UNIVERSITÀ DEGLI STUDI DI GENOVA

MASTER DEGREE COURSE IN ROBOTICS ENGINEERING

Biomedical Robotics

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1 Neural Control of Movements

1.1 Taxonomy of Motor Behaviour

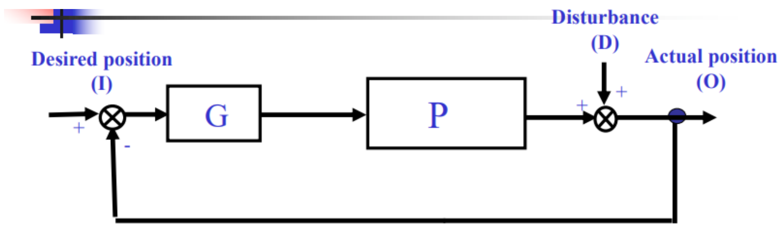
1.1.1 Anticipatory Responses and Error Correction

The ***anticipatory response*** is the ability of the body to predict and prepare for movements in advance, whereas ***error correction*** is the capacity to adjust or correct movements in response to errors during execution.

- ***Coactivation of Agonist/Antagonist Muscles***: Limbs becomes more rigid, helping in maintaining joint's stability for fine-tuning or resistance to external forces.
- ***Reciprocal activation***: Facilitates smooth, controlled movements, enabling efficient force generation and control.

1.1.2 Feedback Control - Response to Sensory Information

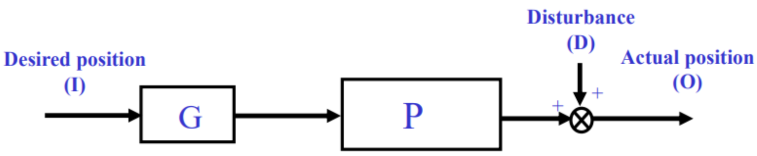
Sensory information is received after an action has been executed, then adjusted by comparing it to a reference signal.



- It is ***simple*** (the basic element is a comparator between desired and actual state).
- However, it ***introduces a delay***, leading to significant ***stability problems*** due to the delay of the sensory feedback.

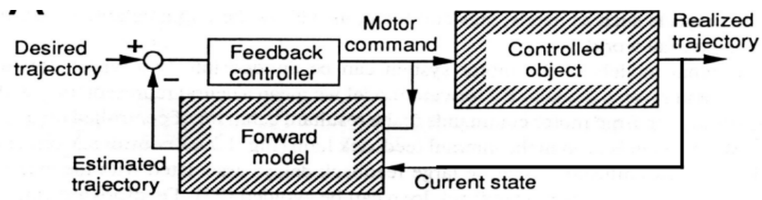
1.1.3 Feedforward Control - Pre-programmed

Anticipatory adjustments made before an action based on a prediction of what will happen.



- It is ***complex*** (it requires an internal model and a learning process).
- It has ***no stability problems*** since it is based on anticipatory compensation.

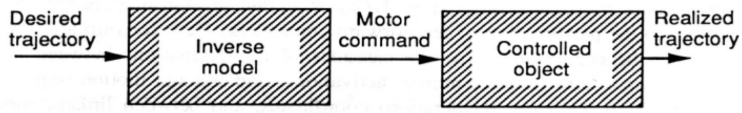
1.1.4 Forward and Inverse Models



Forward models receive a motor command in input directed towards the controlled object (or "plant"). These models integrate this command with the body's current state to generate a prediction of the body's future position. The motor command input to the forward model might take the form of an efference copy, a copy of the motor command issued by the brain.

Once the forward model processes this information, it produces an anticipated position of the body, which is then compared to the actual body position. The actual and predicted position of the body may differ due to noise introduced into the system. This noise can stem from external sources, such as unexpected forces acting on the body, or internal sources, like imperfections in body sensors or sensory noise.

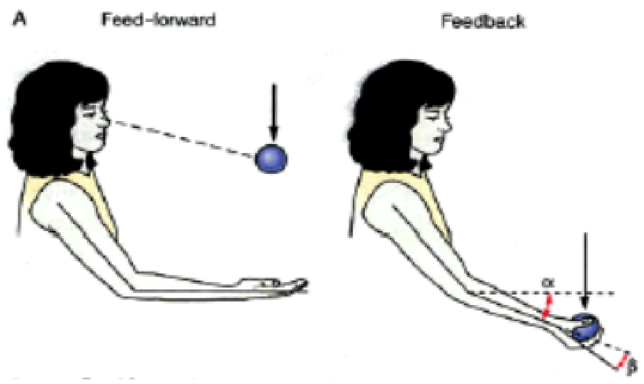
When differences occur between the predicted and actual body positions, these variations, whether they originate internally or externally, are fed back into the system. This feedback loop allows for the integration of these differences as inputs to the entire system. Consequently, the system can adjust and refine the set of motor commands being generated, aiming to create more accurate and precise movements in response to the observed discrepancies.



