Design and Assessment of Human-Inspired Socially Assistive Robotics for Tailored Rehabilitation Environments

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To my family and friends,
whose love and support sustained my academic journey

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Abstract

Rehabilitation plays a crucial role in human health, and with recent technological advancements, it has become increasingly intertwined with machinery and robots. The utilization of these technologies for therapies and assessing rehabilitation outcomes is prevalent in research settings, where their potential is explored and validated. However, despite the broad spectrum of researchers working in this domain, common limitations persist in modern approaches to technological and robotic rehabilitation. Primarily, existing systems often concentrate on specific pathologies or treatments, lacking adaptability to diverse contexts. Additionally, transitioning from one user to another poses challenges in customizing the same treatment for different patients. The primary objective of this work is to develop a system capable of adapting to various patients and therapy contexts, enabling the utilization of the same system for a broader range of therapies.

The validity of robotic rehabilitation extends beyond the execution of rehabilitation tasks to establishing a social connection with patients—a point of ongoing debate. Human connection contributes to patient engagement, satisfaction, and overall well-being, leading to enhanced performance during therapy sessions. Additionally, individual personality traits can significantly impact the differentiation of therapy procedures. The secondary objective of this work is to incorporate social and personality features into the robotic rehabilitation system, customizing the rehabilitation procedure based on these elements. This aims to enhance patient engagement and develop more effective robotic therapy procedures that involve social interaction, leveraging the social component of individuals and increasing their satisfaction.

Finally, another limitation observed in modern robotic rehabilitation pertains to the high specificity of rehabilitation systems. These systems often provide tailored therapy primarily for physical stimulation and less for cognitive stimulation. Finding a system that effectively stimulates both the physical and cognitive spheres, especially targeting the recovery of Activities of Daily Living (ADL), remains a challenge. The third aim of this work is to develop a strategy for seamlessly integrating cognitive and physical stimulation within the same robotic rehabilitation procedure. This involves adding the capability to vary the difficulty of either component, thereby addressing

the need for a more comprehensive rehabilitation approach that encompasses both physical and cognitive aspects.

To achieve the aforementioned aims, this work introduces ROS-MCPyRe, which stands for ROS-based Manipulation for Cognitive and Physical Rehabilitation. The system follows the principles of adaptability and extendability, developed iteratively with each step accompanied by a tailored experiment to test the relevant modules. The initial phase involved creating a customizable robotic controller for executing tasks and testing social robotic movements, alongside an analysis of how individuals with different personality traits respond to a social robotic arm. The subsequent phase focused on determining the optimal combination of social cues for achieving effective social interaction, concurrently testing a rehabilitation task involving pick-and-place interactions between humans and robots. The third phase involved creating a system allowing interaction from external actors, such as therapists, who can intervene and adapt ongoing rehabilitation sessions. The final step integrates physical and cognitive elements within the same session, assessing the efficacy and feasibility of this approach in a robot-managed rehabilitation procedure.

The outcomes demonstrate significant promise in the system developed for this Ph.D. work, showcasing its commendable adaptation capabilities. The findings reveal that a robotic arm equipped with social cues effectively stimulates individuals, making it well-suited for social interaction. Additionally, successful execution of a rehabilitation task was confirmed, and the integration of both cognitive and physical rehabilitation yielded positive results with promising prospects for future development. The tests conducted with participants not only validated the feasibility of these procedures but also unveiled intriguing research possibilities for future exploration.

