Teleoperation and Control Strategies for Humanoid Robots: A Comparative Analysis

Cappellini Matteo (4822622)
Delucchi Manuel (4803977)

Teleoperation of humanoid robots enables the integration of the cognitive skills and domain expertise of humans, with the physical capabilities of humanoid robots. The operational versatility of this kind of robots makes them the ideal platform for a wide range of applications, especially in remote environments. However, the complexity of humanoid robots imposes some major challenges, particularly in unstructured dynamic environments with limited communication. This paper provides an overview of whole-body humanoid robot teleoperation, starting from a basic teleoperation system architecture and exploring its components. In particular, we evaluate the effectiveness of the different state-of-the-art retargeting and control strategies and explore advantages and disadvantages of each of them. Through this analysis, we try to enhance our understanding of maximizing the practical use of humanoid robots across various real-world scenarios.

Keywords: Humanoid Robots, Teleoperation, Whole-Body Control

I. Introduction

Teleoperation, the act of operating from a distance, extends human capabilities by allowing remote control of robots. Teleoperated humanoid robots offer innovative solutions for various real-world challenges, bridging the gap between human capabilities and congnitive demanding tasks.

These versatile robots find applications across diverse high-risk environments, like construction sites [18], chemical plants [26], healthcare [19] and even outer space [7], significantly reducing risks for human operators. Additionally, they play a key role in enhancing virtual communication and physical interaction, enabling immersive experiences in telexistence and telepresence scenarios [9].

What makes teleoperated humanoid robots particularly compelling is their unique ability to combine the physical strength of machines with the cognitive capabilities of humans. In fact current robotic systems, while promising, still struggle with limitations in perception and decision-making, preventing full autonomy. However, unlike autonomous robots, teleoperation allows to replicate complex human-like movements and adapt to unpredictable situations.

A typical physical avatar system consist of three main components: the humanoid robot itself, the operator system, consisting of a set of wearable technologies in charge of retargeting, and the communication layer connecting them with middlewares such as the Robot Operating System (ROS) [9].

Through whole-body teleoperation, human operators equipped with multimodal interfaces are able to experience a sensation similar to being projected into a remote location. This enables them to perceive the environment surrounding the robot and the objects it interacts with. With their human-like structure, these robots can seamlessly mirror human postures and gestures, thanks to advanced motion tracking systems [10].

Unilateral and bilateral teleoperation represent two fundamental modes of operation in teleoperated systems. In unilateral teleoperation, control commands are transmitted from the operator to the remote system, while feedback regarding the system's state is limited or absent. On the other hand, bilateral teleoperation enables bidirectional communication between the operator and the remote system, allowing for real-time exchange of both control commands and sensory feedback.

In the context of teleoperation, retargeting refers to the process of adapting control inputs from the operator to account for differences in the kinematic and dynamic properties of the master and slave systems. However, addressing retargeting in the context of bilateral teleoperation requires acknowledging the significant impact of time delays and information losses on transparency, to ensure a seamless and accurate transfer of mechanical impedance. Failure to do so can lead to discrepancies between the user's perception and the real-time conditions, thus affecting overall system stability. One drawbacks of the teleoperation systems is the limited adaptability to different human users and humanoid robots with different geometries, kinematics and dynamics. System designers have to invest significant time and effort in finding suitable models for different human operators, thus reducing the usability and scalability of each system [5].

The research on teleoperation of humanoid robots can be broadly classified into three categories: upper-body, lower-body and whole-body teleoperation. Each procedure comes with limitations and key challenges that must be considered to enable successful task execution by human-robot teams. This emphasize the importance of ensuring robot stability to guarantee high manoeuvrability and manipulability, while preventing the robot from falling. In this paper we focus on whole-body teleoperation, with specific emphasis on analyzing the latest advancements in teleoperation modalities and control strategies.

The rest of the paper is organized as follows: Section II defines the research question this paper aims to address. Section III discusses the implementation of assistive teleoperation methods compared to direct methods. Section IV explores the details of multimodal interfaces employed in whole-body bilateral teleoperation, while Section V presents an overview on retargeting. Section VI delves into whole-body control methods and finally, Section VII presents our conclusions and potential directions for future researches.

II. Research question

This paper aims to offer a comprehensive review of the current state-of-the-art teleoperation and control strategies for humanoid robots. Through a comparative analysis, we aim to investigate the primary approaches employed in this field. Furthermore, we will evaluate the effectiveness of each strategy and explore challenges and emerging trends.

What are the key teleoperation and control techniques for humanoid robots and what are their main advantages and disadvantages?

III. From Direct to Assisted Teleoperation

In the realm of teleoperation, we can differentiate between **direct** and **assistive** techniques. The former, also referred to as master–slave control methods, involve the real-time control of a remote robot by a human operator. In this setup, the operator manipulates input devices to send commands to the robot. These commands are then translated into corresponding movements or actions in the robot's operational space.