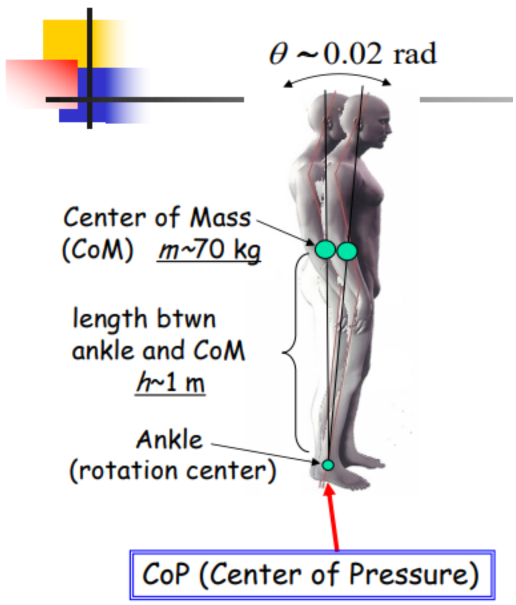
Inverse models use the desired position of the body as inputs to estimate the necessary motor commands which would transform the current position into the desired one. For example, in an arm reaching task, the desired position (or a trajectory of consecutive positions) of the arm is input into the postulated inverse model, and the inverse model generates the motor commands needed to control the arm and bring it into this desired configuration.

1.1.5 Examples

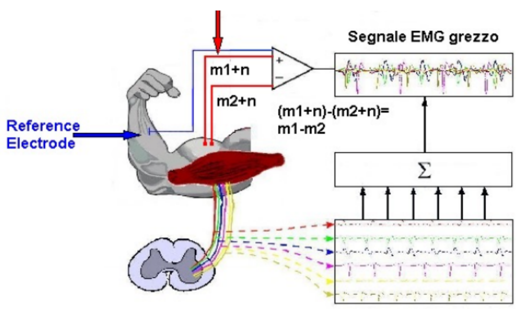
- ***Catching a Ball***: Uses the internal model to estimate the impact time and to pre-activate muscles to be ready for the impact. The feedback control allows to adapt to unpredictable disturbances and feeds information to the controller to improve the internal model.



- ***Postural Sway***: Involves maintaining upright standing posture by using information from the vestibular system, returning to equilibrium after a change in the center of gravity. The ankle provides feedback to balance the body, acting as a pivot point. There are three mechanisms for stabilizing posture:
  - ***Physical Mechanism***: Adjusts muslce and tendon stiffness without introducing delays
  - ***Reactive Mechanism (Reflexes)***: Introduces significant delays due to the propagation of nervous signals, specifically responding only to sudden and major disturbances.
  - ***Anticipatory Mechanism***: Counteracts these delays by predicting and proactively adjusting, mitigating the impact of delays introduced by the reactive mechanism.

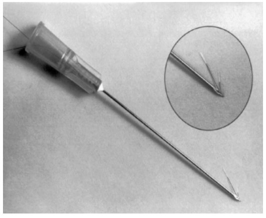


2 Electromyography (EMG)



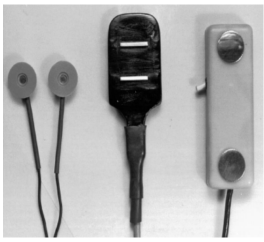
EMG, or electromyography, measures the muscle response or electrical activity in response to a nerve's stimulation of the muscle. The recordings obtained through EMG can be categorized as:

- ***Invasive (using needles or wire electrodes)***: This method impacts a limited number of muscle fibers.
  - *Advantages*: Enables precise differentiation of the activity of individual muscles, reducing cross-talk (happens when the electrical activity from one muscle is picked up by electrodes intended to record the activity of a different muscle), and providing signals with high amplitude and frequency content.



  - *Disadvantages*: Involves penetration of the skin, making it challenging for use in dynamic conditions like sports.

- ***Non-invasive (surface electrodes)***: These electrodes affect a broader range of muscle fibers. Surface electrodes needs to be placed on the center of the muscle of interest. To ensure optimal signal transmission, it's essential to prepare the skin by applying gel and ensuring cleanliness.



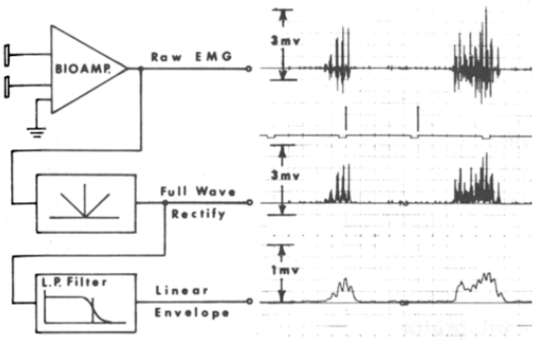
  - *Advantages*: Offers greater comfort and convenience, especially suitable for recording signals from superficial muscles.
  - *Disadvantages*: More susceptible to cross-talk interference.