Contents

Acronyms

ADL Activities of Daily Living

BFI Big Five Personality Test

CAPF Cybernetic Avatar Platform

DoF Degrees of Freedom

HRI Human-Robot Interaction

LMA Laban Movement Analysis

RAS Robotics and Autonomous Systems

ROS Robot Operating System

ROS-MCPyRe ROS-based Manipulation for Cognitive and Physical Rehabilitation

SAM Self Assessment Manikin

SARs Social Assistive Robots

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Chapter 1

Introduction

According to World Health Organization, people in the world are living longer [1] thus leading to an increase in the older segment of the population. The growth of aging population and the increasing frequency of chronic diseases and disabilities [2], bring in the need for effective rehabilitation treatments. Rehabilitation treatments can address physical functions, such as Activities of Daily Living (ADL) [3], and cognitive functions, associated with attention, memory, language, and visuospatial ability [4]. This is burdened by the lack of qualified personnel to deliver effective therapies to patients [5], which implies an evolution in how health challenges are going to be addressed. In this context, robots an autonomous systems are promising tools to provide support to clinicians, strengthen human healthcare, and provide exercises and therapies for people with cognitive and motor disabilities. This is evinced in literature, as technology used for rehabilitation and assistance is an increasingly common topic in the research panorama [1].

1.1 Robotics and Autonomous Systems in Rehabilitation

In robot-assisted rehabilitation, robotic systems, such as exoskeletons, end-effector robots [6, 7], manipulators [8], can be used to provide highly repetitive, intensive, adaptive training [9], thus reducing the therapists' effort, time, and cost [10]. This is possible because of robots'grasping and manipulation capabilities, that allow to replicate therapist tasks during a rehabilitation session. But the power of robots does not only lay on the aid to the therapist; in fact, it is possible to delegate entire rehabilitation processes to Robotics and Autonomous Systems (RAS), where the therapist is delegated only to the analysis of the results. The use of RAS as assistance tools in physical and cognitive rehabilitation seems therefore advantageous for the clinical personnel, who can delegate to robots some repetitive tasks/exercises, like object manipulation [11] and handover [12]. Thus, the clinician can focus in more depth on the clinical assessment and monitoring activities. Another advantage is that RAS could measure real time parameters (e.g., joint excursions, applied forces) that can be used to assess the clinical status of the patients (e.g., number of errors, total time, quality of the movement) in addition to measuring the quality of interaction between themselves and the patients (e.g., emotion, facial mimicry, engagement level). These measures help produce objective data reports relative to each exercise execution. In this sense, robots can be true agents in a collaborative rehabilitation paradigm that seeks to support clinical staff rather than replace them. One field where RAS have proven useful is the autonomy recovery for the ADL, where robots can provide assistance [13, 14, 15], or even in industrial settings where robots can prevent impairments [16] supporting in the most dangerous and heavy tasks of workers. For this reason, robots can be found in clinical environments, home settings, industrial contexts, and so on, which results in a wide variety of devices that can be used in very different applications, for different aims, and that can interact differently with humans. In the literature, other authors have explored RAS for rehabilitation, from different perspectives. Ona *et al.* [17] identify treatment strategies, analytic capabilities, and robot metrics mainly focusing on upper limb motor function rehabilitation for subjects with neurological impairments and including only exoskeletons. Koutsiana *et al.* [18] focus on upper limbs and serious game usage in rehabilitation to identify standard methods, practices, and technology patterns for gocnitive exercises. Chen *et al.* [19] analyze home-based technologies aimed to stroke rehabilitation, whereas Yuan *et al.* [20] focused on robotic rehabilitation for cognitive deficits. Cerasa *et al.* [21] addressed the cooking activity, commenting on its benefit to recovering mobility and cerebral functions (dexterity, planning and scheduling), and Canal *et al.* [22] investigated the activity of putting on shoes, reporting similar health benefits. Along with these daily activities, there are clinical protocols which include the pick-and-place and handover of objects between clinician and patient [23].

One thing needs to be pointed out at this point: rehabilitation and assistance is intrinsecally correlated with human-to-human interaction; when the clinicians are aided or substituted by machines, the paradigm changes and shifts to a human-to-machine interaction. And it is this consideration that brought recent research to investigate the role of social robotics in rehabilitation procedures [24].