Penco L. et al. proposed a teleoperation framework for executing loco-manipulation tasks with iCub3 [8]. The proposed control architecture provides two different modes of teleoperation:

- a high-level teleoperation setting in which the operator uses a joystick to send reference commands to the robot, such as direction and velocity of motion, or even choosing among several predefined task trajectories, without dealing with their actual execution; and
- a low-level teleoperation scenario in which the operator generates whole-body movements for the robot tanks to a motion capture suit (motion retargeting).

In both cases, the human operator receives visual feedback through a VR headset connected to the robot's cameras.

The majority of teleoperation techniques are based on the direct teleoperation principle. However, relying solely on the operator's manual control can often hinder task efficiency. In many scenarios, optimal task performance can be enhanced through a collaborative sharing of autonomy among the human operator and the robot. Delegating robot's full control to the human operator's experience can often limit the efficiency of the teleoperation, resulting in clunky motions, failures, or numerous attempts before being able to accomplish a given task. This applies particularly to humanoid robots where the operator has to control many aspects at once via teleoperation (e.g., the pose of both hands, feet location, balance) and can fail very easily without simultaneous robot autonomy. To address these issues, several teleoperation strategies have been developed:

1) Shared-Control Teleoperation: This approach has the overall goal of integrating decision-making capabilities from both human operator and robot. The primary objective is to augment human control by detecting human intentions, allocating control authority accordingly and providing feedback from the robot.

In the framework proposed in [28], the human operator controls the robot in real-time, directing it towards accomplishing specific tasks, which may involve a set of task parameters (e.g., target position). Simultaneously, the robot tries to infer the human intention and subsequently issues commands based on this inference. The two control outputs are then integrated and sent to the plant for shared control. The human operator's movements are translated into robot commands through a feedforward interface, while feedback to the human operator can be provided through an interface that uses state information to generate sensory stimuli.

Shared control methodologies offer significant benefits, including workload reduction and improved operational efficiency, achieved by combining manual teleoperation and autonomous assistance.

2) Supervised Teleoperation: This approach lets the user act as a supervisor leveraging the task-specific intelligence of the robot. This makes the robot an intelligent co-worker rather than a tool for the user, efficiently reducing the mental and physical workload for the user compared to direct teleoperation. By actively monitoring the robot's activities, the operator can identify and react to unexpected problems, intervening in a timely manner when necessary to directly control the robot in handling uncovered situations. With the main limitation of this system being that the robot requires a higher computation capability than in direct control.

Schmaus P. et al., as observable in [27], have studied a supervised teleoperation methodology tailored to support astronauts with setting up and maintaining infrastructure on planetary surface, before and after the crew's arrival. These robots would be equipped with autonomous capabilities, as direct teleoperation from Earth becomes unfeasible with increasing communication time delays, and only commanding the robot from an orbiting spacecraft could reduce the communication delay. Due to the limited crew time, as many tasks as possible should be delegated to the autonomous capabilities of the robot, whereas the astronaut should only intervene in exceptional situations.

3) Multimodal Teleoperation Control: Multimodal teleoperation, also referred to as multi-sensory mode, involves the integration of different sensory cues to provide a multimodal view to the teleoperator.

Making correct and timely control decisions in complex and dynamic remote environment can pose some challenges. However, control techniques equipped with multi-sensor interfaces can offer efficient control command generation tools along with rich situational awareness, successfully coping with these difficulties.

The provided feedback is combined from multiple sensors to guarantee for an accurate representation of the remote

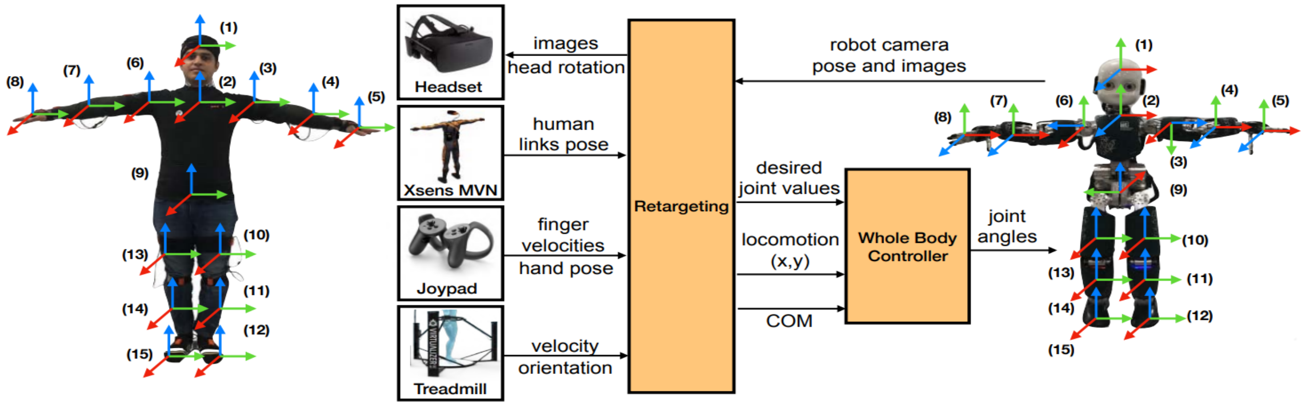

Fig. 1: The architecture of the whole-body teleoperation with active human-robot retargeting. [5]