To mitigate ***cross-talk*** in EMG recordings, precise electrode positioning or the use of a differential amplifier proves effective (serves as a signal amplifier and reduces the unwanted noise). Additionally, the presence of simultaneous activity in agonist and antagonist muscles (co-contraction) can be confused with the presence of cross-talk. For avoiding electrocardiogram (ECG) interference, positioning the electrodes on the right side of the body and placing them farther away from the heart can significantly reduce unwanted signal overlap.

The raw EMG signal is primarily used as an indicator of muscle activation (ON/OFF), the amplitude of the EMG signal holds limited clinical significance on its own. However, it serves as a valuable quantitative measure, commonly categorized based on levels of actuation. Due to the complexity in precisely determining levels of contraction, EMG signals are often generically quantized into low, medium, and high activation levels.

EMG finds diverse applications in fields such as prosthesis control, Targeted Muscle Reinnervation (TMR), Pneumatic Artificial Muscles, and advanced technologies like the EKSO exoskeleton.

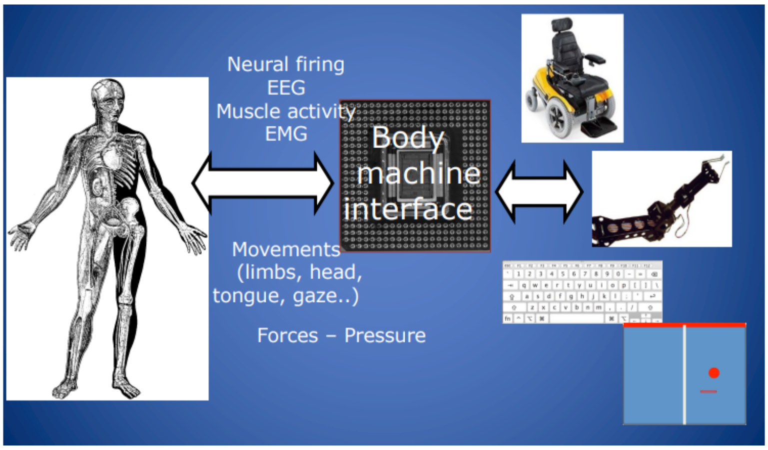
2.1 Pre-Processing



A ***differential amplifier*** is commonly used to enhance EMG signals, amplifying the difference between two electrode inputs while rejecting common signals. This process helps minimize noise and interference in the recorded signal. The ***raw EMG signal***, initially captured directly from electrodes, holds the complete frequency spectrum and forms the basis for subsequent analyses. The highest frequency components of the EMG signal being around 400–500 Hz, it is classically assumed, according to the "*Nyquist frequency*" rule of thumb, that a ***sampling frequency*** of about 1 kHz (2 × 500 Hz) is required. Before further processing, the raw EMG signal undergoes ***band-pass filtering*** (30-450 Hz) to remove high frequency noise and prevent aliasing from occurring in the sampled signal. Next, a ***full-wave rectification process*** converts negative EMG components into positive values, providing a representation of signal magnitude while disregarding polarity. In order to obtain the ***envelope of the rectified EMG signal***, a subsequent step involves applying a ***low-pass filter*** (with a cutoff frequency usually between 4-10 Hz). Note that since the rectification changes the frequency content of the signal, after filtering with a band-pass I can filter again with a low-pass. This process electronically smoothes the signal, reducing its frequency content and aiding in noise reduction. However, this method introduces a delay. necessitating lower sampling rates (e.g., 100 Hz) and reduced memory storage. Consequently, to manage computational load and streamline data handling, the final step involves downsampling the signal. ***Downsampling*** further reduces the signal's sampling rate, offering computational efficiency while retaining essential information within the signal envelope.

3 Body and Brain Machine Interfaces

3.1 Body Machine Interfaces (BMI)

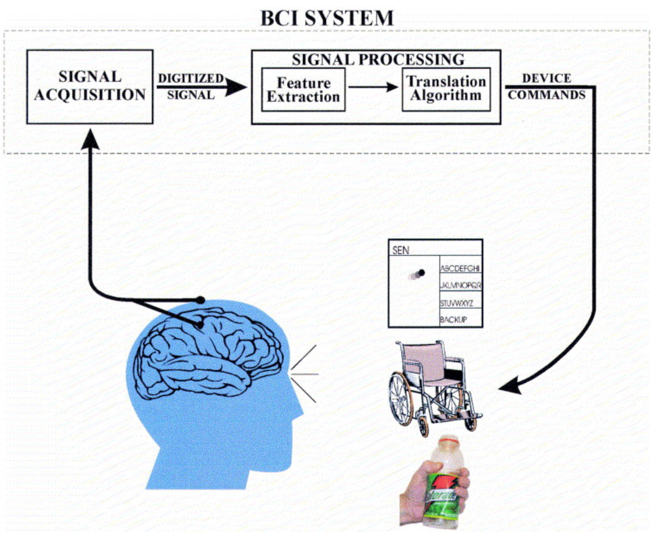


The ***Bodyn Machine Interface (BMI)*** comprises three essential elements:

- The first element is the biological source, the ***body*** (human/animal) from which signals are obtained to operate an external device. Those signals can be derived from a variety of sources, such as muscle activity (EMG), brain activity (EEG) and more.
- The second element is the ***machine***, that refers to the device or system to be controlled, which could include bionic limbs, a powered wheelchairs or cursors.
- The third element is the ***interface*** that links the body and the machine. It transforms the body signals into commands for controlling the designated device (encoding process). It's important to note that the interface may also operate in the reverse direction by encoding the state of the device into stimuli to be delivered to the user.

BMIs are beneficial for applications in rehabilitation, assistive technologies, or controlling devices through bodily movements or gestures.

3.2 Brain Computer Interfaces (BCI)



Brain-Computer Interfaces (BCIs) encompass a multifaceted process beginning with Signal Acquisition and Processing, involving the acquisition of neural signals through diverse technologies that could be invasive or non-invasive. Once acquired, these signals undergo processing to extract meaningful information, filtering out noise and enhancing signal quality. This leads to the development of advanced algorithms in order to neural patterns, translating them into understandable commands, enabling control over external devices like prosthetic limbs, computer interfaces or assistive technologies, entirely driven by users' brain activity. BCIs incorporate feedback mechanisms allowing users to interpret the outcomes generated by the controlled devices, in order to adapt and refine the brain activity to accomplish desired actions effectively.

As we already mentioned BCIs come in two primary forms: invasive and non-invasive.

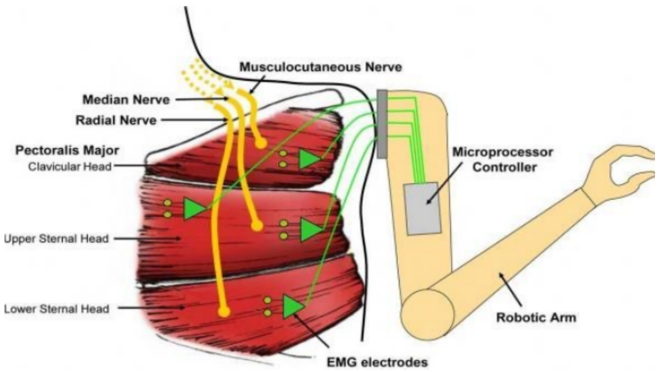
- ***Non-Invasive (e.g., EEG, MEG)***: Non-invasive BCIs utilize techniques such as ***EEG*** (sampling frequency usually 250Hz-1000Hz), offering advantages like easy application with scalp electrodes and no surgical intervention needed. However, drawbacks include limitations in spatial resolution and the inability to utilize higher frequency signals due to skull attenuation.
- ***Invasive (e.g., ECoG, implanted electrodes on cortex)***: Invasive BCIs, employing methods like ***implanted arrays***, yield precise readings but pose potential issues such as post-surgery scar tissue formation and the body's acceptance of the implanted electrodes due to their depth placement. ***ECoG*** (***Electrocorticography***, electrodes placed onto the exposed cortex) presents improved signal resolution compared to non-invasive BCIs, with a lower risk of scar tissue formation, yet it falls short in accuracy compared to implanted arrays.

BCIs are particularly valuable for individuals with motor disabilities, allowing them to control prosthetic limbs, computers, or other technologies using their brain signals.

Note: The ***Kalman filter***, as applied in the context of BMIs, is used for decoding neural activities into cursor motion. It's key aspects are:

- ***State***: The state being estimated involves either the cursor's position and velocity or the historical cursor positions.
- ***Observation***: Neural activities are observed and recorded over time to understand the patterns and correlations between these activities and the cursor's motion.
- ***Model Inference***: The Kalman filter assists in inferring both the process model (how the cursor moves) and the observation model (how neural activities correlate with cursor movement). This inference is done by maximizing the likelihood, aligning recorded neural activities with known cursor states during calibration.

3.3 Targeted Muscle Reinnervation (TMR)



Targeted Muscle Reinnervation (TMR) is a surgical procedure used to improve control and functionality of prosthetic limbs for individuals who undergone limb amputation. This procedure involves redirecting nerves originally connected to amputated limbs towards nearby muscles, effectively reassigning these nerves to new muscle targets. Redirection goes from high (muscle controlling complex movements) to low (muscles used for simpler tasks) functional significance.

In scenarios where individuals thinks about moving their missing limb, the brain continues to send signals along the nerves that used to control that limb. Through TMR, these nerves are surgically redirected to nearby intact muscles. However, these newly connected muscles may not replicate the same functions as the original limb. For instance, nerves previously controlling hand movements redirected to upper arm muscles might lack the precision of hand muscles.

