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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

MODULE 6

BIOMECHATRONICS

Project Title	**European network for 3D printing of biomimetic mechatronic systems** **21-COP-0019**
Output	**IO1 - EMERALD e-book for developing of biomimetic mechatronic systems**
Module	**Module 6 – Biomechatronics**
Date of Delivery	**July 2022**
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Version	**Final Version**

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1. Introduction

Biomechatronics is an interdisciplinary field that combines mechanical, electronic, and biological elements to create innovative devices and systems. It is a subfield of biomedical engineering that focuses on the interaction between mechanics and electronics with human biology [1]. Biomechatronic systems can interact with the human muscle, skeleton, and other biological tissues, such as nervous system, to enhance or replace their functions. It is a key area of study in biomedical engineering.

The term "biomechatronics" is derived from the words "biomechanics" and "mechatronics". Biomechanics is the study of the mechanical aspects of biological systems, while mechatronics involves the integration of mechanical, electrical, and computer engineering to create advanced systems [2]. The goal of biomechatronics is to create devices that can restore or enhance the function of the human body.

Examples of biomechatronic devices include prosthetics that can mimic the movements of natural limbs, exoskeletons that can help people with physical disabilities to walk or stand upright, and neuroprosthetic implants that can restore motor function to people with paralysis [2]. The components of a biomechatronic system typically include a human subject, which represents the biological aspect of the system, and a stimulus, which is the input delivered to the system [3].

Biomechatronics is an exciting field that holds great promise for improving the lives of people with disabilities and medical conditions. By combining knowledge from engineering, biology, and medicine, researchers in this field are working to develop innovative solutions that can help people overcome physical limitations and achieve greater independence and mobility. It is a discipline that has the potential to revolutionize healthcare and enhance human performance.

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2. Basics of biomechatronics technology

2.1 Basic definitions and concepts

Mechatronic engineering can be defined as the synergistic combination of electronic, mechanical, control, and computer systems, while biomechatronics is its application in human biology [3]. Below, some basic definitions and concepts pertaining to biomechatronics are presented.

1. Biomechatronics: It is an interdisciplinary science that draws concepts and knowledge from various fields of science, such as biology, mechanics, electronics, and mechanical engineering. It deals with the interaction between human organs and electromechanical devices or systems [4].
2. Applied Interdisciplinary Science: Biomechatronics is an applied interdisciplinary science that aims to integrate biology and mechatronics, including electrical, electronics, and mechanical engineering. It also encompasses the fields of robotics and neuroscience.
3. Therapeutic, Assistive and Diagnostic Devices: Biomechatronics technology researches and designs devices that can be used for therapeutic, assistive, and diagnostic purposes, with the potential to compensate and eventually replace human physiological functions. This includes prosthetics, exoskeletons, and assistive devices for individuals with disabilities.

Biomechatronics is closely related to other concepts, such as biomechanics, electronics, biomimetics and bionics. Relations of these concepts are presented in Figure 2.1, as devised by Witte (2022). Some definitions of the related concepts are presented below:

1. **Biomechanics** is the study of the mechanical properties of biological systems. Biomechatronics devices must be designed to interact with the body in a way that is safe, effective, and natural.
2. **Robotics**: Biomechatronics often incorporates concepts from robotics, including the use of robotic exoskeletons to assist with mobility, and the development of robots with biological characteristics, such as soft, compliant materials and actuator systems that mimic biological muscle.

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3. **Bionics** is defined as the development of modern systems or functions based on similar systems that exist in nature. It involves the study of biological systems and the implementation of their features into engineering design. This approach can be used to create products that are more efficient, adaptive, and versatile than traditional designs.
4. **Biomimetics** is the study of the formation, structure, or function of biologically produced substances and materials such as enzymes or silk, and biological mechanisms and processes such as protein synthesis or photosynthesis. Biomimetics involves copying or synthesizing natural substances and structures to create new products that have improved properties or functions. The aim is to develop artificial products that are compatible with nature and can provide sustainable solutions to various problems.
5. **Biomimicry**, a term closely related to biomimetics, specifically focuses on applying nature-inspired designs to solve human problems.

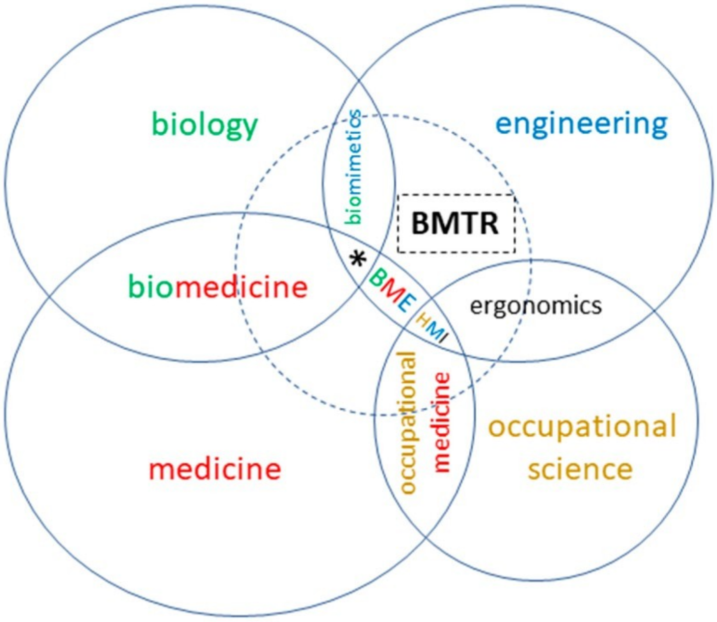

Figure 2.1. Activities of biomechatronics in relation to the related scientific fields. BMTR: biomechatronics; BME: biomedical engineering; HMI: human–machine interaction; Asterisk *: engineering for biology ("E4B") [5]

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Biomechatronics describes the integration of the human body with engineered, mechatronic devices, to:

- emulate and replace natural human function lost through disease or accident and/or
- augment natural human function to generate superhuman abilities.

Examples of some biomechatronic devices are presented in Figure 2.2.

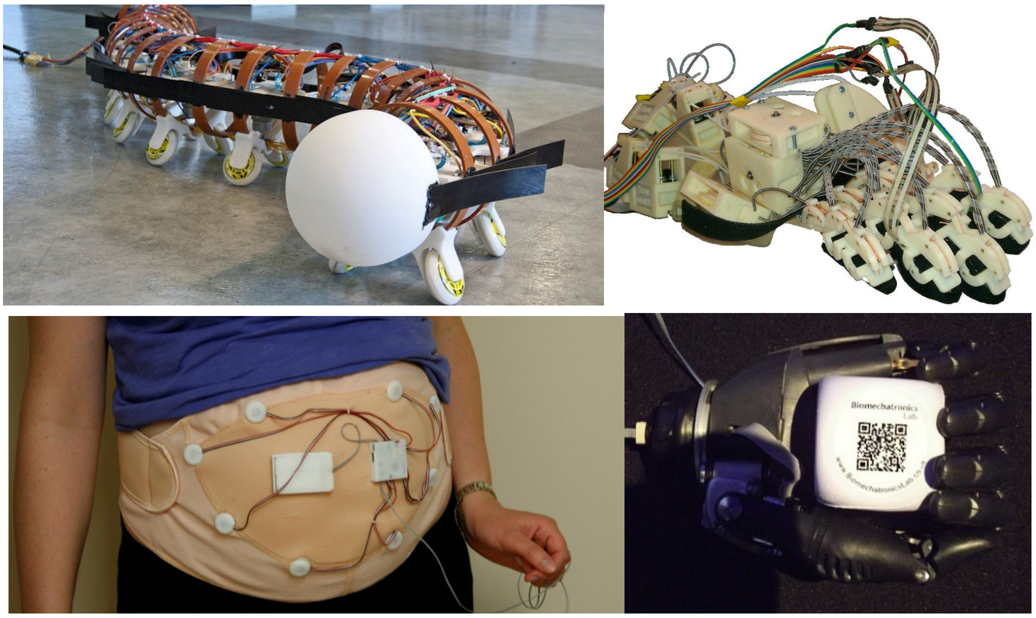

Figure 2.2. Examples of biomechatronic devices [6][7]

2.2 Biomechatronic systems

2.2.1 Basics of biomechatronic systems

A biomechatronic system is a complex system that incorporates biological and mechanical components to achieve a specific function. These systems can be used for a variety of purposes, including rehabilitation, prosthetics, and medical devices. Biomechatronics can be used to restore or enhance the function of the human body, as well as to create entirely new functions that are not possible with biological systems alone.

A scheme of work of a biomechatronic system is shown in Figure 2.3. It is noteworthy that the prominent element in the system – as opposed to typical mechatronic systems – is a human being (that could be replaced with any biological system). The human subject adds *bio*

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to the mechatronic control and monitoring process. The human element is not only the most complex and least understood, but also the most difficult to interface to [1].