environment, that can manifest in different immersive formats, including virtual reality (VR), augmented reality (AR), mixed reality (MR) and other immersive technologies.

However, multimodality requires high computation and bandwidth requirements, which can lead to increased latency and cognitive workload. Meanwhile, direct teleoperation is less forgiving than the other proposed methods when it comes to latency, intermittency, data loss and other communication issues.

IV. Multimodal Interfaces

Multimodal interfaces in teleoperation represent a cutting-edge approach to human-robot interaction, enabling operators to control robots remotely by integrating various sensory inputs, such as sight, sound and touch, allowing for a more immersive and efficient experience. By using multiple senses, multimodal interfaces aim to enhance operator awareness, reduce cognitive load and ultimately improve the performance of humanoid robots in a variety of applications [30]. In this context, we will explore the significance and implications of using such interfaces, revealing their ability to revolutionize the way humans interact with these advanced machines.

A. Interfaces for Manipulation

When it comes to mimicking human-like manipulation ability it is important to combine the three main senses humans use to interact with the real world (sight, hearing and touch). Thus, providing a realistic experience and increasing the feeling of immersion, while easing the difficulty of the task for the operator.

Given that the sense of sight contributes to around 70% of the overall human perception, providing visual information in the best form is of crucial importance. The two primary sources of a visual interface include standard monocular monitors and virtual reality head-mounted displays that provide stereo vision. The latter offers many benefits over monocular screens, since they provide better depth perception and a superior spatial awareness, hence reducing collisions with the surrounding environment and increasing performances during highly dexterous manipulation tasks. This heightened immersion leads to an increased feeling of *telepresence*, in which the operator feels physically present at the remote location. [30]

In light of these considerations, the selection of an appropriate visual interface is crucial. **Virtual Reality (VR) head-mounted displays** have emerged as a game-changer in teleoperation technology, since they offer a flawless integration of visual and auditory feedback. Leading VR headsets such as *Oculus Rift*, *HTC Vive*, *Microsoft HoloLens* and *Meta Quest* have set new standards in this field.

However, it's important to note that while VR headsets offer an exceptional experience, they still have their own set of challenges. Factors like latency, resolution, limits in the field of view and comfort are critical considerations in the selection of an appropriate headset for specific teleoperation applications. Affecting both the level of user immersion and situational awareness, as it can be challenging to control a robot without a comprehensive view of its immediate surroundings. [2]

Furthermore, auditory cues can provide valuable supplementary information. They can alert the operator to events or conditions that may not be immediately visible. This auditory feedback can serve as an additional layer of situational awareness, especially in environments where visual cues may not be efficient. Extra information, such as alarms and alerts, can be presented via an audio interface rather than being displayed visually, which can be intrusive and distracting. [30]

This highlights the significance of a well-designed **human-machine interface (HMI)** in humanoid teleoperation. While various forms of HMI have been developed over the years, they often come with trade-offs. Teleoperation systems have been developed to perform hazardous tasks in extreme environments. Therefore, operating with non-intuitive control interfaces that only make use of a keyboard or a joystick, have made the use of teleoperated robots very challenging, especially for tasks requiring a high level of precision. [23]

In order to overcome these limitations it was necessary to upgrade the interfaces used for tactile interaction. The introduction of **haptic gloves** represents a major shift in this context, as these technologies allow human operators to physically feel the shape, texture and rigidity of the object they are manipulating through the robot. These gloves have drastically improved the precision and accuracy of remote tasks, while also reducing the cognitive load on the operator.

One of the fundamental methodologies employed in haptic gloves involves integrating sensors with actuators, so that it is possible to discern the variations occurring on the manipulated object, while emulating the sensation of touch by employing actuators to induce vibrations or other forms of tactile feedback, providing for a realistic and immersive experience. For instance, when a finger encounters a surface, sensors in the glove detect it and transmit an electrical signal to the actuator, which in turn initiates a vibration or another form of tactile feedback [20].

