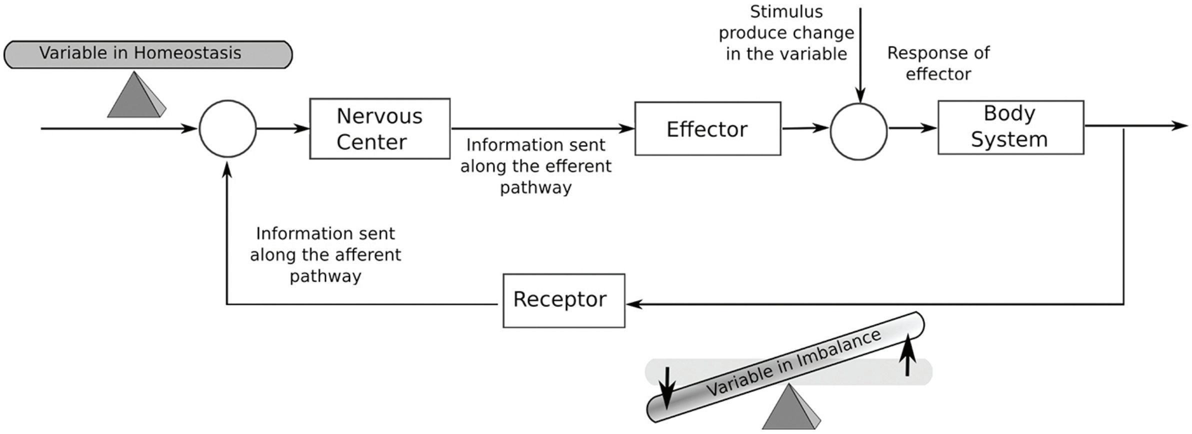

Figure 1. Conceptual scheme of the control of homeostasis system. It is intended to achieve a balance. When this balance is broken, the nervous system activates one of its effectors to correct the situation.

An example of how the human body maintains homeostasis using negative feedback is the glucose concentration on the blood. After a meal, the body increases the glucose by the absorption from the digestive track. To compensate this glucose intake, the alpha cells in the pancreas secrete insulin, a substance which stimulates the liver and muscle cells in order to absorb the excess. Moreover, after certain activity the glucose may drop, in this case the beta cells in the pancreas secrete glucagon, which stimulates the liver to release the stored glucose. Once the levels have returned to normal, the secretion of glucagon stops.

Positive feedback intensifies a condition beyond normal limits: in childbirth, a hormone (oxytocin) is released to intensify and speed up every contraction. The increase in contractions releases more of the hormones, intensifying and speeding up even more. The cycle stops once the child has born and the positive feedback stops. Another examples of positive feedback are lactation and blood clotting where extra production is needed.

2.3. Digestive system control

The digestive system controls the food breakdown into small molecules, which can be absorbed by the body. This is done during several processes: the ingestion of the food is followed by the propulsion, which is performed by moving the food along the digestive track by contracting and relaxing the smooth muscles. Within the body, the food is separated into smaller molecules by mechanic movements and chemical decomposition. As a result, the nutrients can be absorbed by diffusion or active transportation into the blood stream. The unabsorbed material is disposed through the anus. The digestive system is composed of mouth, pharynx, oesophagus, stomach, small intestine and large intestine. It may also use accessory organs such as teeth and tongue, salivary glands, liver, gallbladder and pancreas. Regulation of the digesting system is controlled by neural reflexes and hormones (gastrin, secretin, cholecystokinin and glucose insulinotropic peptide), see **Figure 2**.

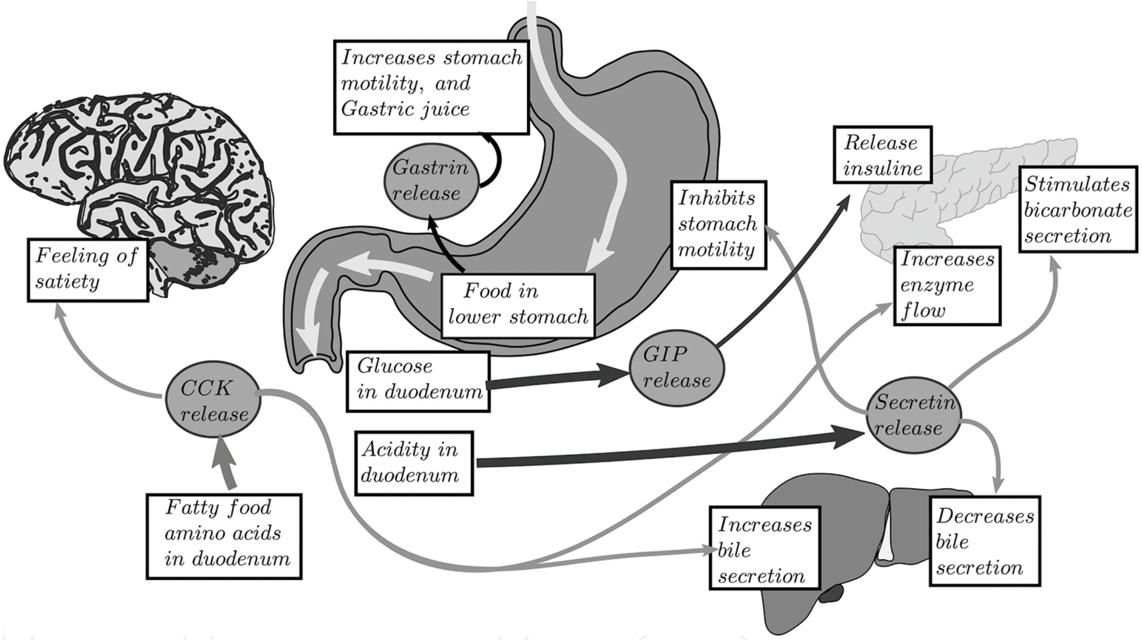

Figure 2. Conceptual scheme of the digestive system with all the different hormones and what they control.

Some of the functions of these hormones are regulate the appetite if the stomach is full (CCK), regulate the insulin released into the body by detecting the sugar levels in the duodenum (Glucose insulinotropic peptide), change the mobility of the stomach if food is detected in the lower stomach (Gastrin), adapt the bile as a consequence of the acidity in the duodenum (Secretin) and many others. It is worth mentioning that those are not the unique tasks and that these hormones adapt and compensate each other to work better.

2.4. Cardiovascular control

The cardiovascular system is composed of blood, blood vessels and the heart. It is in charge of distributing nutrients, hormones and oxygen through the body, as well as removing metabolic waste. It also regulates the temperature, helps to protect the body and regulates the pH. In normal situations, the heart beats without nervous control; but, when there is a change due to exercise or trauma, it is altered by the cardiovascular centre located inside the medulla. A reflex response occurs when there is a change in the blood pressure or the chemistry within the body. This makes the cardiovascular centre to stimulate or inhibit the cardioacceleratory centre, the cardioinhibitory centre and the vasomotor centre until equilibrium or homeostasis is reached [10] (**Figure 3**).