Pros of TMR include a more natural feel, restored connection to the nervous system, and the potential for sensory feedback. However, it's important to note that this procedure is invasive, there may be crosstalk in EMG recordings and also surface electromyography (SEMG), commonly used in evaluating muscle activity, might encounter difficulties post-TMR due to changes in muscle innervation. The redistribution of nerves to different muscle regions can affect the quality and specificity of SEMG recordings.

On the other hand, ***Targeted Sensory Reinnervation (TSR)*** aims to restore sensations like touch and temperature to amputated limbs. This procedure specifically targets reestablishing sensory feedback to improve the user's experience with their prosthetic limb.

4 Surgical Robotics

Why do we want to use robots in a surgical application?

- ***Repeatability*** and ***Precision***
- ***Minimized Trauma***: Smaller incisions lead to reduced patient trauma during surgeries.
- ***Versatility*** and ***Remote Access*** (surgeon doesn't need to be in the same room)
- ***Performing Procedures on Active Organs***
- ***Cost Reduction***: They contribute to lowering healthcare costs by optimizing procedures and resource utilization.

Current drawbacks:

- ***Limited Dexterity***: Robots lack the fine motor skills and dexterity of human hands.
- ***Absence of Sensory Feedback***: Lack of sensory information, force feedback, and tactile sensations hampers their ability to feel and respond to touch.
- ***Visual Feedback Limitations***: Although equipped with cameras, they may face limitations in providing comprehensive visual information to surgeons.
- ***High Cost***: The implementation and maintenance of medical robots entail significant financial investments.

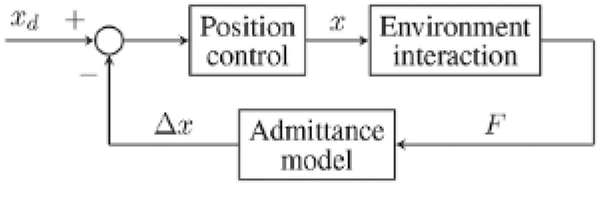
4.1 Cooperative Manipulation

In the realm of cooperative manipulation, notable examples include the ***"steady-hand robots"***, exemplified by *Mako's RIO robotic arm* and the *Johns Hopkins University (JHU) eye surgery robot*. These robots employ advanced control systems to facilitate seamless cooperation between the surgeon and the robotic arm during surgical procedures.

The robot's controller possesses the capability to sense forces exerted both by the operator on the tool and by the tool on the environment. This information is then used in various control modes to provide smooth and tremor-free precise positional control along with adjustable force scaling. Essentially, these systems function as manipulation tools with the precision and sensitivity of machines, but with the manipulative transparency and immediacy associated with handheld tools. This proves especially beneficial in tasks characterized by compliant or semi-rigid contacts with the environment.

4.2 Admittance and Impedance Control

4.2.1 Admittance Control

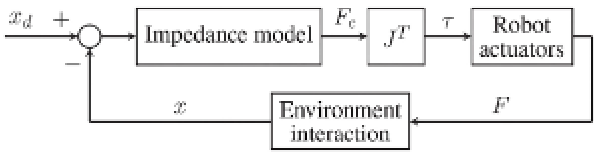


Def: In this control method, the robot responds to external forces applied by the user, adjusting its movement accordingly.

Ex: Let's consider a robotic surgical system equipped with admittance control. As the surgeon manipulates the robot's control interface to perform delicate movements during surgery, force sensors integrated into the system measure the applied forces. The robot's control algorithms then interpret these force readings, allowing the robotic arms or instruments to respond proportionally and adjust their movements accordingly.

Pros and Cons: Pros of using admittance control in this context include the capability to execute very slow and precise motions, crucial for intricate surgical procedures demanding high precision. This control method is adaptable, applicable to both teleoperation setups (remote surgery) and cooperative manipulators where the robot cooperates with the surgeon's movements. However, one of the limitations of admittance control is its dependency on force sensors.

4.2.2 Impedance Control



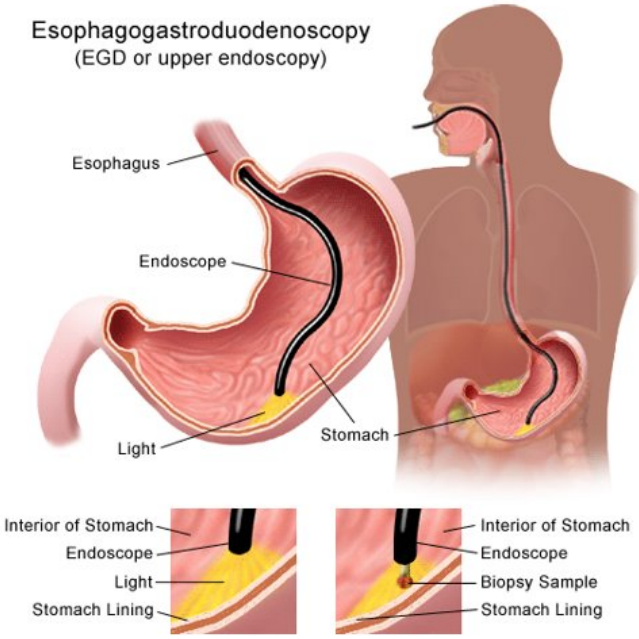
Def: Impedance control is a robotics control method that focuses on regulating the robot's response to external forces by controlling the stiffness, compliance, or resistance of the robot's interactions with its environment (operator).