In the following segment we will provide a brief overview of some literature examples of these devices:

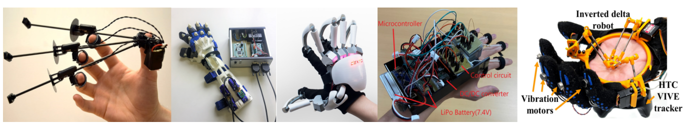

Fig. 2: From left to right we can observe the design of *Wolverine*, *ExoTen-Glove*, *Dexmo Glove*, *MagGlove* and *vDeltaGlove*

- *Wolverine* [3]: a lightweight technology that can provide up to 106N force grasping an object thanks to the brake actuator on the thumb, running on low power and low costs. However, it has limited range of action and is not suited for certain application due to its constant stiffness.
- *ExoTen-Glove* [13]: employs twisted string actuation (TSA) technology and DC motors to give the user force feedback while they are grabbing virtual objects, providing a force of 80N from each actuator and granting great sensibility. However, it requires precise calibration and its haptic feedback is yet not realistic enough.
- *Dexmo* [12]: an haptic exoskeleton that provides kinesthetic feedback in virtual reality, that transfers forces to the fingertips using link-bar mechanism to increase portability and ease-of-use while also decreasing costs. However, due to the controller being based on position it results in a complex system.

Other promising devices are being developed such as *MagGlove* [17] and *vDeltaGlove* [31], the former makes use of magnet actuators, providing high responsiveness and fast fingers movements, while the latter seems to offer a less mentally demanding interface alleviating the cognitive demands on the human operator, however they are still in the early-phase of development.

B. Interfaces for Locomotion

Teleoperating a whole-body humanoid robot presents several challenges, since they are characterized by unstable bipedal dynamics that need to be managed, often modeled as a linear inverted pendulum (LIP) model [15]. Real-time teleoperation requires precise tracking of operator inputs while adhering to dynamic constraints, making it difficult for a standard operator to control the robot directly. Space limitations arise as the robot's movements depend on the operator's actions and a treadmill may be needed to mitigate these issues.

To provide the references for the robot motion, we need to sense human movements. For simple teleoperation cases, the measurements may be granted through simple interfaces such as keyboard, mouse or joystick commands. However, for a more complex system like a humanoid robot, those simple interfaces may not be enough, especially when the user wants to exert a high level of control authority over the robot.

One common approach involves a standing human operator equipped with a **motion capture system**. This is the most popular and simple method for transferring the reference motions, although the reproducibility of the physical interaction and the locomotion workspace is limited. Researchers have augmented this setup with vibration/pressure haptic devices for tactile feedback and bipedal balancing. An example can be seen with the use of the *Xsense MVN Link* motion capture suit to interact with the robots BHR-6 [32] and iCub3 [24].

Another significant advancement is represented by the introduction of a special **treadmill**, used to address the complex challenges associated with replicating human-like movements while ensuring dynamic stability. These systems provide infinite floor exploration using slip walking, making them suitable as a humanoid locomotion interface. However, there is no force feedback, and it is difficult to extend this design to 3D locomotion. An example is presented in [9], where the iCub3 robot is teleoperated using the *Cyberith Virtualizer Elite 2*, an omni-directional treadmill where the operator walks by sliding. While the treadmill can be used for even terrains, it would not work to retarget locomotion on uneven ones. [6]

The development of exoskeletons like *TABLIS* by Y. Ishiguro et al., has been recently studied to offer new solutions to the presented problems. In this setup, the operator's base link (waist) is fixed on the saddle seat, allowing for both 2D and 3D locomotion control. This design provides a broader whole-body workspace and minimizes operator stress during prolonged operations. However, it requires a relatively large installation area and may have reduced stiffness and precision compared to parallel link joint devices [11].

Fig. 3: From left to right we can observe *Xsense MVN Link*, *Cyberith Virtualizer Elite 2* and *TABLIS cockpit exoskeleton*

V. Retargeting

Transferring the motion from a human operator to a humanoid robot is a crucial step to enable robots to replicate human movements. In this process, the **retargeting block**, serves the purpose of converting human commands into references for the robot, covering both limb motion and locomotion. The inputs to this block are adaptable, depending on the specific task and system requirements.

Teleoperation devices can offer different types of input for retargeting, ranging from high-level goals defined via graphical user interfaces, to low-level details such as the Center of Mass (CoM) velocity, base rotational velocity, whole-body motion or user-defined footstep [6]. These inputs can either originate from locomotion interfaces providing velocity and orientation data, haptic devices conveying hand pose and finger velocity or wearable suits offering human link pose details, allowing for high-fidelity and high-frequency data tracking.

The operator's gestures are retargeted onto the robot through the control architecture, with feedback provided through sensors, offering a first-person perspective of the surroundings, this is known as *teleperception*. Additionally, the retargeting interfaces contain the set of commands used by the operator to guide the robot in accomplishing specific tasks within the remote environment. For instance, in systems like the iCub3 avatar, described in [9], retargeting interfaces include voice and facial expressions projection, manipulation and locomotion.