1.2 Social Robotics

Social robots have seen an increase in usage in recent years [25] and their applications span from company to assistance to healthcare [26]. What defines a social robot is the capability to change its behaviour based on humans' emotional status [27] and the capability of expressing emotions itself, thanks to social cues. Social cues are the way the robots use to communicate a piece of emotional or social information and can be related to different means of communication. Some authors have explored the use of facial expressions in the communication of robot emotion and intention, such as in [28] where a social robot that can change its face is deployed in a disabled people care facility to interact with the inhabitants. Other authors have explored the use of non-verbal and prosodic sounds for the communication of intention and synchronisation of a robot with humans [29, 30], leveraging on the non-verbal communication that is common in human-to-human interaction. In other cases, gestures have been the main cue to express emotions, such as in [31] or in [32] where a robot of a non-standard shape was made to interact with passers in a museum. From these considerations, it is clear that social cues have a relevant role in Human-Robot Interaction (HRI) and that the correct use of them can lead to a successful and meaningful experience for humans. Furthermore, there is a large number of studies that involve non-humanoid robots, which leads to another conclusion: social robots can also have non-humanoid shapes but show human-like social behaviour. Non-humanoid-shaped robots have the advantage of overcoming the limits imposed by humanoid design. In the specific, robotic arms offer manipulation capabilities that can not be equalled by any humanoid robot in terms of speed and accuracy. Other authors have used robotic arms for rehabilitation [33, 34, 35], and very few of them coupled this kind of HRI with social features [12]. So the reasons behind this study are the will to merge the robotic arms manipulation capabilities with social features, to lead a rehabilitation exercise that stimulates the physical and the cognitive spheres at the same time.

Incorporating a robot into a HRI scenario requires consideration of human behavior, recognizing that individuals may exhibit diverse behaviors. Researchers such as Rossi *et al.* and Shi *et al.* have explored the impact of personality traits on robotic perception, highlighting evidence of influence, particularly concerning traits like openness and conscientiousness. In line with the paradigm of adapting robotic rehabilitation to individual patients, this work aims to analyze how personality traits and broader past experiences may affect the perception of robots and influence HRI tasks. Consequently, a social robot should not only exhibit social behavior and emotional competence but also possess the ability to understand and adapt to the diverse personalities and moods of individuals.

When to social robots are assigned tasks of assistance to elderly and frail people, it is possible to speak about Social Assistive Robots (SARs).

People who develop mental and behavioral disorders often require 24/7 assistance, increasing the burden on their families. One solution is provided by the assisted living facilities (ALFs), which are nonmedical residential settings for frail people and people with physical and mental disabilities [36]. These homelike environments respect the privacy, dignity, autonomy, and choice of the residents, while providing oversight services 24 hours a day and services to meet scheduled and unscheduled needs as well as to promote the independence of the residences [37]. The residents of ALFs are both involved in rehabilitation therapies with the medical equipment, and in physical, cognitive, social, and leisure activities with the caregivers of the facility [38]. Recent studies highlight the positive impact/effect of introducing assistive technology in these special residential settings. SARs are used for improving the psychological status and overall well-being of their users [39]. The advantages of adopting SARs are double. At the practical level, it may reduce the burden of the professional caregivers, by supporting some patient's related tasks or by continuously monitoring multiple aspects of the patient and providing ongoing quantitative assessments [40]. On the other side, SARs system can establish a relationship with the user that leads toward intended therapeutic goals [40]. Several works present encouraging results on the adoption of SARs as a therapy tool with children with autism spectrum disorders [41], as well as with older adults with mild cognitive impairment [42] and dementia [43]. It is also worth mentioning that most recent advances enabled SARs to show social cues, emotions, and movements to improve the interaction with the human.

In order to perform all the tasks of assistance and support to the rehabilitation, robots are supposed to offer human-like capabilities, at least comparable in terms of performance and results to the ones of humans. Robotics has reached a good level of technological maturity and in the following paragraph the most important features will be presented, so to give to the reader a good understanding of how robots can perceive, plan and act in the real world.