Ex: Let's consider its application in a robotic surgical system. In impedance control, the system governs the robot's stiffness or compliance based on the forces encountered during surgery. As the surgeon interacts with the robot's control interface, force sensors detect the applied forces. Unlike admittance control, where the robot adjusts its movement directly proportional to the applied force, impedance control emphasizes regulating the robot's stiffness or compliance in response to these forces. For instance, in delicate surgical procedures, the robot may exhibit higher compliance (softer interaction) to reduce the applied forces and mitigate potential damage to sensitive tissues. Conversely, in tasks requiring more force or precision, the system increases stiffness to provide better support or control. A practical example of impedance control has been developed in the course assignment related to the *Phantom Omni* robot.

Pros and Cons: Impedance control offers benefits such as adaptability in adjusting the robot's behavior based on force requirements. It's versatile, suitable for various applications beyond surgery, including tasks involving human-robot interaction, manufacturing, and rehabilitation. However, a limitation of impedance control lies in determining the optimal stiffness or compliance settings, which can be challenging due to the dynamic nature of interactions. Additionally, similar to admittance control, impedance control also relies on force sensors for accurate force feedback.

4.3 Endoscopy

Endoscopy, is the examination of internal body cavities using a specialized medical instrument called an endoscope. This medical technique is used to diagnose, monitor, and surgically treat various medical problems. An ***endoscope*** is a flexible tube equipped with lenses and a light source. Thorough one channel of endoscope, water and air is conducted to wash and dry the surgical site. Offering a visual window into the body, the endoscope detects issues like ulceration or inflammation. Moreover, it enables tissue sampling or removal and captures detailed images of internal organs. It can also be used to collect a sample of tissue or remove problematic tissue. The endoscope also has a channel through which surgeons can manipulate tiny instruments. A surgeon introduces the endoscope into the body either through a body opening, such as the mouth or the anus, or through a small incision in the skin.



Navigating the endoscope within the body involves sophisticated maneuvers crucial for precise diagnosis and treatment. The flexibility of the endoscope's tube allows it to traverse intricate internal pathways, guided by the skilled hand of the surgeon or controlled by advanced robotic systems in telesurgery setups. With careful manipulation, the endoscope can explore the internal landscape, moving through complex anatomical structures with ease. Its movement is meticulously controlled to reach targeted areas, providing a comprehensive view of affected regions. This navigation is pivotal in enabling surgeons to visualize, address medical issues accurately and finally operate the patient.

4.4 Telesurgery

Teleoperation (remote control) means simply to operate a system over a distance.

- ***Operator (master)***: human operator who monitors the operated machine and makes the needed control actions;
- ***Teleoperator (slave)***: teleoperated machine.

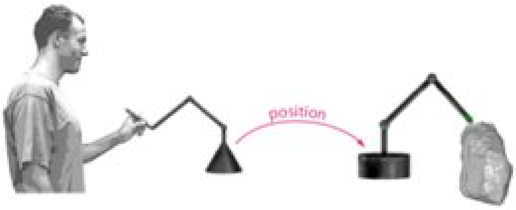
Modern teleoperation techniques involves underwater and space exploration, the use of teleoperated humanoid or non-humanoid robots for example for operating in uneven terrains.

Control techniques for teleoperation:

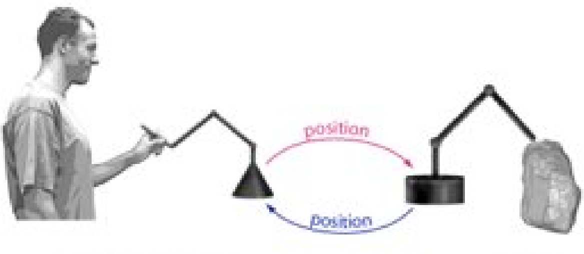
- ***Closed Loop Control (Direct Teleoperation)***: The operator controls the actuators of the teleoperator by direct (analogue) signals and gets real-time feedback. This is possible only when delays in the control loop are minimal;
- ***Coordinated Teleoperation***: The operator controls the actuators, but there is also some internal control included. The internal control loops are used to close the control loops that the operator is unable to control because of the delay;
- ***Supervisory Control***: The teleoperator can perform part of the tasks more or less autonomously, while the operator mainly monitors and gives high-level commands.