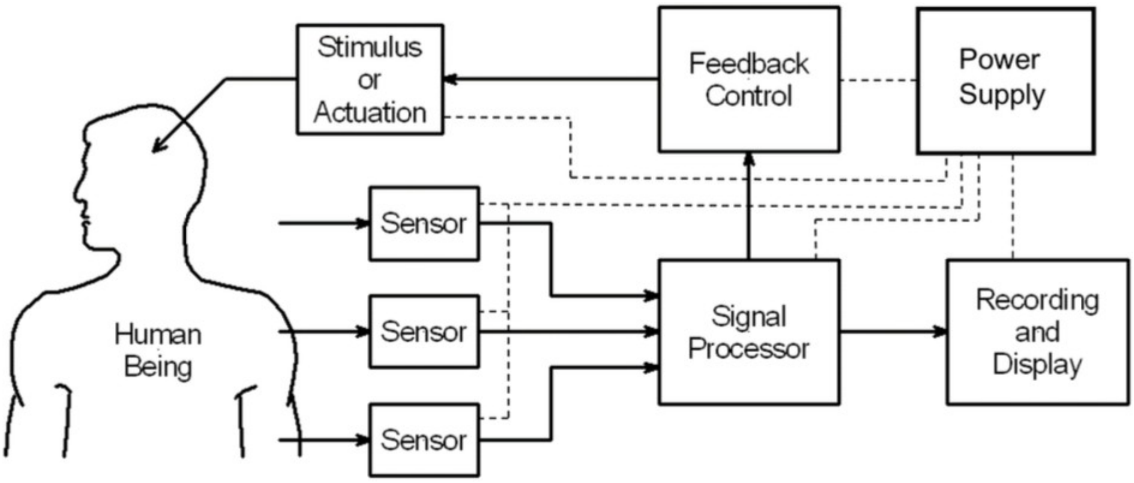

Figure 2.3. Principle of operation of biomechatronic system [1]

Basic elements of mechatronic systems, as mentioned in previous chapter, are:

- actuators (e.g. robotic arms or other powered devices),
- sensors (biosensors),
- signal processors,
- devices for recording and display,
- power supplies.

Some of these key concepts are described below.

1. Actuation: This refers to the ability of biomechatronic devices to create motion, either through the application of force or the generation of a torque. Examples of actuators used in biomechatronics include electric motors, pneumatic systems, and hydraulic systems.
2. Sensors: Biomechatronic devices require sensors to detect changes in the environment or within the human body, such as changes in temperature, pressure, or muscle activity. These sensors may be invasive, such as implantable electrodes, or non-invasive, such as surface electromyography.

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3. Control systems: Biomechatronic devices require sophisticated control systems to regulate and adjust their behavior based on input from sensors. Control systems may use feedback or feedforward mechanisms to ensure the device behaves as intended.
4. Human-machine interface: A key aspect of biomechatronics is the interaction between the human body and the biomechatronic device. Human-machine interfaces can take many forms, including direct neural interfaces, haptic feedback systems, and visual displays. The human subject represents the bio part of biomechatronic systems and makes them unique [1].
5. Signal conditioning elements: Signal conditioning elements are used to amplify, filter, or modify the electrical signals generated by the transducers and sensors to make them suitable for processing by the system.
6. Recording and display: Recording and display elements are used to store and visualize the data generated by the system, which is useful for monitoring and analyzing the system's performance.
7. Feedback elements: Feedback elements are used to adjust the system's output based on the measured performance, which is useful for improving the system's accuracy and stability.

One example of a biomechatronic system is a prosthetic limb. A prosthetic limb is a device that replaces a missing limb and provides the user with the ability to perform tasks that they would otherwise be unable to do. Biomechatronic prosthetics incorporate sensors and microprocessors that allow the device to communicate with the user's nervous system, providing feedback on the position and movement of the limb. This feedback allows the user to control the prosthetic limb in a natural and intuitive way, allowing them to perform tasks such as walking, running, and gripping objects.

Another example of a biomechatronic system is an exoskeleton. An exoskeleton is a wearable device that is designed to assist the human body in performing physical tasks. Biomechatronic exoskeletons incorporate sensors and motors that provide assistance to the wearer's muscles and joints, allowing them to perform tasks that would otherwise be too difficult or impossible. These devices can be used for rehabilitation, enabling individuals with

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injuries or disabilities to regain strength and mobility, or for military applications, providing soldiers with enhanced strength and endurance.

Biomechatronic systems can also be used for medical applications. For example, implantable medical devices such as pacemakers and artificial organs incorporate mechatronic components that allow them to interact with the human body in a controlled and precise way. These devices can be used to treat a variety of medical conditions, including heart disease, kidney failure, and diabetes.

One of the key challenges in developing biomechatronic systems is the need to integrate biological and mechanical components in a seamless way. This requires a deep understanding of both the biology of the human body and the engineering principles that underpin mechatronic technologies. Biomechatronics researchers must be skilled in a wide range of disciplines, including biology, mechanical engineering, electronics, and computer science.

2.2.2 Biosensors

Biosensors are analytical devices that are used to detect and quantify biological and chemical compounds in various applications. In biomechatronics devices, biosensors are used to measure physiological signals such as heart rate, body temperature, and blood glucose levels. These devices can be implanted or worn externally and provide continuous monitoring of a patient's health status. The development of biosensors has opened up new possibilities for monitoring health conditions and improving patient outcomes.

Biosensors used in biomechatronics devices generally consist of three main components: a biological sensing element, a physicochemical detector or transducer, and a signal processing system [8]. The biological sensing element interacts with the analyte of interest, and the physicochemical detector converts this interaction into a measurable signal. The signal processing system then converts this signal into a meaningful output for the user (Figure 2.4).

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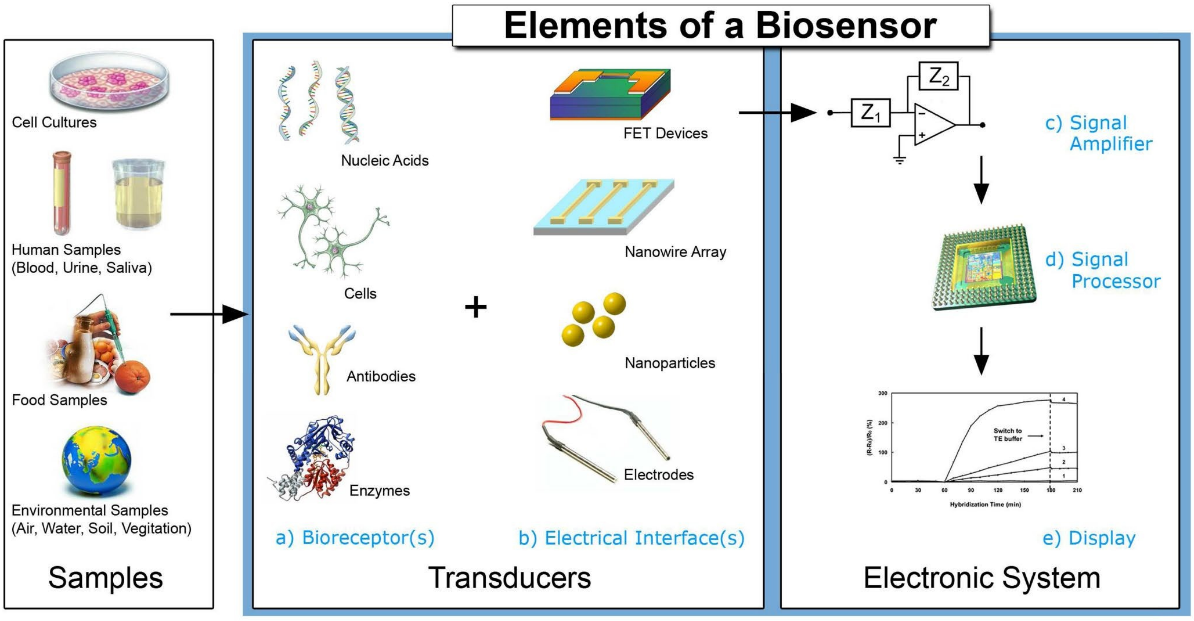

Figure 2.4 Principle of operation of biosensors [10]

The biological sensing element in a biosensor used in biomechatronics devices can be any type of biomolecule that interacts with the analyte of interest. The most common types of bioreceptors used in biosensors are (1) antibody-antigen interactions, (2) enzymatic interactions, (3) cellular (microbial) interactions, (4) nucleic acid interactions, and (5) synthetic bioreceptors (biomimetic) [9]. Each of these bioreceptor types has its own advantages and disadvantages, and the selection of the appropriate bioreceptor depends on the specific application.