1.3 European Market for Social Robotics

The European market for social robotics is poised for significant growth beyond 2025, driven by rapid advancements in technology and increasing demand across various sectors. According to projections, the market for service robots, which includes social robots, is expected to reach \$34 billion by 2025, reflecting a compound annual growth rate (CAGR) of over 10% from 2020 levels [44]. The European startup ecosystem continues to thrive, with significant investments flowing into the sector. In 2022, venture capital funding for European robotics startups hit a record €1 billion, supporting the development of innovative solutions and technologies [45].

Research and development initiatives funded by the European Union, such as the Horizon 2020 and the upcoming Horizon Europe programs, are critical in fostering innovation and ensuring Europe's leadership in robotics technology. These programs aim to support the development of advanced robotic systems with applications in various industries, including healthcare, manufacturing, and service sectors [46]. Collaborative robots, designed to work alongside humans, are expected to see significant adoption, particularly in the automotive and electronics sectors, enhancing productivity and operational efficiency [47].

The healthcare sector, in particular, presents substantial opportunities for social robots. By 2025, the global market for healthcare robotics is projected to surpass \$11 billion, with Europe playing a key role in this growth. Social robots are being increasingly integrated into rehabilitation programs and elderly care, where they assist with physical therapy exercises and provide companionship, respectively [48]. These applications are not only improving patient outcomes but also addressing the shortage of healthcare professionals across the continent.

The impact of robotics on the European labor market is multifaceted. While there are concerns about job displacement, the adoption of robotics is also creating new opportunities and driving the emergence of highly productive ”superstar” firms that leverage automation to gain competitive advantages [49]. By 2030, the European robotics market is expected to be characterized by widespread integration of artificial intelligence (AI) and machine learning, enabling robots to perform increasingly complex tasks and interact more seamlessly with humans [50].

Overall, the future of the European market for social robotics looks promising, with robust growth projections and significant investments driving advancements in technology and applications. The collaborative efforts between industry, academia, and government are crucial in ensuring the successful integration of robotics into various aspects of society, paving the way for a future where robots play an integral role in enhancing productivity and quality of life.

1.4 Robotic capabilities

In the 1980s robotics was defined as the science which studies the *"intelligent connection between perception and action"* [51]. The *perception* can be identified with the sensing capabilities of robots, gained thanks to various types of sensors that provide information about the sorrounding environment (force and tactile, range and vision), and about the state of the robot (position and speed). The *action* refers to how robots can modify the sorrounding environment, and is related to locomotion (wheels, crawlers, legs, propellers) and manipulation (arms, end effectors, artificial hands) capabilities. Finally, the intelligent connection can be referred to as *reasoning*, that is the planning and control strategies of the robots to achieve complex tasks.

1.4.1 Perception

The first caveat when speaking of robotics perception is to be found in the differentiation of *proprioception* and *exteroception*. The former refers to the sensing capabilities that the robot has to understand its own physical state (e.g., joint positions, rotations); the latter is used by the robot to understand its own state with respect to the sorrounding world (e.g., orientation with respect to the magnetic north, or to the center of a known map). The perception is done through sensors, which are hardware component dedicated to the sensing task; they can be grouped in different categories depending on what they measure and how they measure it. Some sensors could be dedicated to the measurement of internal temperature, current and voltage, position of Degrees of Freedom (DoF) (proprioception), or to the distance to an object, interaction forces and material density (exteroception). The perception process starts with the data coming from sensors that are managed by specific modules for the features extraction. For example, a 2D Lidar signal returns a cloud of bi-dimensional points: if there is a cluster of points aligned on a straight line the system can extract this feature and model a wall in that position. Similarly, using depth cameras enables the robot to create point-clouds that represent the sorrounding environment. When looking at it from the perspective of HRI, the *perception* can give information regarding the posture and skeleton position of a human, or a robot could understand the facial expression of a human thorugh observation, enabling it to react to such emotional condition.