Teleoperation Models:

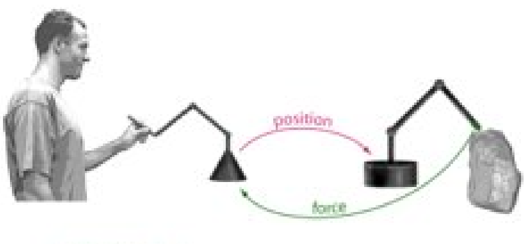
- ***Unilateral Teleoperation Model***: In the unilateral teleoperation model, only one side of the interaction is actively controlled. Typically, this means that one operator (the human) controls a robotic system or device. For instance, in surgery, a surgeon might remotely control a robotic arm or system to perform a procedure. However, the feedback about the environment is not directly transmitted back to the operator.



- ***Bilateral Teleoperation Model using Position***: Bilateral teleoperation involves two-way communication between the human operator and the robotic system. In the position-based bilateral teleoperation model, both the operator and the robot exchange position information. The human operator's movements are detected and transmitted to the robot, which replicates these movements. Simultaneously, the robot's position data is sent back to the operator, allowing them to have a sense of the robot's position in the environment.



- ***Bilateral Teleoperation Model using Force***: The human operator provides position information to the robot instructing it on where to move or how to position itself within the environment. Conversely, in this force-based model, the robot's generates force information. As the robot interacts with the environment, the forces exerted by the robot are measured and transmitted back to the human operator. This feedback allows the operator to feel the forces applied by the robot on the environment or objects, providing a sense of touch or haptic feedback.



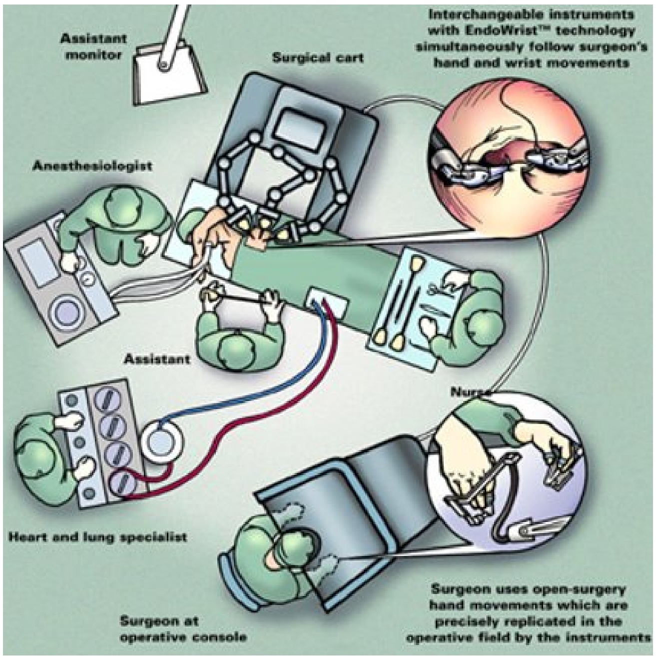
Teleopration Performance Metrics:

- ***Tracking***: Ability of the slave to follow its master;
- ***Transparency*** (for bilateral teleoperation only): Whether the mechanical impedence felt by the user is the same as the impedence of the environment. It is one of the most important metrics after stability, aims to mimick the human motor and sensory functions;
- ***Time Delay***: Crucial metric that affects transparency and stability.

4.5 Da Vinci Surgical System

The ***da Vinci Surgical System*** is a robotic platform designed for ***multi-port laparoscopy*** surgery. It enables surgeons to perform complex procedures with enhanced precision, dexterity, and control through robotic assistance. There exist the ***da Vinci SP*** that is designed for ***single-port laparoscopy***.

4.5.1 Components



- ***Surgeon Console***: This is where the surgeon sits and operates. It provides a high-definition 3D view of the surgical site through a binocular vision system and allows the surgeon to control the robotic arms and instruments using hand and foot controls.
- ***Surgical Cart***: The surgical cart is positioned next to the operating table and holds the robotic arms and instruments that perform the surgery. These arms precisely replicate the surgeon's hand movements with superior accuracy.
- ***Vision System***: The da Vinci System has a 3D stereoscopic high-definition camera (3D endoscope with two separated optic channels) that provides a magnified, detailed view of the surgical area. This system gives surgeons a clear, close-up visualization during procedures.

The system is characterized by EndoWrist instruments and it is equipped with three to four robotic arms (two/three manipulation arms and one camera arm) with interchangeable end effectors for different kinds of operations.