Antibody-antigen interactions are commonly used in biosensors for the detection of proteins and other large molecules. The antibody is specific to the antigen of interest, and the interaction between the two molecules generates a measurable signal. Enzymatic interactions are used to detect small molecules such as glucose and cholesterol. In this case, the enzyme catalyzes a reaction that generates a measurable signal. Cellular (microbial) interactions involve the use of living cells to detect analytes. These cells can be genetically engineered to produce a specific response to the analyte of interest. Nucleic acid interactions are used to detect DNA and RNA sequences. In this case, the biosensor uses a complementary sequence

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of nucleic acids to bind to the target sequence. Synthetic bioreceptors are designed to mimic the function of natural bioreceptors and are often used when a natural bioreceptor is not available [8].

The physicochemical detector or transducer in a biosensor used in biomechatronics devices converts the biological interaction into a measurable signal. There are many different types of transducers, including electrochemical, optical, and mechanical. Electrochemical transducers are the most commonly used in biosensors for biomedical applications. They work by measuring the electrical properties of the biological interaction, such as changes in voltage or current. Optical transducers work by measuring changes in light intensity or wavelength, and mechanical transducers work by measuring changes in pressure or flow [8].

The signal processing system in a biosensor used in biomechatronics devices converts the signal generated by the transducer into a meaningful output for the user. This can be done using various techniques, including amplification, filtering, and digital signal processing [8]. The output can be displayed on a screen or transmitted wirelessly to a remote monitoring system for further analysis.

Biosensors used in biomechatronics devices can be used for a variety of applications, including monitoring glucose levels in diabetic patients, measuring heart rate and blood pressure, and detecting the presence of certain biomarkers for disease diagnosis. These devices can be implanted or worn externally and can provide continuous monitoring of a patient's health status. In addition to medical applications, biosensors can also be used in environmental monitoring, food safety, and other fields.

An example might be a wearable biosensing device, involving machine learning techniques for hand gesture recognition, as described by Moin et al. (2020) [11]. Principle of work of this device is shown in Figure 2.5.

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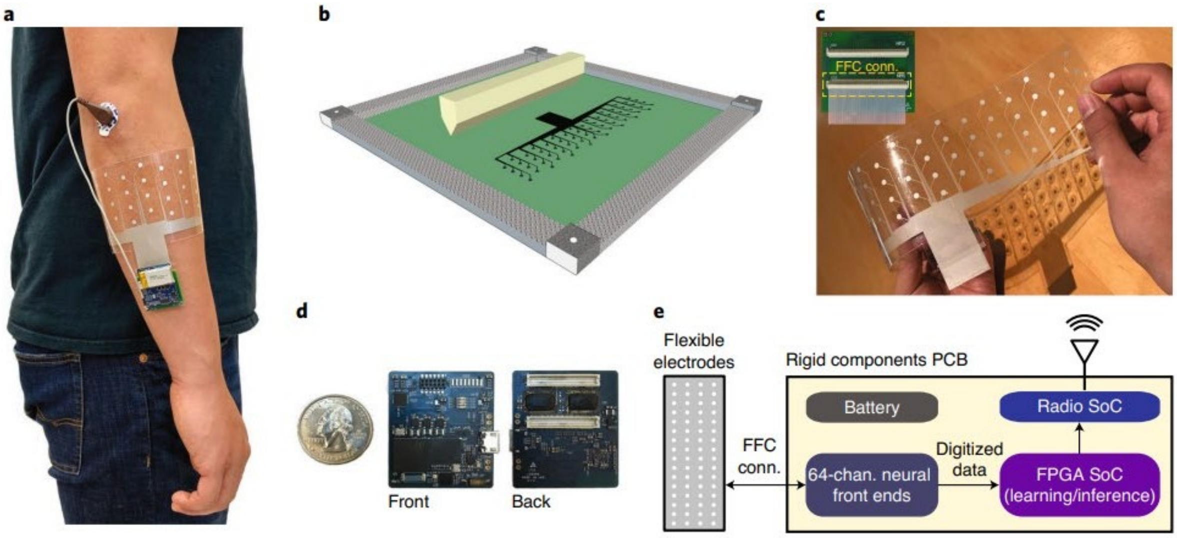

Figure 2.5. Example of wearable biosensing system for sEMG [11]

Here are some examples of the use of biosensors in biomechatronics devices, along with details about their operation and benefits.

1 Prosthetic Limbs: Biosensors are being used to help amputees control their prosthetic limbs more effectively by providing feedback on muscle activity and other physiological parameters. In one study, researchers used electromyography (EMG) biosensors to detect muscle activity in the residual limb of amputees, which was then used to control a robotic prosthetic hand [12]. The biosensors were able to accurately detect the intended movements of the amputees and translate them into movements of the prosthetic hand. This technology has the potential to greatly improve the quality of life for amputees, allowing them to perform tasks that were previously impossible.

2 Wearable Sensors: Biosensors can also be integrated into wearable devices to monitor various physiological parameters, such as heart rate, blood pressure, and body temperature [13]. These sensors can provide real-time feedback on the wearer's health and can be used to track changes over time. For example, researchers have developed a wearable biosensor that can detect dehydration in athletes by monitoring changes in skin conductivity [14]. The biosensor was able to detect

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dehydration in real-time, allowing the athletes to take action to prevent further dehydration.

3 Biofeedback Systems: Biosensors can also be used in biofeedback systems, which allow users to monitor their physiological parameters and use that feedback to control various devices or systems. For example, researchers have developed a biofeedback system that uses EMG biosensors to detect muscle activity in the user's forearm, which is then used to control the movement of a robotic arm. The user is able to control the movement of the robotic arm simply by flexing their muscles, without the need for any external controllers.

4 Brain-Computer Interfaces: Biosensors can also be used in brain-computer interfaces (BCIs), which allow users to control devices or systems using their thoughts (Fig. 2.. The state-of-the-art biosensors are able to accurately detect the user's intent to perform certain actions, such as moving a cursor on a computer screen. BCIs have the potential to greatly improve the quality of life for people with disabilities, allowing them to control devices and interact with the world in ways that were previously impossible.

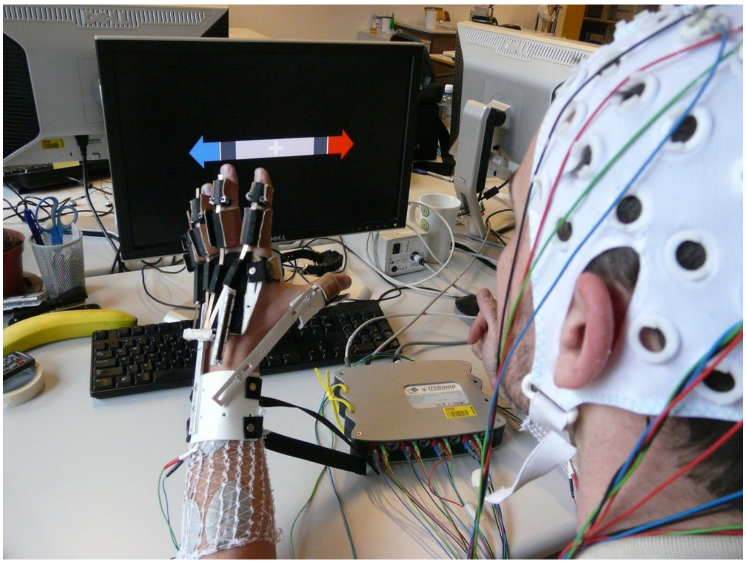

Figure 2.6. Example of a Brain-Computer Interface [15]

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2.2.3. Actuators

Actuators are devices that convert energy into mechanical motion, allowing for movement and control in biomechatronic devices. In biomechatronics, actuators are an essential component of prosthetic and orthotic devices, helping to replace or augment natural muscle function [16] (Figure 2.7). There are several types of actuators used in biomechatronics, including electric, hydraulic, and pneumatic actuators.

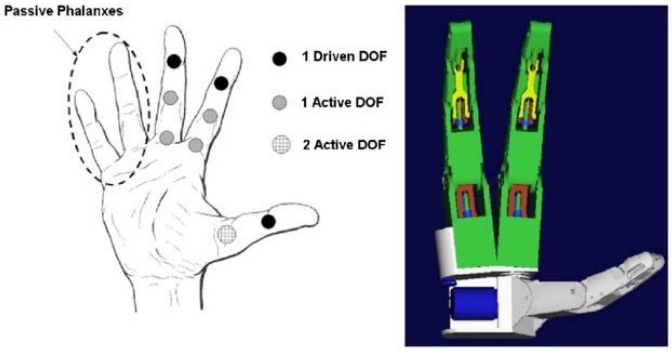

Figure 2.7. Example of a biomechatronic hand with actuated fingers [16]

Electric actuators, such as DC motors or stepper motors, are commonly used in prosthetic devices to control the movement of joints or limbs. These actuators work by converting electrical energy into mechanical energy, allowing for precise control over movement. Some prosthetic devices also incorporate hydraulic actuators, which use pressurized fluid to generate force and motion. Hydraulic actuators are capable of producing high forces and are often used in more advanced prosthetic devices.