1.4.2 Reasoning

Intelligent connection refers to the binding element of robotics that sits between the perception and the action. Connecting these two elements in a clever way means to adapt one to each other and enable a two-ways communication. The communication is used totake decisions and plan the next action to achieve the success of the robotic mission. For example, the robot objective is to navigate from pointa A to point B. The perception module acquires informations about the obstacles on the path, then plans the path to reach point B and activates the wheels to reach that point. In case a new obstacle appears on the map (e.g., a person walking) the robot will perceive it, re-plan the trajectory and control the motors to act acccordingly to the new plan. This robotic feature that allows planning of actions goes under the name of *robotic control* [51]. Robotic control can be achieved in different ways, like reactive behaviour and AI-reasoning. Referring to HRI, the *reasoning* is of paramount importance to build reactive behavior that can adapt the robot to user actions and emotions, in a way that pursues the best interaction possible. Through accurate learning and behavioral models, the robotic reaction and adaptation to human performances can reach a good level of maturity.

1.4.3 Action

Action is crucial for robots as it embodies their ability to interact with and respond to their environment. Through orchestrated movements, robots can perform tasks, manipulate objects, and navigate surroundings, enabling them to fulfill their intended functions effectively. The significance of robotic action lies in its direct impact on a robot's functionality, versatility, and adaptability to dynamic scenarios. In the field of robotics, the functional capacity of a robot is intricately governed by its physical attributes, with manipulation serving as a key domain of interest. The configuration of a robotic system, including the design of its manipulator, choice of end-effector, degrees of freedom, and overall structural composition, establishes the foundation for its manipulation capabilities. For instance, the selection of an appropriate end-effector, whether a gripper, suction cup, or robotic hand, dictates the range and nature of manipulative tasks a robot can perform. Degrees of freedom, representing the articulated joints of the manipulator, determine the system's agility in spatial movements and object interactions. This intrinsic connection underscores the specialized nature of robotic platforms, emphasizing that optimization for distinct tasks necessitates tailored physical attributes. Consequently, not all robotic systems exhibit uniform proficiency in manipulation, with their design intricacies defining their applicability to specific tasks and operational environments. From a HRI perspective, robotic *action* can be declined in cooperation or collaboration, or with robotic assistance in performing some tasks that imply a change in the sorrounding environment (e.g., object pick and place).

It is from the awareness that the shape of a robot is highly impacted by its tasks, that pushed to the investigation and finally the usage in this work, of robotic arms. Such robots offer a huge capability of manipulation and can perform exercises with humans with a good level of dexterity, so as much that they are already used in production environments where they are supposed to interact with other humans to accurately achieve assembling and manufacturing tasks.

1.5 Aims and Objectives

When *perception*, *reasoning*, and *action* are integrated, it becomes possible to create a robot with multiple capabilities. However, despite these advancements, robots still exhibit various weaknesses and limitations, especially in specific application scenarios. In this Ph.D. work, situated in the domain of robotic rehabilitation, the challenges addressed arise from the limitations of existing robotic systems highlighted in the literature. The aims and objectives are all reported in this Chapter and summarized in Figure 1.1