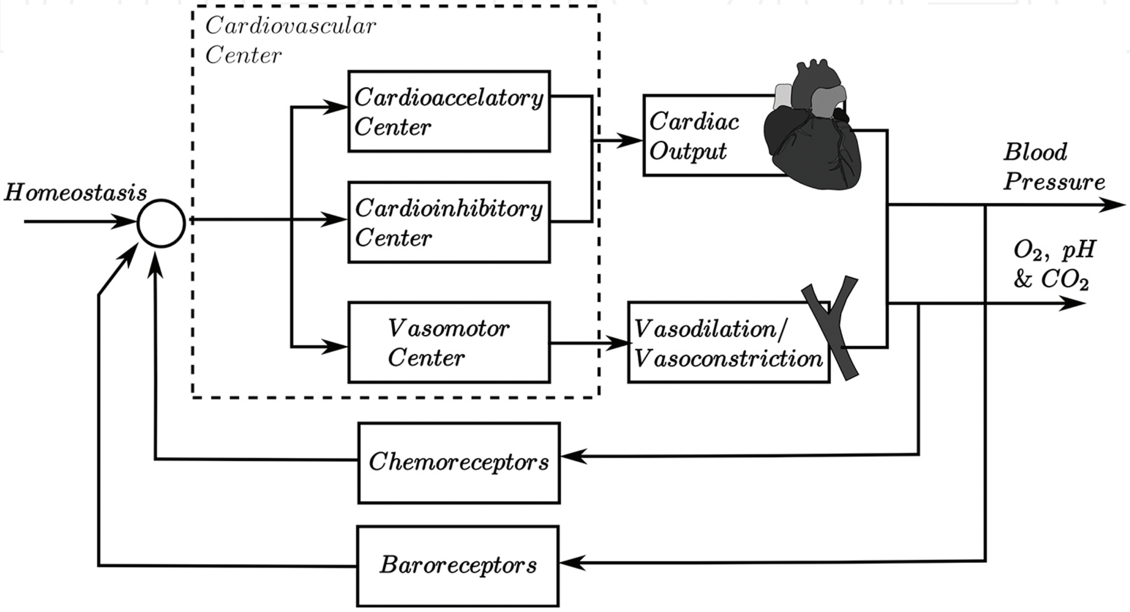

Figure 3. Conceptual scheme of the cardiovascular control with its sensors, what they control and what they alter.

2.5. Respiration control

Respiration is the intake of the air, in order to absorb the oxygen necessary for metabolic processes in the body. Respiration is done by the contraction of the intercostal muscles and the diaphragm. The areas in the brain in charge of stimulating the contraction are called respiratory centres. These centres are the medullary inspiratory centre, the pheumotaxic and the apneustic areas. The medullary inspiratory centre, located in the medulla oblongata, controls the contraction by stimulating rhythmically the nerves of the external intercostal muscles and the diaphragm. The expiration occurs when the muscles relax, except if the breathing is happening fast; in these cases, the expiration is done by stimulating the expiratory muscles: the internal intercostal muscles and the abdominal muscles. The pheumotaxic and the apneustic areas are in charge of inhibiting or stimulating the inspiratory centre, first to avoid the lungs for over inflating and second to prolong the contraction of the inspiratory muscles.

There are three sensors that have influence over the stimulus generated by the respiratory centres: the stretch receptors, the central and the peripheral chemoreceptors. The stretch receptors, located in the walls of the bronchi and bronchioles, inform when the lungs are expanded to their physical limit, stop stimulation to the inspiration muscles and start expiration. The central chemoreceptors send a signal to increase the air intake when they detect changes in the cerebrospinal fluid acidity, caused by the entrance of CO_2 from the plasma. Finally, the peripheral chemoreceptors monitor the acidity in the blood caused by an increase of pH or pCO_2, or a decrease in pO_2.

3. Neuromusculoskeletal system

The human skeletal and muscular systems create the forces to perform several tasks. Generally speaking, this system is the one that allow us to interact with the directly. In order to activate the muscles, it is required an electrical current that comes from the nervous system, which can be seen as a control apparatus that poses a linkage system (body segments), actuators (muscles), sensors (proprioceptive and tactile sensors, visual and vestibular system) and the controller (CNS), see **Figure 4**.

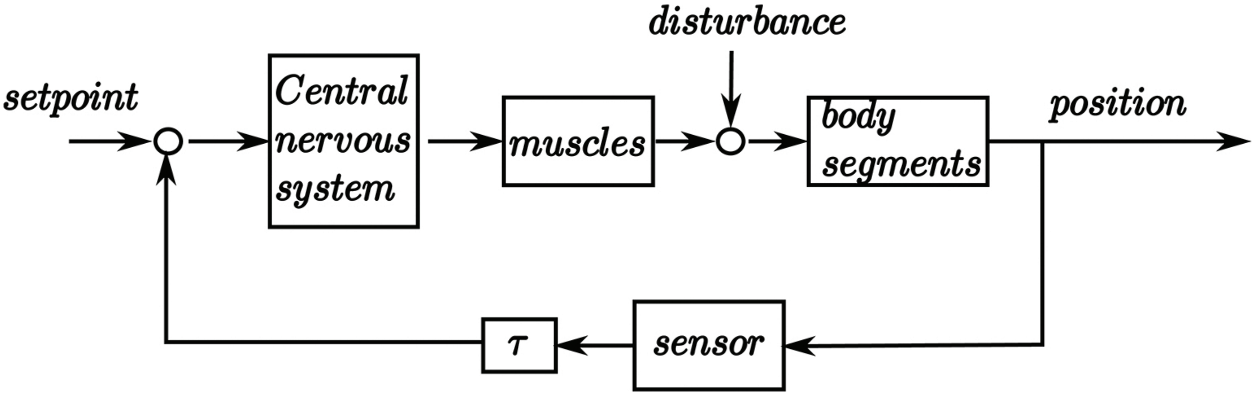

Figure 4. Conceptual scheme of the neuromusculoskeletal system where the nervous system controls the muscles that would move the bones and that would send information about its state back to the brain.

The CNS controls the system through "wires" conducting electrical currents called Nerves. To generate this loop, a desired position (set point) is created somewhere in the brain. This position is compared with the actual position of the limb and the CNS sends a neural signal to the correct muscles. The muscles, by means of contractions and relaxations, pull or release forces to the bone; thus, together start moving if there are no restrictions by the environment. An extra input in the system is the external forces or disturbances that act on the body, deviating it from the desired set point. The movements and positions are detected by the sensors located in muscles, joints, skin, etc. besides the visual and vestibular systems analysis.

To study this control system, it is required to analyse the biomechanical behaviour of the body. One of the biggest problems is that, without invasive techniques, it is hard to measure the necessary variables in living subjects. The problem complicates the analysis of the body mechanisms, since only external and a few internal signals can be measured.

The variables that are used in the description of any movement can be grouped as: kinematics, kinetics, anthropometry, muscle mechanics, electromyographic and the human senses [11].

Kinematics: The Kinematic variables only deal with movements, and they do not take into consideration the forces that cause that movement. These variables include linear and angular displacements, besides velocities and accelerations. They can be referred to another segment, anatomical land marks or a global coordinate system (normally outside the body). The skeletal system consists of joints, bones and ligaments; and it defines the degrees-of-freedom (DOF) of motion. In general, one bone referred to another has three rotations and three translations. These motions are limited by either another bone or by passive structures, such articular surfaces and ligaments. If one of the motions is limited or it is constrained to a small movement, the number of DOF is diminished by one. Once the reference is understood, the movements can be recorded and analysed. The movements are recorded using either a camera, markers, accelerometers, electromagnetic devices or a combination of them all.