Pneumatic actuators, which use compressed air or gas to generate movement, are also used in biomechatronics. These actuators are often used in soft robotics, as they are lightweight and flexible, making them ideal for applications that require a high degree of compliance and adaptability. Pneumatic actuators can be used to create soft robotic grippers or manipulators, which can be used in biomedical applications such as surgical robots or exoskeletons.

Nowadays, a paradigm shift can be observed in biomechatronics actuators, towards use of soft robotics approach, with quasi-direct drives controlled by force rather than position, with

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lightweight components, able to be implemented mostly in orthotic and prosthetic devices for people with special needs [17] (Figure 2.8).

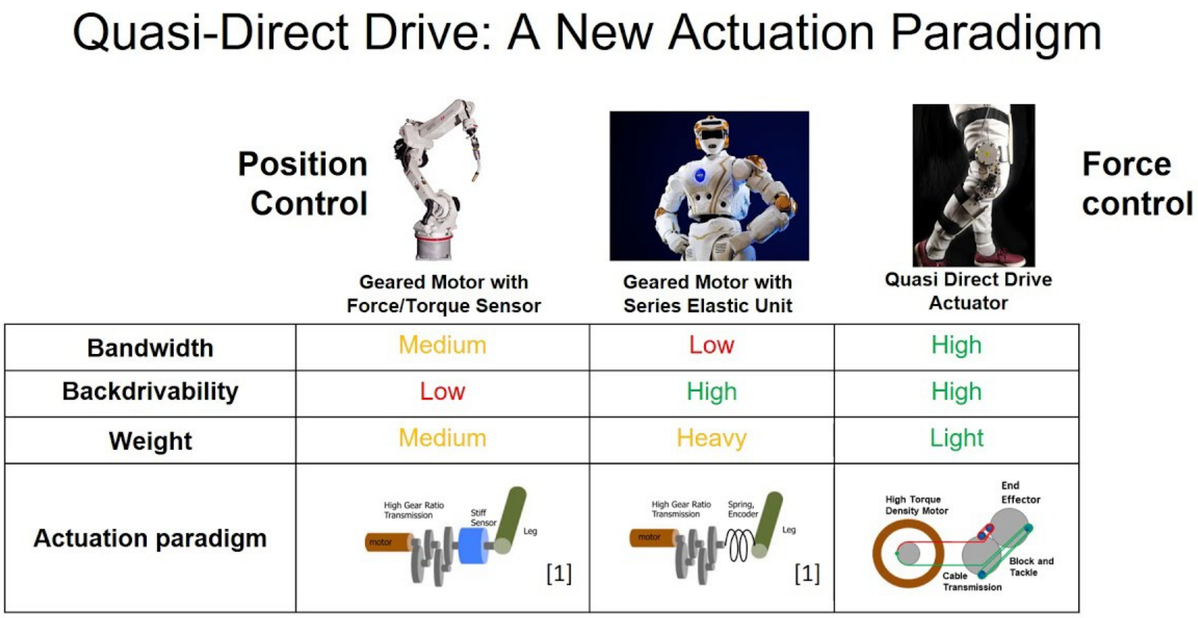

Figure 2.8. Quasi-direct drive in biomechatronic devices: paradigm shift [17]

Overall, actuators are a crucial component of biomechatronic devices, allowing for precise control over movement and enabling the development of advanced prosthetic and orthotic devices as well as soft robotics applications. The choice of actuator type depends on the specific requirements of the device and the intended application.

2.2.4. Signal conditioning and processing devices

Signal processing in biomechatronics is a crucial part of operation of these devices, especially in terms of safety and functionality in aiding human users in operations they need to perform. Processing of signal is realized as shown in Figure 2.9. Output from conditioning elements are in the form of DC/AC voltage / current. Certain calculations (processing) need to be performed on these signals, in order to establish value of variable being measured, which will be then interpreted and send for further use, e.g. to the actuators.

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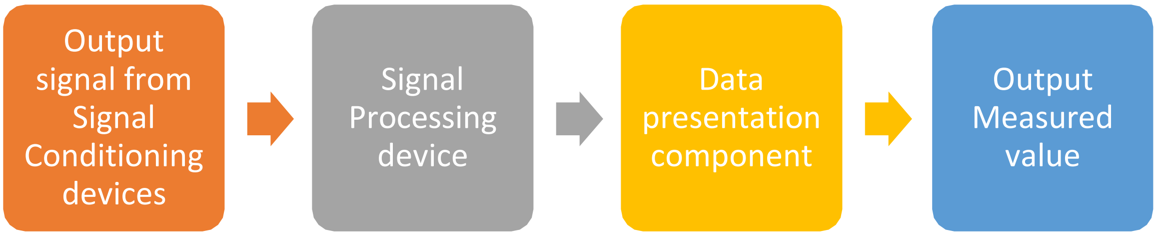

Figure 2.9. Signal transferring in biomechatronic devices

Signal conditioning elements are used in biomechatronics to manipulate signals from various transducers and sensors to prepare them for further processing. These elements are responsible for amplifying, filtering, and converting signals to a form that can be easily interpreted and analyzed by the system. Some common examples of signal conditioning elements used in biomechatronics include:

1. Amplifiers: used to amplify low-level signals from sensors to a level that can be easily processed and analyzed by the system.
2. Filters: used to eliminate noise and unwanted frequencies from the signal.
3. A/D converters: used to convert analog signals to digital signals that can be easily processed and analyzed by digital systems.
4. Instrumentation amplifiers: used to amplify low-level signals while rejecting common-mode noise and interference.
5. Signal isolators: used to electrically isolate the input signal from the output signal to prevent any unwanted coupling.

Examples of transducers and sensors that require signal conditioning in biomechatronics include accelerometers, thermocouples, thermistors, resistance thermometers, strain gauges, and bridge sensors. Signal conditioning is a critical aspect of data acquisition and analysis in biomechatronics, as it ensures accurate and reliable measurement of biological signals.

Signal processing devices are an essential component of biomechatronic systems. These devices are responsible for collecting and processing data from the biosensors and mechanical sensors that are integrated into biomechatronic devices. The collected data is then analyzed to extract features that can be used to control the movements of the actuators. The signal

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processing devices also enable the extraction of useful information from wearable physiological signals, such as ECG, EEG, EMG, BP, and PPG, which are crucial for monitoring the user's physiological responses. The signal processing devices must be designed to operate in a low-power environment to conserve battery life and enable the development of autonomous, intelligent, and connected biomechatronic devices. Overall, signal processing devices are critical to the functionality of biomechatronic systems, as they enable the real-time processing and analysis of data, which is necessary for the precise control of the actuators and the detection of the user's physiological responses.

Example of signal flow in a biomechatronic device is shown in Figure 2.10.

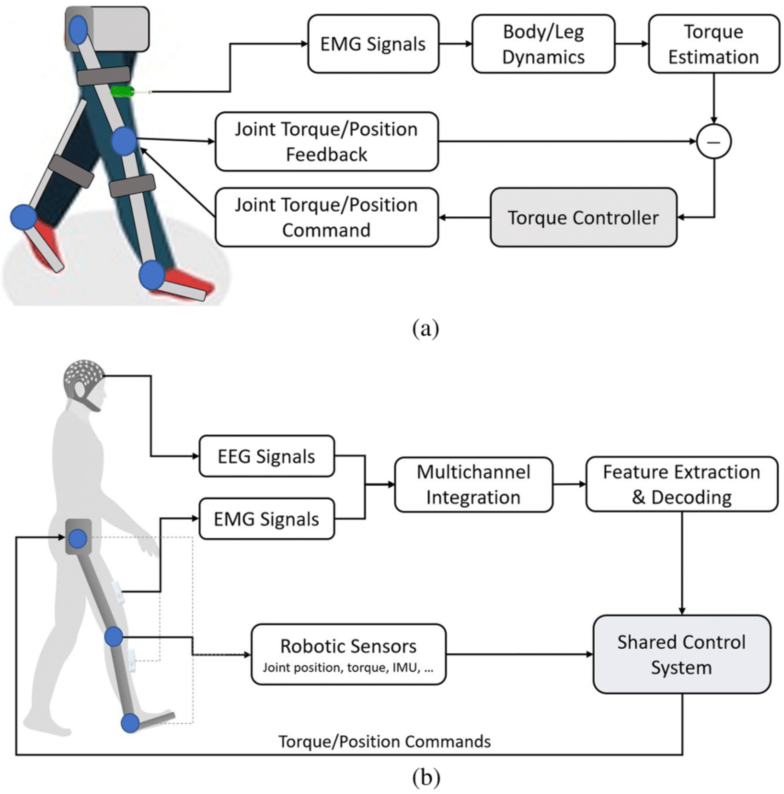

Figure 2.10. Lower limb exoskeleton control scheme [18]

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3. Examples of biomechatronic applications

3.1. Review of applications of biomechatronics

The biomechatronics has many biomedical applications. Some of them are listed below:

- Bio-interfaces for diagnostics and control
- Robotics for high-speed screening and analysis
- Passive and active prosthetic limbs and joints
- Bio-electrical signal processing
- Sensing and biofeedback
- Medical imaging and diagnostics
- Rehabilitation systems
- Neural and brain stimulation
- Tele and robot-assisted surgery
- Mobility aids
- Home care and elderly care
- Implants [3]

In the future, biomechatronics could also be used in [3]:

- Brain prostheses
- Autonomous hospitals
- Memory down/upload
- Nano-machines and micro-robots
- Powered exoskeletons
- Hyperspectral vision – artificial eyes
- Pervasive neural interfaces

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3.2. Biomimetic example – hand prostheses

3.2.1. Introduction

Hand prostheses are a great example of biomimicry, where engineers and designers create products and technologies that imitate nature's solutions to various problems. Hand prostheses are designed to mimic the functionality of natural hands, enabling individuals who have lost their hands or fingers due to injury or illness to perform daily activities with greater ease and independence.