The retargeting block provides critical information to the robot, such as desired joint values, locomotion parameters and the CoM data used in the whole-body controller, mapping human limb poses or velocities to corresponding robot joint values while considering their constraints. Yet, real-time retargeting of entire whole-body movements is challenging for humanoid robots. First, direct mapping is not possible because of significant differences in kinematics (e.g., joint limits, limb lengths) and dynamics (e.g., mass distribution, inertia); second, the robot needs to maintain its balance while imitating the human, so there is a trade-off between imitation and feasibility/safety. Third, since we do not know a priori which motion is going to be retargeted on the robot by the operator, it is not possible to tune offline the controller and/or the retargeting parameters for specific motions: rather, we need to provide a generic solution that is able to handle a variety of motions. [24]

VI. Whole-body Control

Based on our research, we were able to conclude that the general hierarchical control architecture for a robot with both upper and lower body structure, is usually composed by the following components: **trajectory generator**, **stabilizer**, **whole-body controller** and **low-level joint controller**.

The trajectory generation loop is in charge of generating foothold trajectories, such as the desired walking direction and speed, from high-level commands. The output of this layer is then fed to the stabilizer block, with the aim of generating feasible centroidal positions associated with stable walking instances. The whole-body control layer is designed to generate joint torques, ensuring the robot's adherence to the desired trajectory. Finally, the low-level joint controller takes the torques provided by the whole-body control layer and translates them into commands for individual joints.

In this section of the paper, we will discuss the strategies applied in the stabilizer and in the Whole-Body Control blocks.

A. Stabilizer and Balancing

As already discussed at the end of Section V, many challenges may arise when elaborating the retargeted reference trajectories, since these can potentially destabilize the robot's behavior. To solve this problem, it was necessary to introduce the **stabilizer** inside the control architecture. This component has the purpose of implementing a control policy that dynamically adapt to the reference inputs, guaranteeing that the robot can effectively respond while maintaining balance and stability.

The concept of stabilizer is strictly coupled with trajectory generation, as it is responsible of generating the trajectory of the **center of mass (CoM)**. This block offers a foundational level of stability to the robot allowing it to maintain balance while keeping its manoeuvrability and manipulability high, so that the human and the robot team can successfully perform the given task [5].

In order to provide the needed stability many applications use established algorithms, we here report the most used:

1) ZMP Approach: This is the most common strategy. It relies on the concept of **Zero Moment Point (ZMP)**, which specifies the point with respect to which reaction forces, at the contacts between the feet and the ground, do not produce any moment in the horizontal direction. Dynamic equilibrium is granted by keeping the ZMP within the robot support polygon at all times. Many successful techniques for generating stable gaits are based on a simplified linear dynamic model relating the ZMP to the CoM, derived by neglecting any rotational contribution around it [8].

This strategy has the advantage of being computationally simple and being widely diffused, however, this type of control introduces several limitations. If the robot is subject to high disturbances, it does not adapt online to footstep locations to prevent the robot from falling. Additionally, this approach hardly extends to non-flat terrains or when the support foot rotates or slides [6].

2) DCM Approach: This approach takes into account both the linear and angular dynamics of the robot's motion. It focuses on synchronizing the **Divergent Component of Motion (DCM)** trajectory of the robot with that of the human, by imposing dynamic similarity between the two. This means that the motion of the robot's CoM should dynamically resemble that of the human operator. This method has been proven adequate for generating the CoM trajectory of a humanoid robot even on rough and uneven terrains, as demonstrated in [21]. However, due to its unstable nature, this strategy is often merged with ZMP. Also, since rapidly estimating the human DCM could be difficult, given the inclusion of a CoM velocity term that is usually noisy, there is the need to simplify the system considerations. A reasonable simplification can be obtained if the human pilot mostly steps in place during teleoperation. [4]

B. Controllers

The Whole Body Controller block gets as input the retargeted human references, corrected by the stabilizer, and