Kinetics: Contrary to Kinematics, kinetics study the force that causes the movement. These forces can be either internal or external. Internal forces include muscle activity, the ligaments or friction from muscles and joints. Moreover, external forces come from the ground or from external loads. Kinetics includes the moments produced by forces, the mechanical power, and the energy changes in the human body.

Anthropometry: Anthropometry is used since the metrics of the body are necessary to create a good model. This model requires the mass of limb segments, the use of mass centres, centres of rotation, moments of inertia, angles of pull of muscles, muscle cross-sectional area and more.

Muscle Mechanics: Muscles are the ones that generate the internal forces to control the system. Their actuation is highly nonlinear, with varying possible forces according with its length and contraction velocity. Muscles also possess underlying properties as mass, viscosity and elasticity. These properties, either active or passive, need to be considered to construct a better model. Two basic muscle models are generally used: the Hill-type and the Huxley-type. The first one considers more the dynamical properties, while the second one goes one step beyond considering muscle contraction on micro-level.

Electromyographic: The brain [6] controls the activation of the muscles through an electrical signal, known as electromyography (EMG) which describes the precise contraction of each muscle. Besides, EMG signals give information about the joint activity of different types of muscle fibres and the fatigue state of the muscle.

Human sensors: Humans are filled with sensors for the correct control of the body (feedback). These sensors go from tactile, pressure and stretch, length and velocity in the muscle fibres, force sensors in the muscle tendons with even more global the use of the visual and vestibular system (see Section 3). Although there are many more sensors, they are not particular essentials for any motor control scheme.

The relationship between all this pathways and groups can be observed in **Figure 5**. Where the pathways interconnect to create a connection with excitations and inhibitions capable of generating movement. Some of these sensors can be seen in the Section 3.1. Have to be noted that although is in general command of the movement, there are still some reactions that are control peripherally. This is done as a reaction to harmful situations and prevents the body from damaging.

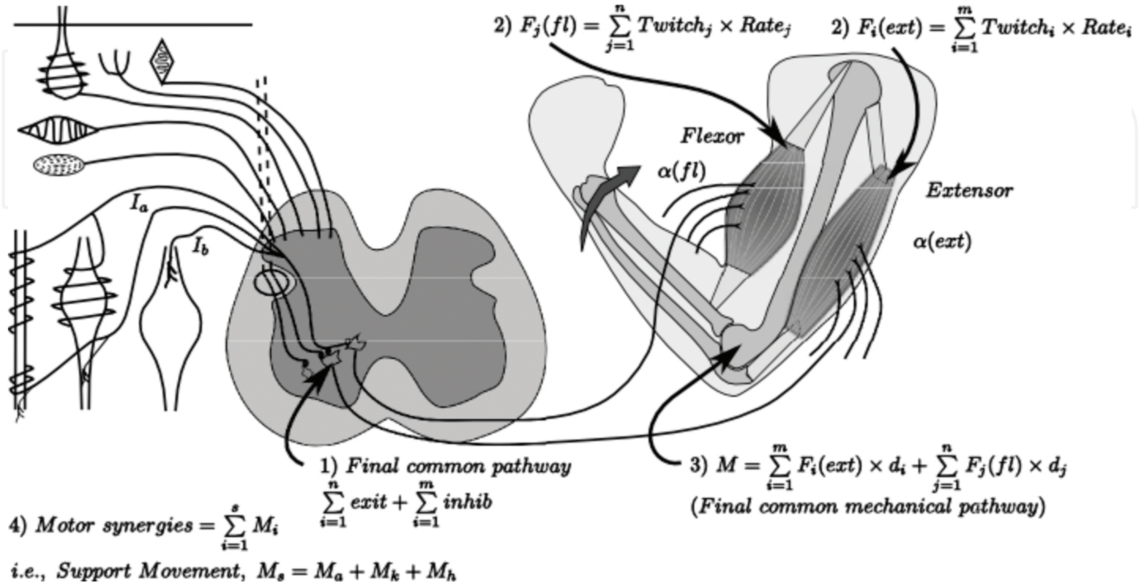

Figure 5. Neuromusculoskeletal integration. Four levels of integration in the neuromusculoskeletal system, which provides control of movement. (1) Summation of all neural excitatory/inhibitory inputs to the α motoneuron. (2) The tendon force resulting from the summation of all motor twitches from the recruitment of all active motor units. (3) The resulting movement of the agonist and antagonist muscle movements. (4) Combination of movements acting synergistically towards a movement.

3.1. Human perception

Human perception is related to our natural sensory system. In general, a sensor is a device that receives and responds to stimuli. The sensors are a fundamental part in control systems, as they provide information to the operator for compensation of variables against disturbances. The human body has several sensors for detection of sound waves, light rays, flavours, odours or physical contact. Those environmental signals are transduced by the sensory system into neural impulses for the brain.

In other words, the perception is the feedback for controlling external systems, since information from different variables in the environment is sensed at the same time. As an example, consider the activity of driving: the human operator senses the world by the vision (combining external aspects from the road and the car´s gauges), the somatosensory (both in the arms and legs), the equilibrium (mainly rotational movements) and the hearing (surrounding alerting sounds). The collected information is transduced into neural impulses that travel to the brain for interpretation and processing. Finally, decisions are made and orders are sent to the corresponding actuators. Particularly, adjustments in the steering and braking are achieved by moving our limbs.

The natural transducers in the human body are epithelial cell or neurons, classified by the type of stimulus they sense. Five main categories are distinguished: mechanoreceptors for detecting vibrations, tapping and pressure in the skin; photoreceptors located in the eye to detect light stimuli; chemoreceptors, which are present in smell and taste senses, and are stimulated by chemical reactions; Thermoreceptors to detect temperature changes in the skin; and pain receptors, located in the skin for detecting tissue damage.

Moreover, the human sensations are classified as the somatesthetic senses and the special senses. The former senses are located over wide areas of the body, and they communicate to the spinal cord first and then possibly with the brain. These sensations are known as cutaneous. The second category includes those senses to detect changes by specialized organs in the head, and they conduct information directly to the brain (the taste, the smell, the hearing, the equilibrium and the vision). A specialized area of the brain receives information from each sense, and thus the collected information from all the senses is interpreted together to perceive the environment.

3.2. The somatosensory system

Sensory receptors in skin, muscles, joints, tendons and some internal organs are connected with the dorsal column system by nerve fibres. Thus, the nerve impulses from those sensors are received by the somatosensory areas of the cerebral cortex. There are three types in this system:

Proprioceptors: These mechanoreceptors are specialized cells wrapped by nerve endings, which generate nerve impulses with the muscles stretching information. This information is used to maintain the muscle tone for the equilibrium and posture, despite of external forces acting over our body.