Biomimetic hand prostheses use advanced technologies such as sensors, motors, and microprocessors to mimic the movements of natural hands. The sensors detect the movements of the user's remaining muscles or residual limb, and translate these signals into movements in the prosthetic hand. The motors and microprocessors then coordinate the movements of the fingers and hand to perform various tasks such as grasping, holding, and releasing objects. Some modern hand prostheses use myoelectric sensors to detect the electrical signals produced by the remaining muscles in a person's arm, which are used to control the movements of the prosthetic hand. This is similar to how the human hand is controlled by electrical signals from the brain that travel through the nerves and muscles.

Additionally, some hand prostheses are designed to mimic the movement and grip strength of a real hand. They may use mechanisms like pulleys and cables to achieve this, similar to the tendons and muscles in the human hand.

Biomimetic hand prostheses can provide individuals who have lost their hands with more natural movements and greater functionality, allowing them to perform a wider range of tasks with greater ease and precision. Some biomimetic hand prostheses are designed to look and feel like natural hands, with skin-like coverings and realistic-looking fingers. Others are designed to be more functional and practical, with a more mechanical appearance and greater durability.

3.2.2. Soft biomimetic prosthetic hand

The figure 3.1 presents the soft biomimetic prosthetic hand. The child's prosthetic hand contains six independent, soft and flexible pressure-driven actuators. Each finger uses one

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actuator and can be controlled independently of the other fingers. The thumb is equipped with two actuators that allow it to bend and change its position between opposition and recumbent. The hand is designed so that it can be easily manufactured without expensive equipment. It is made of two types of two-component silicone reinforced with polyester thread. The main part of the device, the rubber exoskeleton, is made of the relatively rigid SmootOn SmoothSill 940 (Shore A40) silicone, while the actuators are made of the much softer SmoothOn EcoFlex 0050 (Shore 00 50) material. This combination of materials allows the mechanical properties of the fingers to be pre-programmed into the hand structure and transform the linear deformation of the actuators into the required retraction motion of the fingers.

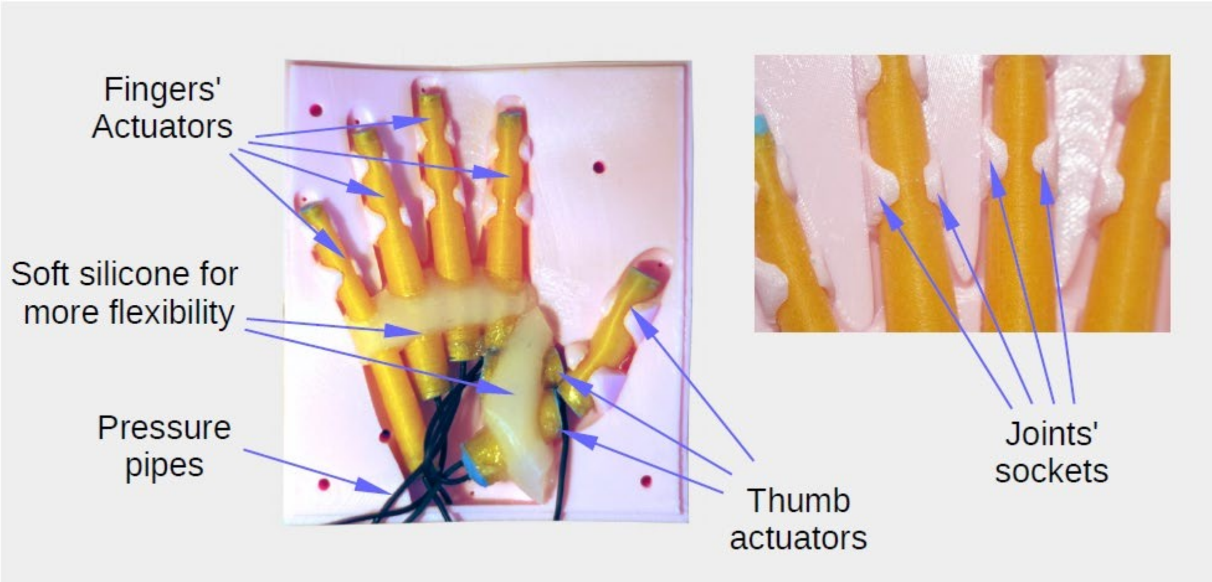

Figure 3.1 Alignment of pneumatic actuators in the main mould [20]

The valves are controlled by providing voltage signals in a range from 0 to 10 V. In our case the voltage signal is emulated by a PWM signal generated by a Raspberry PI running a Python script.

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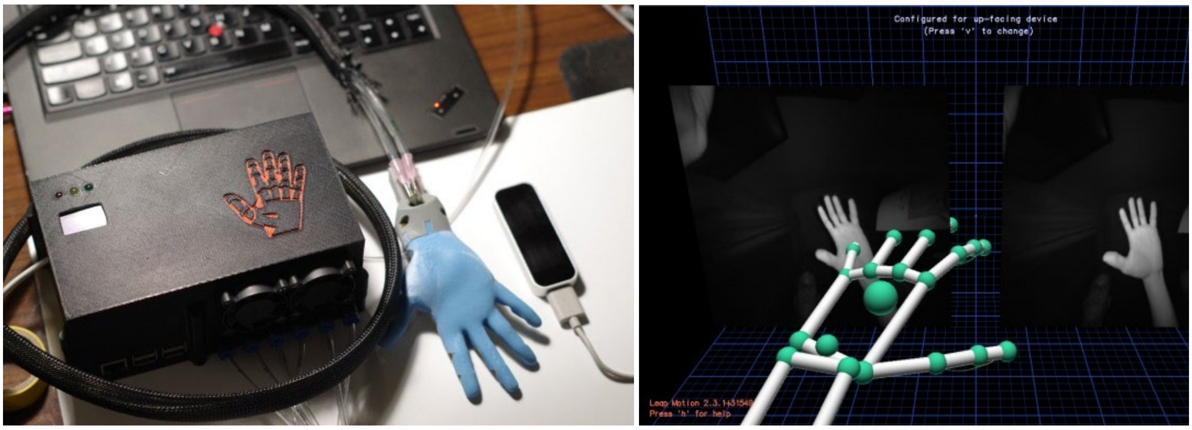

Figure 3.2 (a) The control unit and the LeapMotion controller, (b) LeapMotion-based hand tracking [20]

3.2.3. Rigid prosthetic hands

The figure 3.3 presents the next type of custom hand prosthesis. a biomimetic prosthetic augmentation attachment that interfaces with human body to serve as an additional limb. The project consists of an open source 3D printed prosthetic hand mounted on an aluminum pylon dressed with biomimetic fairings that interfaces with forearm through a mount with micro adjustable tensioners and an adjustable elbow joint. Thumb opposition, pinch-release, and power grasp movements of the prosthetic hand are mediated through three servo motors controlled by an Arduino that translates muscle movements sensed by an infrared proximity sensor into open hand and close hand commands.