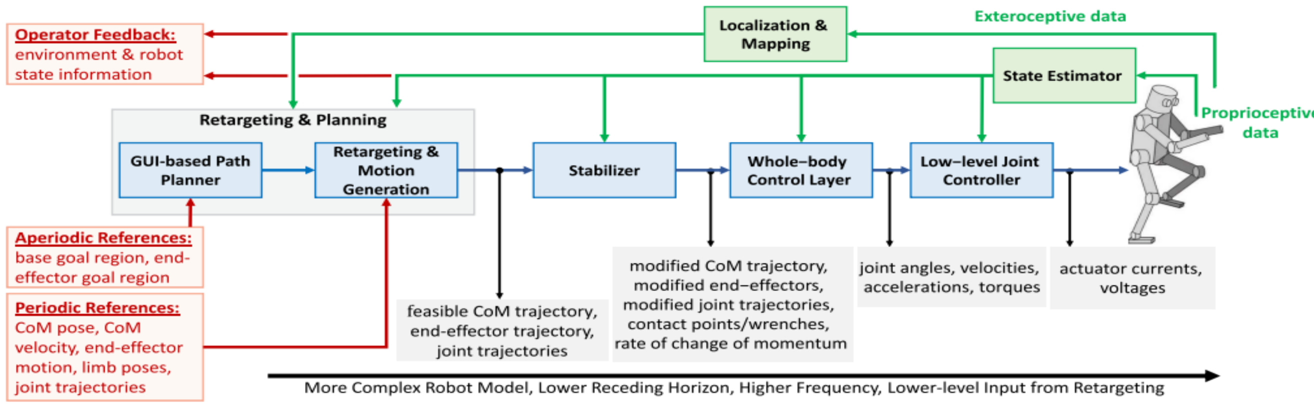

Fig. 4: Flowchart of a humanoid robot retargeting, planning and control architecture (red: references/feedback of human; blue: retargeting, motion generation and control; green: perception and estimation). [6]

generates as output the robot joint angles, velocities, accelerations and/or joint torques. In essence, it manages the robot's intricate motions and ensures that it faithfully emulates the human operator's intentions. As for the most relevant control strategies, we have singled out a number of them highlighting some favourable/non favourable aspects. Note that most of the time these algorithms are used together, complementing each other to accomplish various tasks effectively.

1) Quadratic Programming Controller: Firstly, it is important to talk about **Quadratic Programming (QP)**, as the whole-body control and the stabilizer problems can be formalized with different cost functions and be solved with an optimization approach, with the most common approach being treating them as a QP problem. The various control strategies that we will discuss in this section are usually treated in QP fashion, as it enables the possibility of formulating an objective function that represents the optimization goals.

Furthermore, QP algorithms can be structured as controllers themselves. In fact, they have been proven appropriate for teleoperation, since they allow to define Cartesian and postural tasks together while satisfying all the robot constraints, even when there is a great difference in size between the human operator and the robot. An example can be observed with the QP controller built for the HRP-4CR robot, successfully achieving human dynamics reconstruction and optimal control within a single optimization problem [22].

2) Inverse Kinematic Controller: **Inverse kinematics (IK)** refers to the use of the kinematics equations of a robot to calculate the joint configurations, necessary to achieve a specified position or pose of the robot's limbs and body parts.

IK coupled with nonlinear optimization is the most common approach for teleoperation scenarios, as it can be observed in iCub [24], DRC-Hubo [33], MAHRU [1] and many more. Using IK methods, human joint angles or velocities are computed and mapped to the corresponding joints of the humanoid robot, taking into account its limitations. However, there are some key restraints that are important to consider when applying this method:

- The need to determine a customized mapping for each of the robot's joints with respect to the corresponding human ones;
- Differences in human and robot kinematics;
- Different human subjects have different physical properties, resulting in different human models. [5]

3) Inverse Dynamic Controller: **Inverse Dynamics (ID)** refers to the problem of finding the joint torques of the robot to achieve the desired motion given the robot's constraints (i.e. joint torque limits and feasible contacts). The main challenge in teleoperating highly dynamic motions is to ensure smooth and stable movements in real time, while guaranteeing the robot's balance. ID approaches would be ideal for handling the changing dynamics of the robot during teleoperation, but they are computationally expensive and prone to numerical ill-conditioning. For this reason, classical approaches rely on Inverse Kinematics [8].

4) Momentum-Based Controller: **Momentum-based control** is a strategy used to facilitate smoother and more natural movements. It involves controlling the robot's motion by considering its momentum, similar to how humans adjust their movements to maintain balance and stability.

Several momentum-based control strategies have been implemented in real applications, i.e., Atlas [16] and Valkyrie [14], allowing to control the robot's momentum while guaranteeing stable zero-dynamics. These controllers determine the configuration space acceleration and ground reaction forces, this ensures that the robot follows the desired rate of change of whole-body momentum. Eventually, external wrenches and joint accelerations are used with an Inverse Dynamics algorithm to compute the robot joint torques.

Momentum-based strategies have proven their effectiveness for controlling humanoids balancing and limb motions, but a comprehensive stability analysis of these controllers is still missing.

5) Machine Learning-Based Controller: A novel control approach involves the implementation of machine learning algorithms and data-driven models by leveraging artificial neural networks, capable of approximating highly complex nonlinear functions and able to enhance the robot's adaptability.

Neural networks are widely used to design **Model Predictive Control** *(MPC)* approaches, to enable adaptive and predictive control strategies. These networks learn from various inputs, such as environmental cues, operator behaviors or from datasets relative to similar robot conditions. This allows the system to anticipate and respond dynamically to changing conditions, enhancing the adaptability and flexibility of the robot. The only drawback of using an MPC approach in a teleoperation framework is the underlying computational cost.