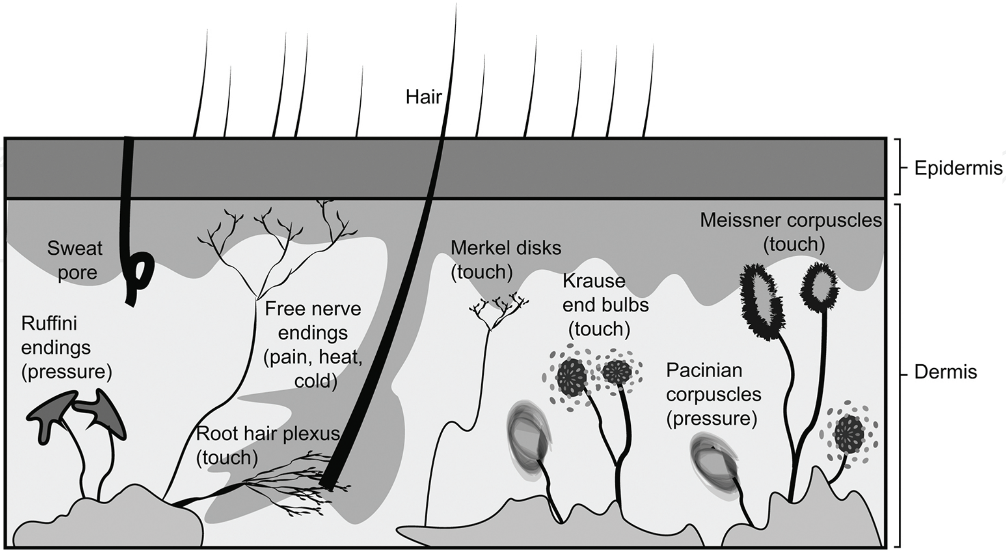

Figure 6. The sensory receptors contained in the skin layers. These receptors are connected with the dorsal column by nerve fibres.

Cutaneous receptors: The dermis is a skin layer which contains tiny receptors for the sensations of fine-touch, pressure, vibrations and temperature, as shown in **Figure 6**. The Meissner corpuscles, located in the most sensitive parts of the body, and the nerves around hair follicles are related with fine touch sensations. Moreover, the receptors to detect cutaneous pressure changes are formed by connective tissue and nerve fibres; there are three different types: Pacinian corpuscles, Ruffini endings and Krause end bulbs. Finally, warmth and cold temperatures are detected by free nerve endings in the epidermis. It is worth to mention that there are specialized receptors for cold and others for warmth.

Pain receptors: Nociceptors detect chemical substances, which are released when the tissue is damaged because of inflammation. Pain receptors are free nerve endings located within the skin and internal organs. These fibres enter the spinal cord and terminate in the dorsal horn.

3.3. The smell and the taste

The smell and the taste senses are very similar as both of them use chemoreceptors, which are the special cells that generate nerve impulses when they react with molecules present in food or air. The olfactory and taste anatomies, besides the chemoreceptors for those senses, are illustrated in **Figure 7**. Conceptual scheme of the digestive system.

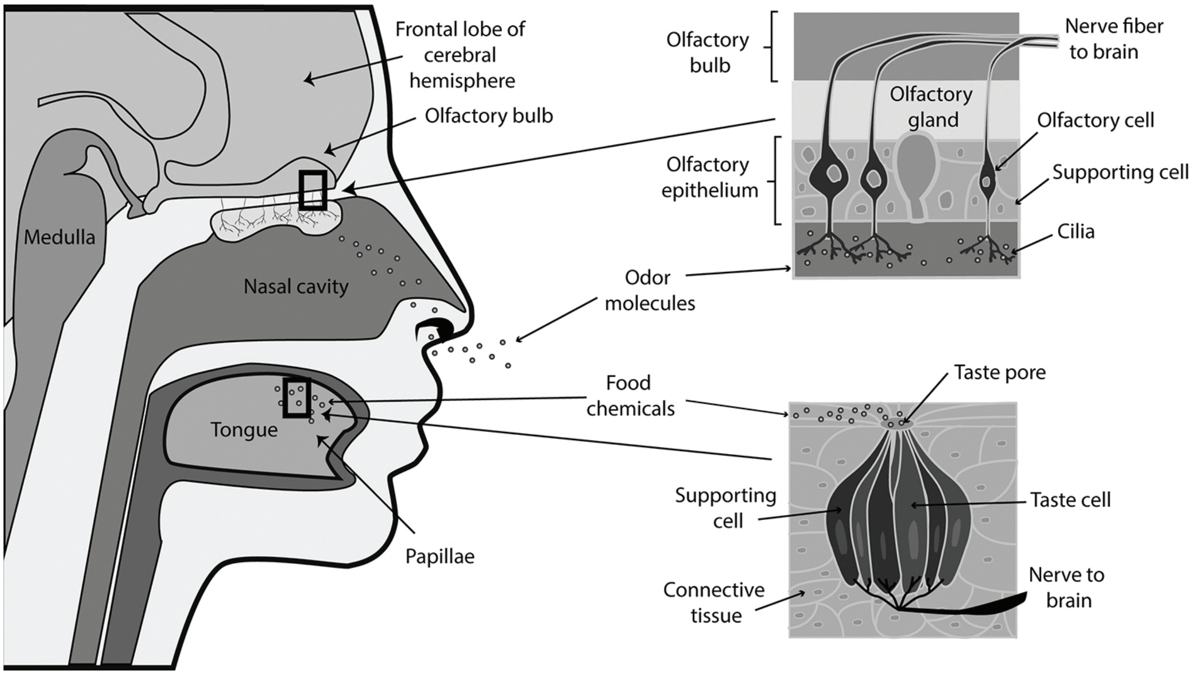

Figure 7. Conceptual scheme of the digestive system.

The olfactory cells are located in the olfactory epithelium, a special epithelial tissue in the superior nasal cavity. These cells end in thick protuberances, called cilia, which bear proteins for odour molecules. The cilia are sensitive only to one type of odour molecules; consequently, the activated neurons in the olfactory bulb area of the brain correspond to that class exclusively.

An odour contains different molecules, which stimulate a combination of different neurons. So on, those neurons are communicated by the olfactory tract with the olfactory areas of the brain to interpret odours.

For the case of the taste sense, the chemoreceptors are located on taste buds distributed on specialized papillae at the tongue. These cells end in protrusions, called microvilli, which bear receptor proteins for special molecules. According to the tongue area, the taste buds are more sensitive to particular tastes, and the brain is able to distinguish sour, salty, bitter and sweet tastes. The taste cells emit nerve impulses for the brain, who is able to integrate the incoming information from other taste buds to interpret the taste.

3.4. The vision

The eye is the organ responsible of vision for perceiving the world. The eyeball has three layers: the sclera, the choroid and the retina. There are two types of photoreceptors located in the retina: the rod cells and the cone cells. The rods are sensitive to low-intensity light; as a consequence, they are responsible for night vision. On the other hand, the cones are sensitive to high-intensity light and different wavelengths; thus, they are responsible for day vision. When acute vision is required, the light is focused in a special region of the retina called the fovea centralis, where a high density of cones is allocated.

The photoreceptors have membranous disks with special visual pigments. As the molecules in the membranes are stimulated by light, sequences of reactions provoke nerve impulses. The sensory fibres, going from the retina to the optic nerve, carry those impulses to the brain for interpreting the image. The parts described are shown in **Figure 8**.