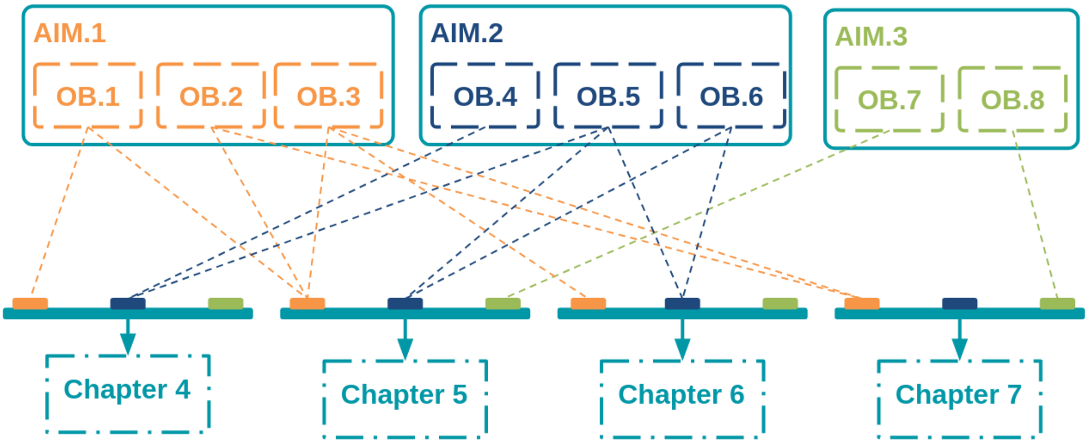


Figure 1.1: Summary of the aims and objectives, with their respective locations within the thesis chapters.

1.5.1 AIM.1: A robotic system that adapts to therapists and patients needs

One of the primary unresolved issues in robotic rehabilitation pertains to HRI encompassing social, physical, and cognitive aspects. Notably, numerous authors, including Najafi *et al.*, Mucchiani *et al.*, and Valle *et al.* [52, 53, 54], have emphasized the challenge of adapting robots to different individuals. During rehabilitation procedures, treatments are often customized for the executing individual. When another patient takes their place, the rehabilitation machine requires retuning. The primary objective of this work (AIM.1) is to harness robotic programming and capabilities to address this issue. The goal is to develop a robotic rehabilitation system that seamlessly auto-tunes to a new patient, adapting rehabilitation exercises in real-time based on data such as emotional state, degree of fatigue, historical performance, and past failures. For its completion, this aim has been decomposed in three objectives:

1.5.1.1 OB.1: Achieving Seamless Adaptation in Robotic Control for Varied Platforms

The first objective involves implementing a module for robotic control that facilitates adaptation to different robots with minimal effort. This objective is pursued in Chapters 4 and 5.

1.5.1.2 OB.2: Dynamic Management of Rehabilitation Exercises for Tailored Patient Engagement

The second objective focuses on creating a module to manage the various phases of a rehabilitation exercise. This module should have the capability to adjust difficulty and modify exercises based on the patient's needs and the therapist's preferences. This objective is pursued in Chapters 5 and 7.

1.5.1.3 OB.3: Data-Driven Therapeutic Interaction

The third objective is centered around establishing two channels that influence the rehabilitation session: historical data retrieved from a structured database and an interface that enables the therapist to interact with and control the system. This objective is pursued in Chapters 5, 6 and 7.

1.5.2 AIM.2: Pursue social engagement for the success of the rehabilitation session

Another gap that is present in robotic for rehabilitation is the need to keep the patients engaged in the rehabilitation tasks, which can be problematic, depending on the pathology and age of the patients [34, 55, 56]. Engagement is often debated among roboticists, beacuse in a HRI scenario the human should be interested and focused on the robot, rather than unattentive, in order to perform the HRI task in the best, safest, and fastest way. The solution proposed by many authors, such as Arora *et al.* [57] or Sorrentino *et al.* [28] is the inclusion of social features in the rehabilitation robots, to connect them with humans at a social and emotional level, strenthening their bond and the attention the person has about the robot. Moreover, it has been verified in literature by Weidemann *et al.*, Bajones *et al.*, and Henschel *et al.* [58, 59, 60] that an increased engagement in performing the HRI tasks is beneficial for any participant and has a good impact in both user satisfaction and engagement in a robotic scenario. For its completion, this aim has been decomposed in three objectives:

1.5.2.1 OB.4: Creating Social Robotic Arm Movements

The objective revolves around the analysis and study for the realization of social movements on a robotic arm, aiming to verify its capability to convey an emotional intention solely through movement. This objective is pursued in Chapter 4.