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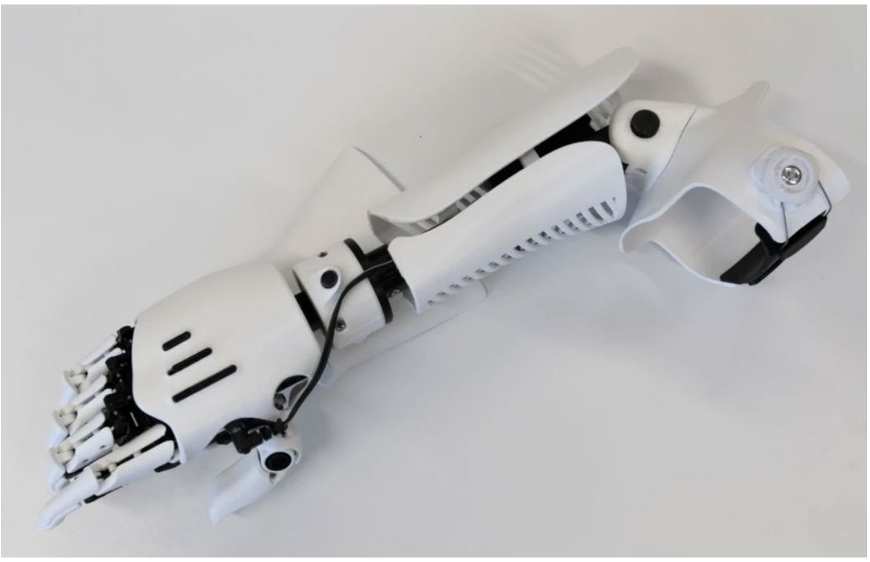

Figure 3.3. A view of the fully assembled prosthetic hand made by Rodolfo Antonio Salido Benítez [19]

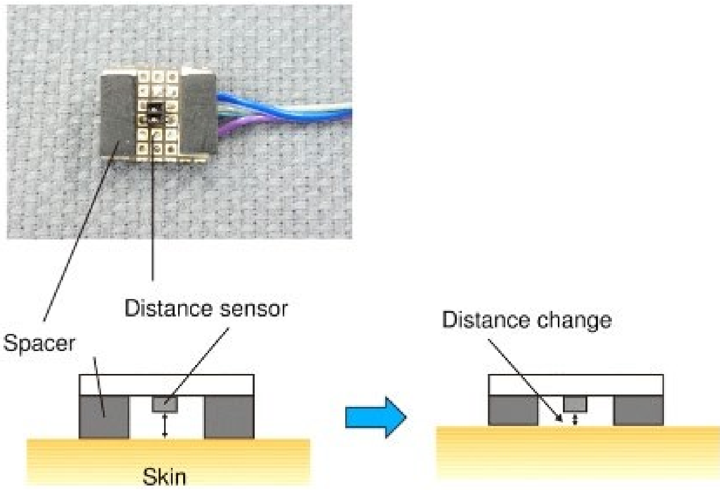

Figure 3.4. Method of operation of the proximity sensor used [19]

- prosthesis with surface electromyography

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The figure 3.5 shows a prosthesis with surface electromyography (EMG) capability. The device has a small surface EMG sensor that detects myoelectric signals in the stump (Figure 3.5 b). The maximum voltage difference when the patient contracts the flexor or extensor muscles of the wrist was used as the reference myoelectric signal to control the device (Fig. 3.5c). In each patient, the EMG sensor site in the support socket showing the maximum voltage difference was identified and used (Fig. 3.5 c). Manipulation of the prostheses was performed using the EMG signal produced by the patterns formed during each voluntary muscle contraction.

a) b) c)

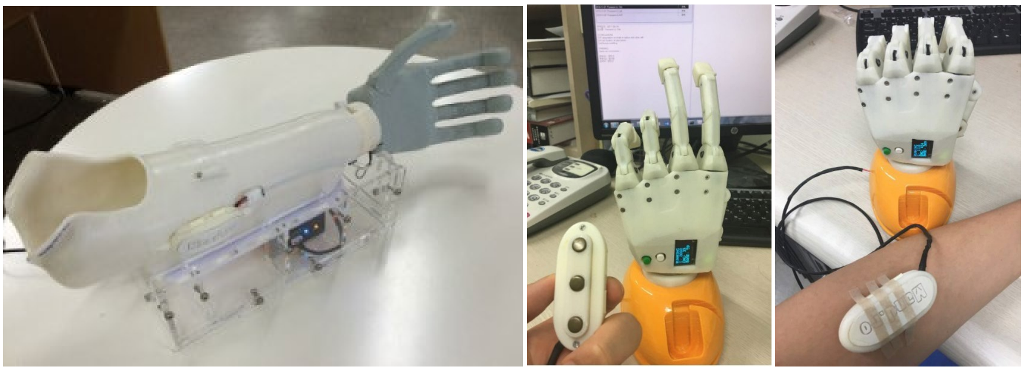

Figure 3.5. (a) A single-channel electromyography (EMG) sensor was installed in the socket where the maximum voltage change in the amputated forearm was checked. (b, c) A prosthesis model with a surface EMG sensor detects the site of the largest voltage change in the myoelectric signal in the stump when the patient moves the rest of the forearm muscle. The voltage change is displayed on a screen on the hand. This model can be used for pre-application testing and for patient observation, three-dimensionally [21]

- prosthesis arm

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Figure 3.6. A prosthesis simulator for use in anatomically intact individuals. The socket is designed to fit over the forearm and fist. Straps allow the socket to be pressed against the person's arm. It is not possible to customize the electrode placement for each person [22]

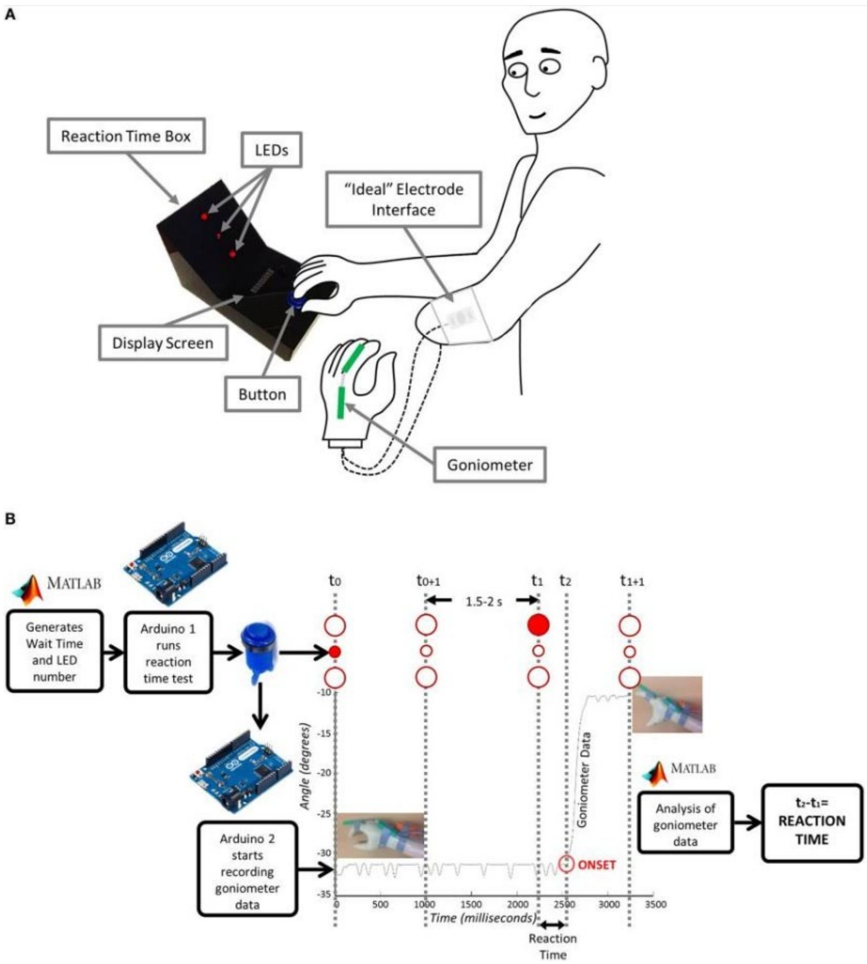

Figure 3.7. Reaction time test: (A) Experiment setup and (B) basic instrumentation [22]

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The figure 3.7. presents, how Matlab generates the wait time and LED number and sends them to Arduino1, which starts the test. The user confirms its readiness by pressing a button. The goniometer starts recording and the central LED lights up for 1 s. After a period of 2.5-3 s, one of the larger LEDs lights up and the user performs a hand movement. An Arduino2 connected to the goniometer sends the motion data to Matlab, where it is analyzed and the reaction time is sent back to the user.

The Figure 3.8 shows a multifunctional myoelectric prosthetic hand system for upper limb amputees. The hand has five fingers, each of which can be actuated by a controller with a six-axis motor driver to perform flexion and extension movements. In the case of the thumb, adduction and abduction movements can be performed manually or automatically by driving the motor at the temporomandibular joint. Two EMG signals are used to perform various hand gestures and grip movements of the developed hand. The electrical signal is output as an envelope according to the movement of the muscle.

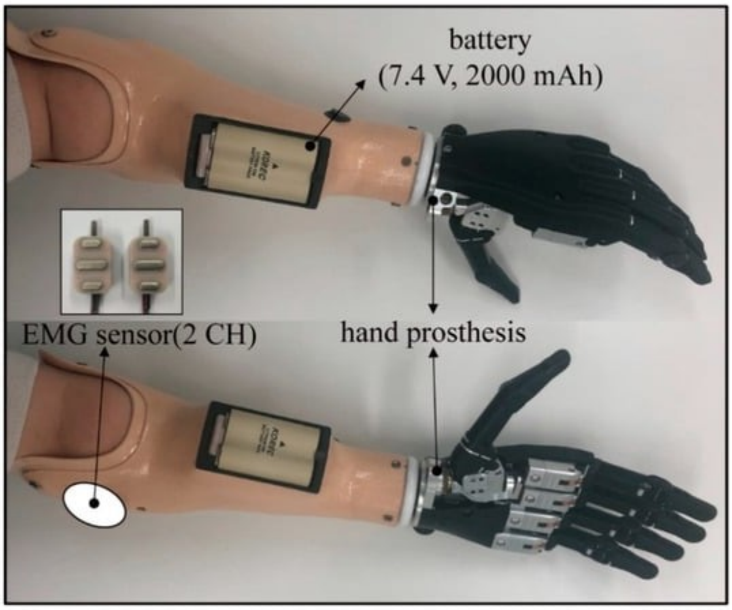

Figure 3.8. The developed multifunctional myoelectric hand prosthesis system [23]

A rechargeable lithium-ion battery with an input voltage of 7.4 V and a capacity of 2000 mAh was used to drive the hand.