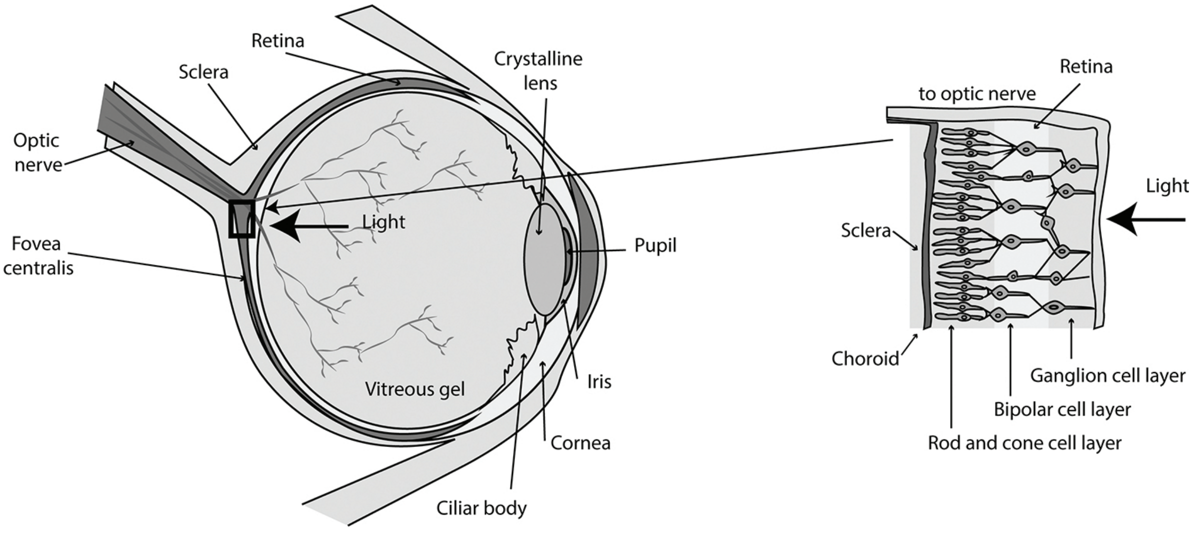

Figure 8. The eye anatomy. The enlargement of the area marked with a rectangle shows the retina layers, besides the rods, the cones and other supporting cells.

3.5. The hearing

The ear is the organ for hearing. The ear contains two sensory systems based in mechanoreceptors: the hearing and the equilibrium. The structure of the ear is divided in three parts: the outer ear, the middle ear and the inner ear, as shown in **Figure 9**. In the outer ear, sound waves are collected into the auditory canal. In the middle ear, those waves make vibrate the tympanic membrane and the auditory ossicles (malleus, incus and stapes). The ossicles amplify the sound and concentrate the sound waves from the tympanic membrane onto the oval window. The stapes strikes the membrane of the oval windows to pass the sound to the fluid contained in the inner ear.

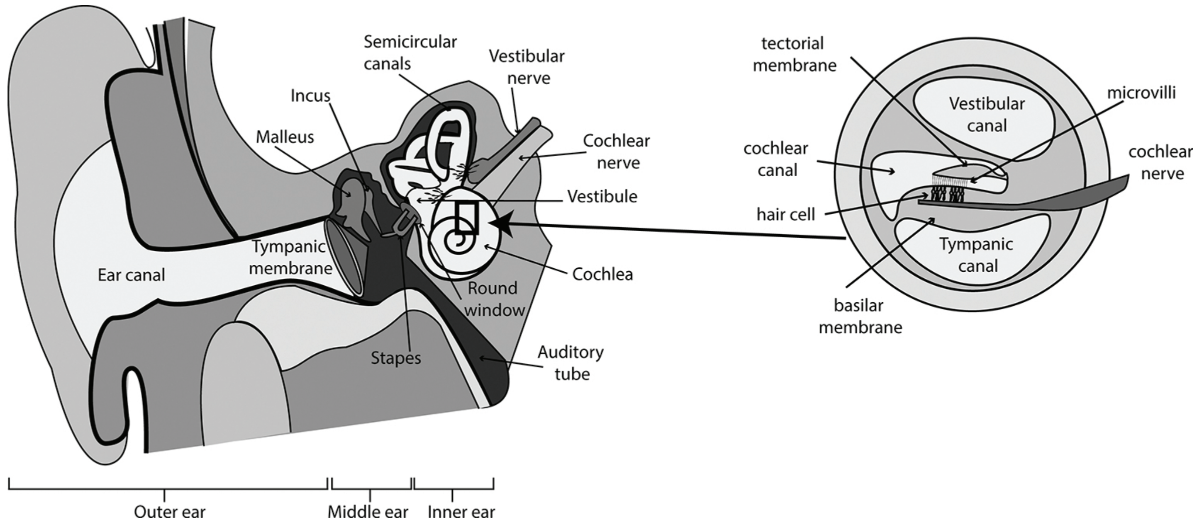

Figure 9. The ear anatomy and its parts. The enlargement of the area marked with a rectangle shows the cochlea cross section.

In the inner ear, there is a bony labyrinth, formed by semicircular canals, the vestibule and the cochlea. A spiral organ, called the organ of Corti, is located within the cochlea, and it contains hair cells, which are the receptor cells for auditory. When sound waves provoke vibration in the organ of Corti, the elasticity of the basilar membrane causes the hair cells to bend. The bending of the stereocilia causes an oscillating potential of the hair cells, firing intermittently the cochlear nerve. These impulses reach the auditory cortex of the brain to be interpreted as sounds.

3.6. The equilibrium

The semi-circular canals and the vestibule are the parts of the ear used to detect angular and linear acceleration of the head (shown in **Figure 10**). The brain interprets this information for maintaining rotational and gravitational equilibrium of the body.

Rotational equilibrium: There are three perpendicular semi-circular canals for sensing each dimension of the space. At the end of each canal, there are hair cells as the receptors, whose cilia is contained in a gelatinous part called cupula. When the head rotates, the cupula is dragged with the movement and bends the cilia. As a consequence, impulses travel to the brain into the vestibular nerves.

Gravitational equilibrium: The utricle and saccule, located in the vestibule, are responsible for sensing the vertical or horizontal movement of the head. Those membranous contain hair cells, whose cilia is contained in a gelatinous material called otolithic membrane. The utricle is sensitive to horizontal (back–forth) movements, and the saccule is sensitive to vertical (up–down) movements. When the head or the body moves in those planes, the otholits in the utricle and saccule are dragged with the movement, bending the cilia and changing the nerve impulses.

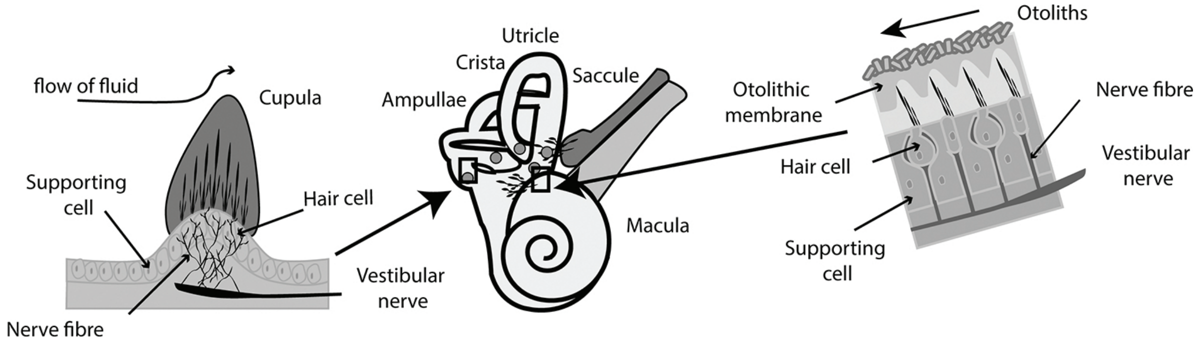

Figure 10. Receptors for equilibrium sense. The enlargement of the areas marked with a rectangle shows the rotation receptors in semicircular canal and the gravitational equilibrium receptors in the vestibule. Neuromusculoskeletal system.