There are numerous studies focusing on implementing these methods in different aspects of teleoperation. As an example, we can cite a study by Christopher Stanton et al., which involves the training of a feed-forward neural network for each of the 23 DoFs on the robot NAO through full-body motion capture. This aims to develop a seamless method for calibrating any human-robot teleoperation pairing, regardless of differences in physical embodiment, motion capture device and/or robot morphology [29].

6) Low-level Joint Controller: At last, we can highlight the **low-level joint controller**. This component plays a critical role in translating the high-level control inputs into precise and coordinated joint movements. It has the function of generating accurate motor commands, considering either joint torque or joint position, that are then transmitted to the robot's joints and links, ensuring that the desired configurations are reached.

VII. Conclusions

In this paper we provided a brief description of the fundamental components of the teleoperation framework. Furthermore it investigates different methodologies employed in this field, with a closer look on retargeting and control techniques. We can ultimately conclude that, while current techniques demonstrate accuracy, they still requires significant research to address key challenges within this domain.

Problems encountered in the retargeting phase are difficult to address, as they are common in many technologies and they mostly revolve around noise and latency in the means of communication, potentially leading to information losses. However, we predict that these can be minimized in the near future through advancements in communication technologies, thus contributing to improved transparency, accuracy and overall performance in teleoperation systems. Regarding the difficulties encountered when pairing the human and the robot operators, our study was limited by the scarcity of relevant articles, as we were only able to find the previously referenced study of Stanton et al., which was conducted in 2012 [29]. Due to lack of comprehensive and recent information, we were not able to draw a conclusion on this aspect.

Further challenges that have to be addressed are related to improving stability and balance algorithms, reducing computational costs of control strategies and enhancing the robustness of teleoperation systems in dynamic and unstructured environments. Besides, many existing techniques for teleoperating humanoid robots often rely on simplified models, which, although computationally efficient, come with limitations due to their initial assumptions.

In contrast, Model Predictive Control (MPC) tackles these challenges but it is computationally demanding, since implementing it in teleoperation systems involves solving complex optimization problems in real-time, particularly when dealing with large amounts of datasets or inputs. Despite it being a viable solution, it falls short in dynamic, unstructured environments with varying compliance (how easily the robot can yield to external forces) and slip characteristics (how the robot interacts with surfaces). Data-driven approaches focusing on robot dynamics and stability have been proven promising to address these limitations, with the possibility of integrating machine learning for recovery situations, enhancing the robot's adaptability and performance [25].

Addressing all of these issues while maintaining system stability presents a major challenge for teleoperation control techniques. Despite a large number of control theories and mechanisms documented in the literature, the absence of a universal applicable control technique remains evident. The selection of a teleoperation control strategy for humanoid robots is a multifaceted decision influenced by factors such as task requirements, operator expertise and robot capabilities. The comparative analysis presented highlights the importance of considering these factors when designing these kind of systems. As research progresses, hybrid strategies and advancements in technology hold promise for addressing current limitations and optimizing the interaction between operators and teleoperated humanoid robots.

In conclusion, there remains opportunities for further research and development. Future efforts should focus on addressing the identified limitations and advancing the state-of-the-art to enable more effective and efficient teleoperation across various applications and environments.

Based on the current state of the world, we predict an increased application of teleoperated humanoid robots in space missions, as can be observed by the upcoming deployment of NASA's first humanoid robot Valkyrie; in nuclear applications, as evidenced by the growing number of countries developing nuclear power plants; and in telepresence applications, especially with the ongoing development of the Metaverse.

References

[1] Young-Hwan Chang, Yonghwan Oh, Doik Kim, and Seokmin Hong. Balance control in whole body coordination framework for biped humanoid robot mahru-r. In *RO-MAN 2008 - The 17th IEEE International Symposium on Robot and Human Interactive Communication*, pages 401–406, 2008.

[2] Yang Chen and Leyuan et al. Sun. Enhanced visual feedback with decoupled viewpoint control in immersive humanoid robot teleoperation using slam. In *2022 IEEE-RAS 21st International Conference on Humanoid Robots (Humanoids)*, pages 306–313, 2022.

[3] Inrak et al. Choi. Wolverine: A wearable haptic interface for grasping in virtual reality. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 986–993, 2016.

[4] Guillermo Colin, Joseph Byrnes, Youngwoo Sim, Patrick Wensing, and Joao Ramos. Whole-body dynamic telelocomotion: A step-to-step dynamics approach to human walking reference generation, 2023.

[5] Kourosh et al. Darvish. Whole-body geometric retargeting for humanoid robots. pages 679–686, 2019.

[6] Kourosh et al. Darvish. Teleoperation of humanoid robots: A survey. *IEEE Transactions on Robotics*, 39(3):1706–1727, 2023.