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The human hand can perform various grasping movements. The developed system can perform four hand gestures - thumb up, OK, win and point - and four grasping movements - strong grasp, hook grasp, side grasp and peak grasp - using an easy and effective control algorithm (see Figure 3.9).

Figure 3.9. The hand gestures and grip motions performable by the hand [23]

3.3. Bioinspired robotic hands – modular grasping (ModGrasp)

Mimicking the human hand's ability, one of the most challenging problem in bio-inspired robotics due to large gap in terms of performances. Classical approach, analysis of the kinematic behavior of the human hand involves simplified human hand models with minimum and optimal degrees of freedom. A promising solution is modular grasping, as it provides minimum number of degrees of freedom necessary to accomplish the desired task.

Modular grasping is a trade-off between a simple gripper and more complex human like manipulators. It adheres to the principle of minimalism: choose the simplest mechanical structure, the minimum number of actuators, the simplest set of sensors, etc. In modular grasping, identical modules are used to build linkages to realize the grasping functions. The modular grasping meets the requirements of standardization, modularization, extendibility and low cost [24].

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Figure 3.10 Modular grasping – a) possible functions, b) modular structure

ModGrasp is an open-source rapid-prototyping framework for designing low-cost sensorised modular grasping hands, developed by author of this module [25]. The rapid-prototyping approach is combined with the modular concept so that different manipulator configurations can be rapidly modelled. This method consists of an immersive design process that involves mechanics, hardware and software. A real-time one-to-one correspondence between virtual and physical prototypes is established. The on-board, low-cost torque sensors provided within each module allow for evaluating the stability of the obtained grasps. An intuitive visual feedback is also provided during the designing phase by means of a 3-D visualisation environment. Moreover, both the virtual models and their physical counterparts can be controlled by using the same input device [26].

Architecture of the system is presented in Fig. 3.11. It is based on master-slave communication. Each module is controlled by a slave controller board, which communicates with a master controller board. The controlled manipulators are simulated in a 3-D visualisation environment that communicates with the master controller. If one or more modules break or are disassembled from a prototype, the manipulator keeps working with the remaining functioning joints.

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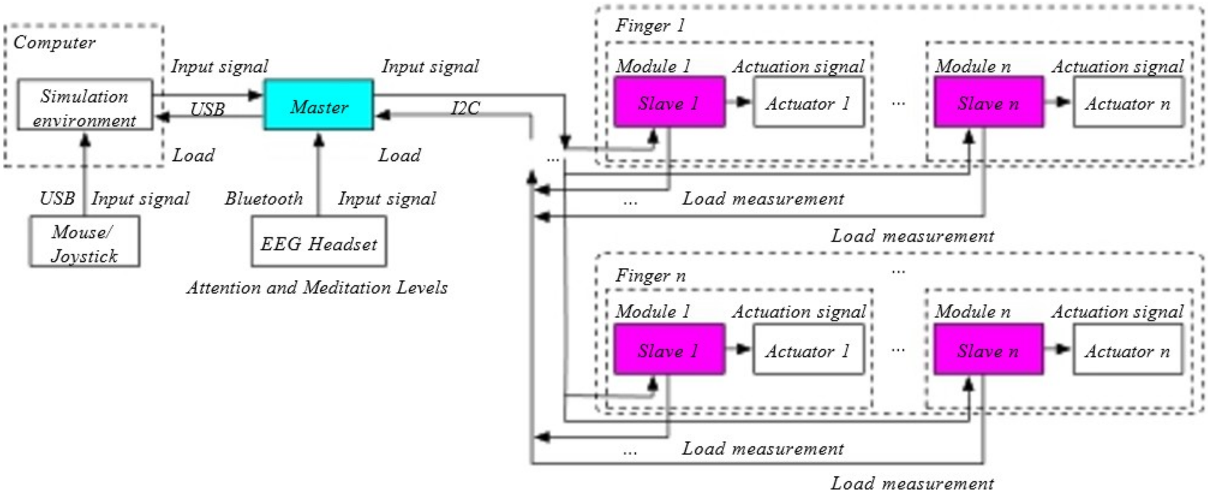

Figure 3.11. ModGrasp architecture

For control of the modular grasping device, open hardware with Arduino is used. An Arduino Uno board based on the ATmega328 micro-controller is used as the master, while one Arduino Nano board is used as a slave to control each finger joint. Support for different input devices is assured – device can be directly controlled from the simulator environment by means of a computer mouse/joystick or work stand-alone and be controlled by means of a set of potentiometer shafts that are used as input controllers. The standard I2C is used as a communication protocol. The physical manipulator models communicate with the simulation environment through the serial interface. Example of implementation is shown in Fig. 3.12.

As method of input is irrelevant, various sources can be used for controlling of the grasping device. In spirit of biomechatronics, human biology can be directly used, via means of brainwaves registered and transmitted real-time through EEG headset. This allows to obtain a low-cost sensorized modular hand controllable by human mind (Fig. 3.13.)

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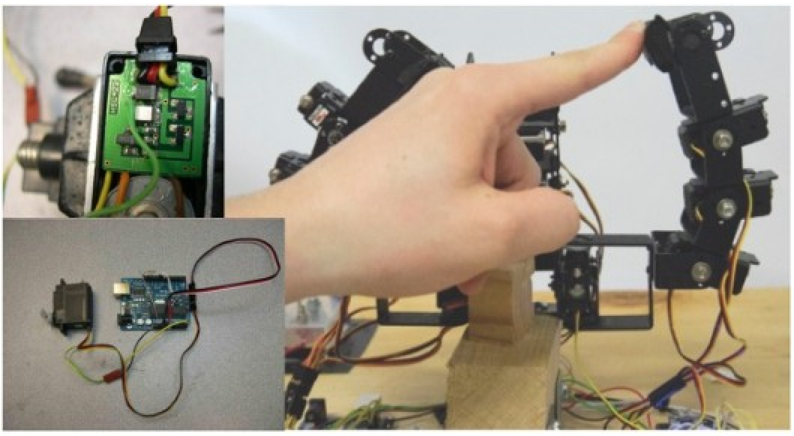

Figure 3.12. ModGrasp implementation – sensing of torque

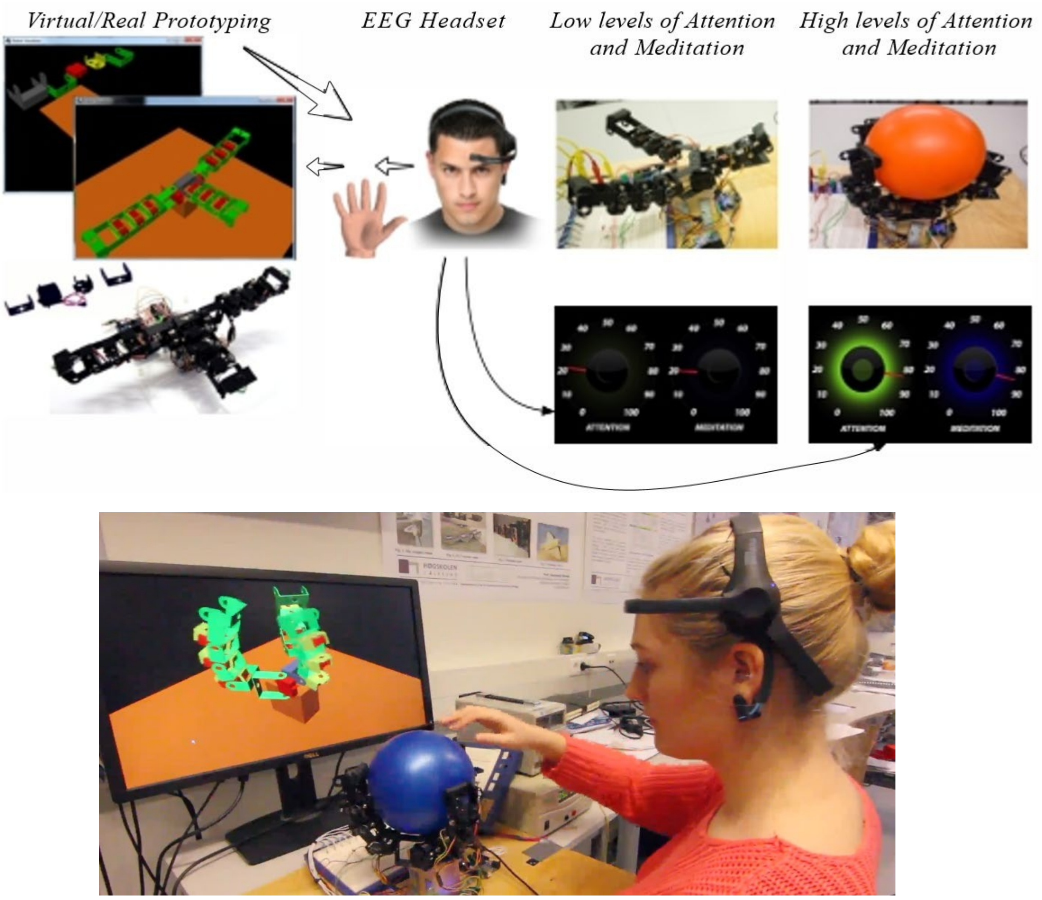

Figure 3.13. ModGrasp implementation – mind control – concept (top) and experiment (bottom) [27]