3.7. Senses involved in a natural control mechanism: human gait

As an example of the motion control that humans can achieve is the walking mechanism. This mechanism is one of the most important control systems, allowing people to move within their environment. Walking has proven to be complex, hard to achieve and hard to replicate. Robot prototypes trying to mimic this behaviour had proved that this is not a trivial task because it has a high degree of complexity, it is unstable in many situations and it is easily disturbed. The control system for walking has many variables to analyse: where the joints are located, where the joints are located within each other, what force can they achieve, and what are the disturbances to compensate against them. To start the walking analysis, it is necessary to observe the cycle time, the step length, the walking velocity and the reference system. If that was not enough for completely understand walking, it is necessary to understand all the components that feedback the system: the pressure points, the muscle current situation as well as the incredible mechanism that allows us to control stability (vestibular system).

The vestibular system explained early is the one in charge of the sense of balance. This balance has the purpose of coordinating the movement. This means that, according to the sensation, it will correct and adjust every step during the walking. It also corrects when the position of a vehicle changes the orientation with respect to the gravity field by tilting the body based on this reference.

It is possible to observe the human movement control as a system that possesses several internal and external interaction. It uses inputs, muscular adjustments and disturbances, to initiate or deviate the movement. Humans try to compensate the disturbances by observing their muscles, their bones and the equilibrium currents states with the sensors, and the set point using the CNS.

4. Human as the operator

The feedback information, usually displayed in a computer or in an industrial panel, can be perceived and interpreted by a human operator, or by an automatic intelligent system to drive the actuators that regulate the process. In the block diagram shown in **Figure 11**, there are presented the two control options: manual and automatic/semi-automatic [12]. In the former case, the human operator acts as the controller, characterized by $g_c(t)$, and determines the control outputs u(t) for regulating the plant g(t). The process output y(t) has to follow the reference r(t) despite of the disturbances d(t) against the process. On the other hand, in the automatic/semiautomatic case, there is cooperation between the man and the machine to ensure the control goals. The artificial operator $g_{iac}(t)$ makes the control decisions, which are supported by the human with the information provided by the system, or the human operates the system with machine supervision programmed to minimize errors.

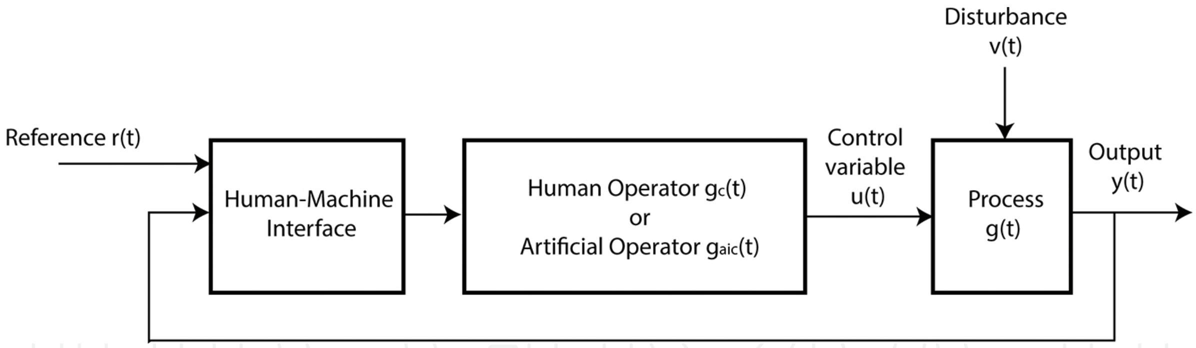

Figure 11. The block diagram of a control system.

Good examples of the cooperative control applications are found in complex multivariable systems. For instance, the action of flying an aircraft involves the control altitude, weighting, lifts, headings, drag, engine power, and many other variables [17]. Engineers know how to construct airplanes and engines; however, it is the nature of planes to be unstable, even the modern high-performance airplanes, but they rely on automatic control systems to maintain stability during the flight. Besides, modern airplanes involve the use of a lot of sensors to measure internal and external conditions, and several processes are controlled by on-board computers. It is impossible to imagine a commercial flight controller only by human operators.

Complexity in today's systems demands not only the control engineering, but other theories must be involved: human factors, human–machine interaction and cooperative control [13]. A brief description of these areas is presented next.

4.1. Human factors

Even if the cooperative scheme is manual or automatic, the human operators have the same role in control systems: to ensure the control goals efficiently and safely. As an element in the control loop, the operator response is attached to his experience, training or knowledge. Thus, the performance of the complete control system depends of the computing. Human factors are related with the understanding of the decision-making behaviour in humans. A description of their performance will help to design better interfaces and secure interaction in the control to minimize errors. This process was modelled by [14] at three different levels: the Skill-, Rule- and Knowledge-based levels.

Skill-based behaviour (SBB): Describes a performance which takes place without conscious control or attention, like a reflex. The operator's response is automatic because he is really familiarized with the situation, and it is executed with speed and accuracy. In this model, he is barely able to describe how to do the performance and what information is necessary.

Rule-based behaviour (RBB): The operator follows a sequence of subroutines previously used and documented. Also, other persons are able to communicate the process or follow it, as the process is well known or a list of instructions is available. Accuracy and speed are good, but not as in the SBB.

Knowledge-based behaviour (KBB): The operator is not familiarized with the situation and needs to establish a strategy to solve the problem. The operator has to consider different plans, based in his knowledge, and proceeds the execution with trial and error process. For those reasons, the KBB performance tends to be risky and slow.

It is desired that the operators' skills evolve from the KBB to the RBB, and then to the SBB which presents the lowest error rate. However, there are two fundamental aspects to be considered in the migration process: time and training level. As indicated in [32], to understand and take advantage of the human–machine interaction, it is important to understand the cognitive processes of humans.

4.2. Human–machine interaction

As an element in the system presented in **Figure 11**, the human–machine interface (HMI) closes the loop in the control process. The HMI provides visualization for the operator in order to monitor and control the variables. However, recent developments in technology have increased the complexity in control systems, including multiple inputs and processes running at the same time.

It was a common practice that machines were designed according technical requirements, without considering the needs and characteristics of the operator; however, that paradigm has changed into the user-centred design or adapting tools to the capabilities, limitations and needs of the human beings. Nowadays, ergonomics is a determinant factor in order to minimize human errors and to improve the operator's health and safety.