5 Assistive and Rehabilitation Robotics

Rehabilitation robotics can offer robot-assisted therapies or enable automated training and recovery. Assistive robots, including robots for either functional enhancement and functional compensation, are aimed at helping individuals with impaired physical functions to better manage activities of daily living, supporting independence and reducing the demands on nursing and other supportive staff,

5.1 Interaction with Rehabilitative Robots

Rehabilitative robots often guide individuals through specific movements or exercises. The robot's mechanisms, such as exoskeletons or robotic arms, support and assist the user in performing these movements, aiding in muscle activation and motor skill improvement.

Negative Impact of Excessive Assistance: Overreliance on assistive forces can hinder learning. Subjects tend to quickly incorporate these assistive forces into their motor plans. Consequently, to minimize effort while maintaining performance, they reduce voluntary control.

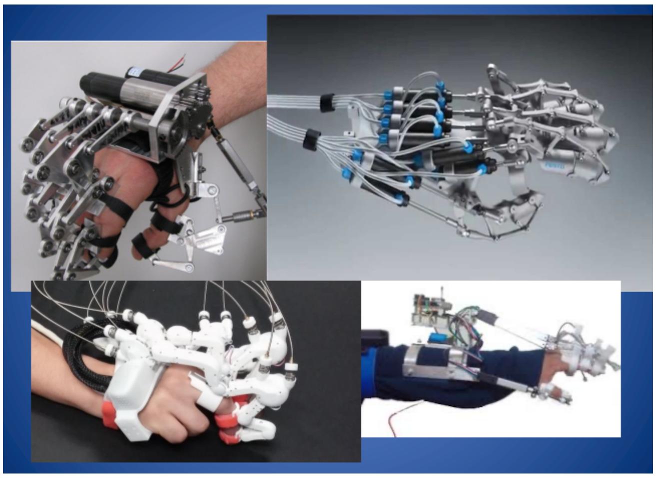
Optimal Solution: Providing "just enough" minimum assistance essential for task completion—particularly decreasing as learning progresses, can enhance skill acquisition and prevent overdependence on assistance.

Rehabilitative robots offer real-time feedback on a user's performance. This feedback might include metrics like joint angles, force exertion, or movement accuracy, aiding individuals in understanding and refining their movements.

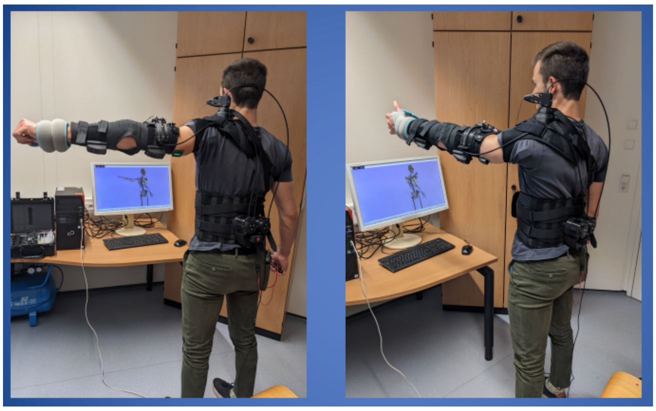
5.1.1 Types of Rehabilitative Robots

Rigid exoskeletons are typically made from solid materials like metals or hard plastics, offering robust support and structure. These exoskeletons have fixed or limited joint mobility, consisting of rigid segments and articulated joints that mimic human body movements. These exoskeletons are often heavy, bulky, less adaptable to natural movements, and can be more costly to produce and maintain compared to soft exosuits.

On the other hand, ***endpoint robots***, differently to rigid exoskeletons, target specific body parts or joints for therapy, such as wrists, elbows, knees, or fingers, offering precise control over movements, allowing therapists to customize therapy programs according to individual needs and facilitating controlled and repetitive exercises, aiming to improve motor skills, muscle strength, and joint mobility.



Exosuits are wearable robotic garments made from lightweight, flexible materials that complement a person's natural muscle movements. Their purpose is to address various issues like congenital physical disabilities, limitations due to aging, diseases, injuries, physical strain in manual labor, rehabilitation needs, and enhancing physical capabilities. There are advantages of Soft Exosuits over Rigid Exoskeletons such as, an higher portability due to their lightweight nature, an enhanced adaptability and comfort as they are flexible and less constraining and the fact that they are cost-effective compared to rigid exoskeleton.



In summary: *Why wearable robotics?*

- ***Congenital physical disabilities***: Assist individuals with physical limitations from birth.
- ***Physical limitations*** (due to ageing, diseases, injuries . . .).
- ***Manual Labor Strain***: Alleviate physical strain in labor-intensive tasks.
- ***Rehabilitation***: Facilitate recovery and therapy for mobility and strength.

Why not rigid exoskeletons?

- ***Low Portability***: Heavy and bulky design hampers mobility.
- ***Limited Adaptability***: Rigid structure constrains natural movements.
- ***Discomfort***: Lack of flexibility leads to discomfort during prolonged use.
- ***Costly***: Expensive to produce and maintain, limiting accessibility.