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3.4. Biomechatronic exoskeletons

An exoskeleton is an external support structure that provides protection and support for an organism's body. In biology, exoskeletons are found in many invertebrates such as arthropods, crustaceans and insects. These organisms have a tough, protective outer layer that serves as both armour and structural support for their bodies.

In recent years, exoskeletons have also been developed that can be used in robotics and human assistance. These exoskeletons are typically made of lightweight materials, such as carbon fibre, and are designed to increase the user's strength and mobility. They are used to help people with disabilities or injuries to walk, and to assist workers in physically demanding occupations such as construction or manufacturing.

Exoskeleton technology is still developing, but it has the potential to significantly improve the quality of life for people with limited mobility and increase the productivity and safety of workers in physically demanding jobs.

The figure 3.14 shows an example of an exoskeleton that also has wheelchair functions. Wheelchair mode allows the skateboard to move on smooth surfaces at high speed with increased safety and reduced energy consumption. Compact wheel modules using skateboard hub motors can be stowed away to prepare for walking. Considering that the backward movement of the exoskeleton's joints is a major concern for safe physical human-robot interaction, the parameters of the wheelchair were designed based on a simplified human model, so that the torque limitation of the actuators is still sufficient to support seat-motion to standing.

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Figure 3.14. Alpha prototype of a wheelchair-exoskeleton hybrid robot in standing position (for walking over obstacles) and in wheelchair mode (for safe and energy-efficient movement over smooth surfaces) [28]

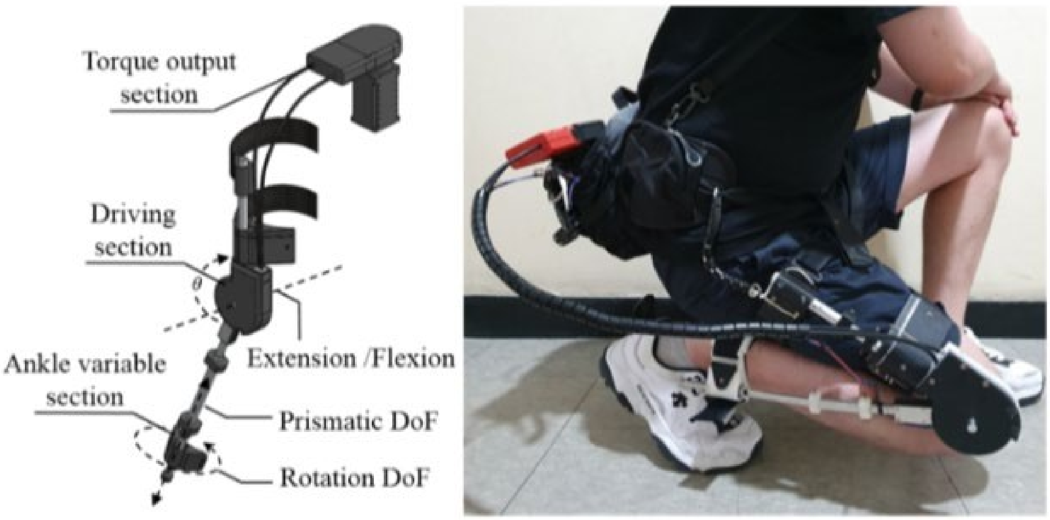

Figure 3.15. The full appearance of the exoskeleton and the actual wearing appearance, which presents the range of operation. The exoskeleton has three degrees of freedom (DoF). The knee has a flexion/extension DoF, the angle of which is indicated by θ. In addition, the ankle has a passive rotation DoF and a passive prismatic DoF. The range of motion of the exoskeleton is 145◦. The compliant structure allows the user to sit completely [30]

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The figure 3.16 shows a model of an upper limb exoskeleton that provides motion support for the elbow joint. A stepper motor with a torque of 1 Nm was used as the drive. In order to increase the torque of the drive system, an additional gear ratio was used and a pinion gear was used. A stepper motor was used to drive the exoskeleton, the housing of which was connected to the exoskeleton's "arm". On the axis of the motor, a gear wheel was used, which cooperated with a gear wheel connected to the exoskeleton's "forearm". This resulted in a toothed gear with a ratio of 1:5, increasing the torque transmitted by the stepper motor. Since the minimum travel of the motor is 1.8 degrees at full-step operation, the minimum movement of the forearm is 0.36 degrees. At ½ step setting, the minimum movement is 0.18 degrees.

Figure 3.16 Prototype of upper limb exoskeleton [29]

The exoskeleton is controlled by a TB6560 controller (Fig. 3.17) connected to a computer via an LPT port. The whole thing is powered by an industrial power supply unit with a power of 600W, an output voltage of up to 36V and an output current of 16A. The software used was Step2CNC, a program for controlling numerically controlled machine tools. The program allows both manual control using the buttons of the manual control panel and automatic control. Automatic control is performed using a G-code file. The codes used allow control of the angular position of the forearm, the speed of the movement, as well as the programming of breaks in the movement. The control file can be prepared both in the Step2CNC program editor and developed as a text file in any editor (such as Notepad). The control file can be then

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entered from the computer's memory into the program. By using this program in automatic mode, it is possible to apply a certain sequence of movements that will be performed by the stepper motor.

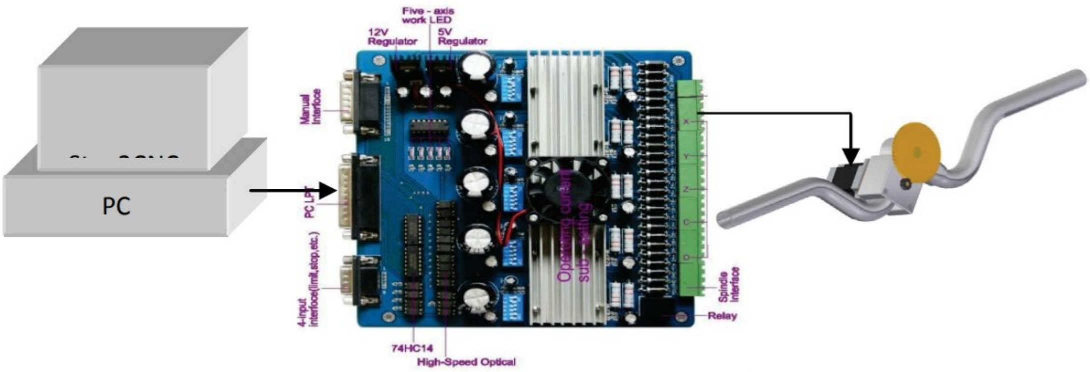

Figure 3.17 Control system of upper limb exoskeleton [29]

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4. Summary

In this e-learning module, basics of biomechatronics were shown. Some key concepts, descriptions of exemplary systems, as well as technical problems, challenges and opportunities were mentioned. The aim of this module was to familiarize the readers with the notion and get their attention to biomimetic, mechatronic systems possible to manufacture using additive manufacturing.

Despite the challenges, the potential benefits of biomechatronic systems are enormous. Biomechatronics has the potential to revolutionize healthcare and rehabilitation, enabling individuals with disabilities and injuries to regain function and independence. In addition, biomechatronic systems could be used to create entirely new functions that are not possible with biological systems alone. This could lead to new opportunities in fields such as robotics and space exploration.

In conclusion, biomechatronics is an interdisciplinary field that holds enormous promise for the future of healthcare and rehabilitation. Biomechatronic systems incorporate biological and mechanical components to achieve a specific function, and can be used for a variety of applications, including prosthetics, exoskeletons, and medical devices. Developing these systems requires a deep understanding of both biology and mechatronic engineering, and researchers in this field must be skilled in a wide range of disciplines. The potential benefits of biomechatronic systems are enormous, and this field is likely to continue to grow in importance in the coming years.

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