Ergonomics is concerned with the concept of "usability" or user-friendly in technical systems, machines and tools [29]. In order to be intuitive and easy to use, the HMI needs to embed the operator in the control feedback by visual, somatosensory, propioceptive or a combination of those interfaces. This multi-modality involves human senses stimulated directly by visual, auditory or haptic (kinestesic, tactile, temperature) interaction to confront the challenge of the human operator working closely in complex machines [30].

4.3. Cooperative control

Finally, the cooperative control systems incorporate decision support capabilities implemented with artificial intelligence techniques. The main idea using the information acquired by the sensors to feed computer algorithms and then execute the most suitable actions for the current conditions. These intelligent control techniques are applied to different engineering areas such as robotics, aeronautics, financial and household appliances.

Fuzzy Logic, Artificial Neural Networks, Neuro-Fuzzy Systems, Genetics Algorithms, among other techniques are known as Artificial Intelligence computational methods [15]. Those techniques are based on characteristics observed in biological systems; moreover, a system with artificial intelligence may have the abilities of learning from experience, adapting to environment conditions, recognizing patterns, using knowledge and other tasks of intelligent beings. Artificial control [5] techniques can improve the control performance and the system autonomy.

Fuzzy Logic (FL): This technique uses vague data to make decisions, in a similar ways humans do. It uses linguistic descriptions for the variables and IF–THEN rules connected with logic operators.

Artificial Neural Networks (ANN): The ANNs are mathematical models which emulate the learning process in biological neurons. They are able to be trained in order to learn and acquire knowledge. Their application is pattern recognition, values prediction, data validation and classification.

Neuro-Fuzzy Control: This technique combines the characteristics of Fuzzy Logic Systems and Artificial Neural Networks, and thus, these systems are able to make decisions with vague information and are able to learn and adapt to the problem conditions.

Genetic Algorithms (GA): This is an optimization method based on biologic evolution principles. GAs are used to numerically evaluate functions and to obtain minimum and maximum values. Genetic programming techniques are used to find approximate solutions in different applications like economics, materials, computer-aided design, among others.

5. Biomedical control applications

A specific field in control engineering is related with biological and medical systems, explored in recent years to develop technology to impact on human life. Biomedical control is relatively new, but there are solid applications that demonstrate the usability of control theory for solving medical problems.

Physiological control mechanism maintains homeostasis in the human body; however, they could be compromised by a disease or an accident, as well as by the effects of aging. When the physiology control mechanism has been broken and cannot be recovered naturally, it is required external assistance to help in the restoration. This can be either achieved by drug dosing, therapies or medical devices for assistance.

There are mainly three areas to cover when talking to biomedical control:

- Drug delivery
- Medical instrumentation
- Rehabilitation engineering

While the drug delivery tries to recover homeostasis by creating biological reaction by means of chemical or biological changes, medical instrumentation and rehabilitation engineering try to recover it by means of physical reconstruction, mechanical assistance, external stimulation or changes over the environment.

5.1. Drug delivery

Drugs can be used to control how internal systems work (e.g. glucose, blood pressure, heart rate, etc.). Although drugs are intended to correct an abnormal behaviour, they can still create negative effects within the body (causing toxicity or side effects), so it is important that they are administrated in the correct dosage. Drugs are also required to be delivered when they are required and not just in any random moment, so they have a mayor impact and not just some reduced effect. One final case of drug delivery is the use of Anaesthesia that is of high importance during surgery or pain control. The fact that drugs have to fulfil different activities and have to be regulated translates into an adaptation of the drug dosage depending on their concentration and effects. The basic understanding over drug release mechanisms includes dissolution, diffusion, osmosis and ion exchange-based mechanisms.

Drug time delivery has change over the past decades, changing from a simple intake of pills in certain periods of time (e.g. twice-a-day), to using smart polymers that are environmentally sensitive, to currently using drugs that are sensitive to changes in concentrations of the body (like glucose or pH) and only release when needed.

Like previously said, it is important part of drug delivery is to the area that they are attacking. One important aspect is, for example, what system they are regulating and what side effects they can create. For example, when trying to reduce the blood pressure, an infusion of sodium nitroprusside is injected that rapidly will reduce the heart pressure, the problem is that its effects fade quickly and they can only be applied in certain time to avoid cyanide poisoning. It has been proposed to insertion control the release of that drug to counteract this effect and have extended periods of time with lower blood pressure.

Another example of drug delivery is trying to help the immune system. The immune system is in charge of protecting the body against diseases. These systems must detect pathogens and viruses, and distinguish them from other organisms that are not infectious. But there are cases that these systems are not capable of working against the intruders of the body, like in the case of HIV. A way to counteract the damage by this virus is by a therapy known as antiretroviral. The intention of this is to reduce the viral replication limiting the transmission of the HIV virus, as well as limit the possibility of acquisition [18]. The main problem of this therapy is the high amount of drugs introduced into the body at the same time, which limits the adherence of the therapy. To improve the benefits of this treatment, it has been proposed that the drug delivery is adjusted by using viral plasma levels.

A final example on how drug delivery control is of importance is the use of anaesthesia. Anaesthesia in general tries to control hypnosis, analgesia and relaxation of the body. These variables have to be adapted using EEG, heart rate, CO_2 and blood pressure as feedback signals, to adjust the anaesthetics, muscle relaxants, ventilation parameters, Nacl and others. The adjustment is normally done by an anaesthesiologist that acts like a feedback controller [19]. This could be change to an automatic control, which would in return improve parts of the complex decision process, providing the drug delivery and avoiding overusing. Resulting in a less drug consumption and shortening the time spent recovering from the anaesthesia.

5.2. Medical instrumentation

There exist several external variables, like temperature and humidity that affect the state of the body (e.g. temperature, heart rate, breath and humidity of the skin). They are normally regulated using heaters and humidifiers which act over the environment. The problem is that these variables change slowly, which can be overshoot, and in the case of humidity, it cannot be easily measured to correctly adapt it. The control of these variables has to constantly observe the inner state as well as the outer parameters to adjust and avoid overshooting.

One of the most important parts during a surgery is the feedback the surgeon can get through his eyes, hands and specially instruments. This feedback has to be sufficient to avoid unnecessary grasping or cutting and good enough that do not reduce performance [20]. This effect has become even more pronounce with current technology, like as robotics and minimal invasive surgery, where the surgeon cannot directly feel the object he/she is grasping. In these cases, a different type of feedback has to be provided to the surgeon that replace the one that was lost or enhance the one that remains. A normal approach is to try to transmit directly the touch of the tools to the handle using haptic (or tactile feedback) to the surgeon. Another type of feedback can be using visual or audial stimulation using video recordings of the surgery. These technologies can be added into a more robust system, which makes possible to have minimal invasive surgery and the specially to incorporate robotics into the surgery.

5.3. Rehabilitation engineering

The aims of the rehabilitation engineering are to develop devices and methods for helping individuals with disabilities in their everyday tasks, and helping to recover lost functions because of diseases. For instance, rehabilitation engineers build assistive devices like wheelchairs, scooters and prostheses for helping in everyday tasks. Moreover, control theory, signal acquisition and signal processing are combined to solve the problem of controlling powered prostheses, which can replace deficient or amputated extremities [21]. Efficient and intuitive interfaces are needed for controlling artificial limbs with body signals. High accuracy and quick response in these assistive devices will improve the quality of living for persons with disabilities.