[7] Al Tariq Sheik et al. Challenges in threat modelling of new space systems: A teleoperation use-case. *Advances in Space Research*, 70(8):2208–2226, 2022.

[8] Luigi Penco et al. A multimode teleoperation framework for humanoid loco-manipulation: An application for the icub robot. *IEEE Robotics & Automation Magazine*, 26:73–82, 2019.

[9] Stefano Dafarra et al. icub3 avatar system. *ArXiv*, abs/2203.06972, 2022.

[10] Stefano Dafarra et al. icub3 avatar system: Enabling remote fully immersive embodiment of humanoid robots. *Science Robotics*, 9(86), January 2024.

[11] Yasuhiro Ishiguro et al. Bilateral humanoid teleoperation system using whole-body exoskeleton cockpit tablis. *IEEE Robotics and Automation Letters*, 5:6419–6426, 2020.

[12] Sebastian et al. Friston. Position-based control of under-constrained haptics: A system for the dexmo glove. *IEEE Robotics and Automation Letters*, 4(4):3497–3504, 2019.

[13] Mohssen et al. Hosseini. Exoten-glove: A force-feedback haptic glove based on twisted string actuation system. In *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, pages 320–327, 2018.

[14] Steven Jens et al. Jorgensen. Deploying the nasa valkyrie humanoid for ied response: An initial approach and evaluation summary. In *2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids)*, pages 1–8, 2019.

[15] S. Kajita and F. et al. Kanehiro. The 3d linear inverted pendulum mode: a simple modeling for a biped walking pattern generation. volume 1, pages 239–246 vol.1, 2001.

[16] Twan et al. Koolen. Design of a momentum-based control framework and application to the humanoid robot atlas. *International Journal of Humanoid Robotics*, 13:1650007–1, 03 2016.

[17] Mikiya Kusunoki, Shogo Yoshida, and Haoran Xie. Magglove: A haptic glove with movable magnetic force for manipulation learning. In *2022 International Conference on Cyberworlds (CW)*, pages 155–158, 2022.

[18] Donghyeon Lee, Wan Kyun Chung, and Keehoon Kim. Safety-oriented teleoperation framework for contact-rich tasks in hazardous workspaces. pages 4268–4275, 2021.

[19] Daniel Leidner. The covid-19 pandemic: An accelerator for the robotics industry? [young professionals]. *IEEE Robotics Automation Magazine*, 28(1):116–116, 2021.

[20] Shanmugam et al. M. A comprehensive review of haptic gloves: Advances, challenges, and future directions. pages 227–233, 2023.

[21] George et al. Mesesan. Dynamic walking on compliant and uneven terrain using dcm and passivity-based whole-body control. In *2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids)*, pages 25–32, 2019.

[22] Kazuya Otani, Karim Bouyarmane, and Serena Ivaldi. Generating assistive humanoid motions for co-manipulation tasks with a multi-robot quadratic program controller. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3107–3113, 2018.

[23] Sungman Park, Yeongtae Jung, and Joonbum Bae. A tele-operation interface with a motion capture system and a haptic glove. pages 544–549, 2016.

[24] L. et al. Penco. Robust real-time whole-body motion retargeting from human to humanoid. pages 425–432, 2018.

[25] Luigi Penco. *Whole-body Teleoperation of Humanoid Robots*. Theses, Université de Lorraine, June 2022.

[26] Janko et al. Petereit. Robdekon: Robotic systems for decontamination in hazardous environments. pages 249–255, 2019.

[27] Peter et al. Schmaus. Knowledge driven orbit-to-ground teleoperation of a robot coworker. *IEEE Robotics and Automation Letters*, 5(1):143–150, 2020.

[28] Stefania Pellegrinelli Siddhartha S. Srinivasa Shervin Javdani, Henny Admoni and J. Andrew Bagnell. Shared autonomy via hindsight optimization for teleoperation and teaming. *The International Journal of Robotics Research*, 37(7):717–742, 2018.

[29] Christopher Stanton, Anton Bogdanovych, and Edward Ratanasena. Teleoperation of a humanoid robot using full-body motion capture, example movements, and machine learning. 12 2012.

[30] Eleftherios et al. Triantafyllidis. Study of multimodal interfaces and the improvements on teleoperation. *IEEE Access*, 8:78213–78227, 2020.

[31] Daria Trinitatova and Dzmitry Tsetserukou. Study of the effectiveness of a wearable haptic interface with cutaneous and vibrotactile feedback for vr-based teleoperation. *IEEE Transactions on Haptics*, pages 1–6, 2023.

[32] Chenzheng et al. Wang. Intuitive and versatile full-body teleoperation of a humanoid robot. pages 176–181, 2021.

[33] Matt et al. Zucker. A general-purpose system for teleoperation of the drc-hubo humanoid robot. *Journal of Field Robotics*, 32:n/a–n/a, 02 2015.