1.5.2.2 OB.5: Analyzing Human-Robot Interaction and Perception Diversity

This objective focuses on the analysis of how different people interact with the robot, and how their perception and engagement level changes. Different people means on one side people with different personality profiles or different past experiences and backgrounds, and on the other side difference in the role the person has with the robot; namely if just interacts with the robot or if can operate it. This objective is pursued in Chapter 4, 5 and 6.

1.5.2.3 OB.6: Defining Optimal Social Cues for Robotic Arm Integration

In addition to the social movement study, this work also concentrates on identifying the best set of social cues to be integrated into a robotic arm. This objective is pursued in Chapter 5 and 6.

1.5.3 AIM.3: Commistion of cognitive and physical rehabilitation in the same system

To make a rehabilitation system adaptive to the users, means also to make it capable of switching levels of difficulty, variate the type of stimulation and realize exercises of different kind. In the work of Eizicovits *et al.* [11] the robotic arm plays a tick-tack-toe with a user, performing the physical and cognitive stimulation. In rehabilitation there are exercises that involve this kind of approach, where a manipulation task, such as object sorting or assembling of a small objects, stimulate cognitive capabilities like planning and short term memory. Therefore, it is possible to focalize the third aim of this Ph.D. work (AIM.3) as the will to combine the physical and cognitive stimulation of humans through the transposition of currently made rehabilitation exercises to the robotic world. For its completion, this aim has been decomposed in two objectives:

1.5.3.1 OB.7: Development of Robotic Movements for Physical Patient Stimulation

This objective focuses on creating robotic movements for the physical stimulation of patients. The primary emphasis is on defining a physical interaction achievable by the robotic arm in human interaction. This objective is pursued in Chapter 5.

1.5.3.2 OB.8: Integration of Physical and Cognitive Features in Rehabilitation Exercises for Human-Robot Interaction

Finally, this objective encompasses the last segment of the HRI, incorporating both physical and cognitive features into the rehabilitation exercise. This objective is pursued in Chapter 7.

Chapter 2

Laban Movement Analysis: Integration into Robotic Systems for Enhanced Human-Robot Interaction

2.1 Fundamentals of Laban Movement Analysis

Laban Movement Analysis (LMA) traces its origins back to the 1960s, emerging from the groundwork laid by I. Bertnieff [61], who built upon the teachings of Rudolf Laban [62]. His foundational belief posited that emotions find expression through body movements, asserting, "Motion and emotion are kinesthetically intertwined and produced together through a conjunction of bodies, technologies, and cultural practices" [63]. LMA serves as a comprehensive system for delineating, deliberating, and recording human body movements, scrutinizing motion across various dimensions—Body, Space, Effort, and Shape. In this particular endeavor, the focus rested on Effort and Space, which were employed and replicated in robotic movements. Effort describes the dynamic qualities of movement, addressing factors like speed, force, weight, and flow. By examining effort qualities, choreographers can add nuance to their choreographies, creating movements that range from light and delicate to strong and intense; space explores how movement occupies and travels through space. Choreographers can use Laban's spatial concepts to design movements that utilize the entire performance area, creating immersive and dynamic choreographies.

Laban Effort (LE) comprises four four primary elements, often referred to as the effort factors:

- Space: Describes the directional quality of movement. Movements can be categorized as Direct or Indirect. Direct movements move towards a specific point, while Indirect movements are more circular or curvilinear.

- Weight: Refers to the degree of force or energy exerted in a movement. Movements can range from Light to Strong, influencing how much power is applied in performing an action.
- Time: Addresses the speed or timing of movements. Movements can be categorized as Sudden or Sustained, representing whether they have a rapid or gradual initiation and termination.
- Flow: Describes the continuity or fluidity of movement. Movements can be Free or Bound. Free-flowing movements have a sense of continuity, while Bound movements may have pauses or interruptions.

Information on these parameters in robotics can be found in Burton et al. [32] and their schematic representation is available in Figure 2.1.