Another application of rehabilitation engineering is the functional electrical stimulation (FES), in order to control or recover body functions by electric signals. Voltage pulses are applied to the muscles searching for correction of clinic dysfunctions. Besides, neuromuscular stimulation is used to electrically activate nerve cells. The FES has been successfully used in stroke rehabilitation, spinal cord injuries, head injuries, limb motor dysfunctions and neurological disorders.

Finally, biofeedback is used to consciously control body functions that are normally regulated automatically, like blood pressure, heart rate and temperature. By monitoring its heart rate, electroencephalographic or muscle activity, a trained patient is able to regulate certain anomalies, like migraines, attention deficit, hyperactivity disorder, epilepsy, diabetes, high blood pressure and incontinence. However, the feedback performance depends of the accuracy in the variable measurements and data presentation.

Research in rehabilitation engineering involves the development of new devices and techniques, like robotics for aiding in therapies, intelligent assistive devices for rehabilitation and mobility, virtual reality simulations for physical and cognitive rehabilitation, sophisticated interfaces for enabling severely disabled patients to interact with everyday devices, among others.

6. Case study: the smart wheelchair

This section presents the implementation of an assistive device considering the human operator aspects presented above. As an element in the control system, the operator takes part in the control loop to share navigation tasks with an artificial intelligence. Through his human senses, the operator is able to plan and correct a route to reach a desired place. At the same time, a running algorithm uses distance sensors to avoid collisions with objects. The whole system takes advantage of both, the human and the artificial intelligence, to minimize errors in the navigation process.

A smart wheelchair is a rehabilitation engineering application developed to assist persons with strong disabilities. The smart wheelchairs incorporate sensors, specialized software and mobile robot techniques to solve some mobility problems. Many prototypes have been implemented in different institutions around the world [22, 31]. These assistive robotic systems are in close contact with the user, as both of them share the same space; consequently, it is determinant to have a user-friendly relation between the human and the machine, and intuitive interfaces for users without knowledge of technical aspects [23, 28].

According to Ref. [24], it is recommended a collaborative or semi-autonomous control for driving the smart wheelchair. Under that scheme and despite of his disabilities, the user is still able to command the system by himself and plan routes to destinations meanwhile an intelligent assistant guarantees a collisions-free trajectory. As a result, the semi-autonomous control complements the user's skills without replacing him completely.

Figure 12. Semi-autonomous wheelchair.

The semi-autonomous smart wheelchair presented in **Figure 12** uses speech recognition and head movements detection as alternative interfaces to steer and manoeuvre. An obstacles avoidance controller is included, based on fuzzy logic control and range sensors as those implemented successfully in Ref. [25, 26]. In the prototype, developed at Tecnologico de Monterrey Campus Ciudad de Mexico, eight ultrasonic sensors were distributed around the wheelchair for a complete coverage and the distance measurements are the inputs for the controller. The fuzzy logic algorithm makes the navigation decisions similarly to a human operator; thus, when an object is detected near to the wheelchair, the control reduces the wheelchair speed and modifies the orientation carefully. The controller and the data acquisition routines were implemented in a Field Programmable Gate Array (FPGA), included in a Compact-RIO 9103, for high-speed processing. This device shares the data with the HMI running in a laptop with a touch screen to interact easily. The HMI shows the sensors indicators, virtual buttons to select among the interfaces and text indicators with instructions for the user.

As indicated, the user is able to operate the smart wheelchair in normal or assisted navigation; and by any of the available interfaces: virtual joystick, head movements or speech commands. The virtual joystick is similar to a real joystick, but it can be personalized according to the user requirements. With this interface, the user moves the cursor from its home position in the vertical or horizontal directions of the workspace. Moreover, the head movements control is used to command the wheelchair by head movements, as illustrated by **Figure 13**. This interface uses a tilt sensor, mounted in the headset presented in **Figure 12**, which detects movements in the 'x' and 'y' axes. This interface uses a function for mapping the sensor data into useful voltages for softly moving the wheelchair. Finally, the speech recognition interface uses nine voice commands to operate the wheelchair: 'action', 'move', 'run', 'stop', 'forward', 'backward', 'left', 'right and 'down'. They are classified as attention and orientation instructions. With the attention instructions, the user selects discrete or continuous movements; and after that, an orientation instruction starts the movement. As an example, the wheelchair displaces during 2 s by commanding 'Move' and then 'Forward'. In the case of 'run', the wheelchair moves continuously and accumulates orientation instructions to change the speed and orientation. The voice commands are obtained by the headset microphone shown in **Figure 13**.

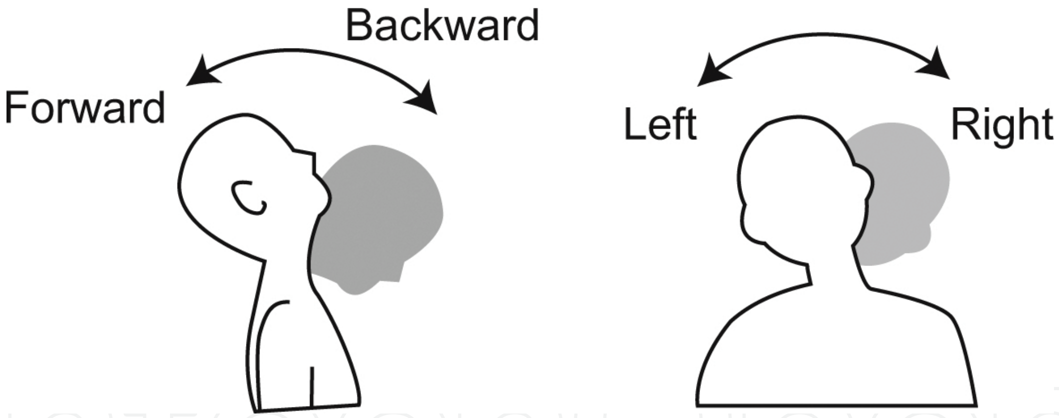

Figure 13. Head movements for commanding the wheelchair.

7. Discussion

Control engineering has been widely applied for creating technology, not only to make life more comfortable, but to improve life quality and life expectancy. Research has been done to develop applications in order to achieve those objectives. Even though these theories can be used to study and describe physiological systems, several considerations need to be done as there are important differences between these and conventional engineering.

Furthermore, it is imperative to study the cases where humans need to interact for closing the control loop. However, humans are prone to errors and their cognitive processes are limited by factors such as training, knowledge, speed reaction, and experience. For those cases, external assistance is recommended to complete safely the control goals.

The smart wheelchair presented is a clear example of a complete control system, which involves human factors, human–machine interaction and artificial intelligence. The user-centred design was applied for the interfaces to be comfortable and useful, besides the use of the HMI is very intuitive. The artificial intelligent algorithm helps the user to be involved in the system control, to monitor the environment variables and to complete the navigation.

Undoubtedly, biomedical control applications have proven to be very useful; however, that is not the only science field to create biomedical devices. Thus, the research continues in developing new technology applied to improve monitoring, therapies and helping patients. Hence, it is needed research on the developments of new sensory systems, drug delivery, robotics, assistive devices and new materials. Obviously, the technology needs to work under unfavourable conditions and being compatible with the human anatomy. Finally, the research must be oriented by other important factors, like the balance between cost and robustness in order to have affordable products.

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