Laban Effort is a valuable tool for choreographers seeking to add depth and variety to their choreographies. By integrating different effort qualities, choreographers can convey specific emotions, intentions, or characters through movement. For example, a choreographer might use Strong and Bound qualities for a powerful, assertive character, while Light and Free qualities may be employed for a more delicate and flowing movement. Understanding Laban Effort allows choreographers to go beyond the external appearance of movement and delve into its dynamic essence, enriching the overall expressiveness and storytelling potential of a dance piece. It provides a framework for analyzing and crafting movement that goes beyond the traditional focus on shapes and steps, emphasizing the ”how” rather than just the ”what” of movement.

Laban Space (LS), explores how movement occupies and travels through space, providing choreographers and movement practitioners with tools to analyze and enhance the spatial aspects of movement. Laban Space includes the following key components:

- Vertical: Movements can occur at different levels—high, middle, or low—dictating the vertical dimension of space.
- Horizontal: Refers to movements happening in a narrow or wide spatial range, influencing the horizontal dimension of space.

- Wheel: Describes movements occurring close to the body or extending outward, determining the depth or proximity of movement.

Information on these parameters in robotics can be found in Zhu et al. [64] and their schematic representation is available in Figure 2.1.

In LMA, the combination of different spatial elements creates what is known as "space harmony." Space harmony refers to the intentional and coordinated use of the spatial components to achieve a particular aesthetic, emotional, or expressive quality in movement. Choreographers use Laban Space to craft movements that consider not only the shapes and forms created by the body but also the pathways and relationships between the body and its surroundings. By manipulating height, width, depth, and focus, choreographers can create movements that range from expansive and dynamic to introspective and contained.

In the realm of choreography, the synergy between Laban Space and Laban Effort provides a powerful toolkit for dance creators to craft expressive and dynamic movement sequences. By skillfully combining spatial elements and effort qualities, choreographers can shape the character, emotion, and visual impact of their choreographies. The interplay between Laban Space and Laban Effort contributes to the creation of compelling dance pieces. In essence, the integration of Laban Space and Laban Effort allows choreographers to transcend the mere execution of steps and movements. It enables them to create choreographies that are not only aesthetically pleasing but also emotionally resonant and intellectually stimulating. Through this thoughtful fusion, choreographers unlock a rich and versatile palette for artistic expression, bringing depth and sophistication to their dance creations.

Table 2.1: Correlation of Robot's Micro-Movements (M1-Emotional, M2-Handover) and literature reference

Movement	**Group**	**Refs**
HAPPY	M1	[65, 66, 67, 68, 32, 69, 64]
ANGRY	M1	[65, 66, 68, 32, 69, 64]
SAD	M1	[66, 68, 32, 69, 64]
CONFIDENT	M2	[65, 66, 67, 69, 64]
SHY	M2	[66, 67, 69, 64]
NEUTRAL	N/A	Implemented using the standard planning algorithm provided in the MoveIt Library [70]

Table 2.2: Definition of Robot's Micro-Movements based on Laban effort

	Space		**Time**		**Weight**		**Flow**	
Movement	**Laban**	**Robot**	**Laban**	**Robot**	**Laban**	**Robot**	**Laban**	**Robot**
HAPPY	Indirect	Curved	Sudden	No scaling	Light	Joint rotation	Free	5 waypoints
ANGRY	Direct	Linear	Sudden	No scaling	Strong	Minimal joint rotation	Bound	2 waypoints
SAD	Direct	Linear	Sustained	Scaling (0.2)	Light	Joint rotation	Bound	2 waypoints
CONFIDENT	Direct	Linear	Sudden	No scaling	Light	Joint rotation	Bound	2 waypoints
SHY	Direct	Linear	Sustained	Scaling (0.1)	Strong	Minimal joint rotation	Bound	2 waypoints

Table 2.3: Definition of Robot's Micro-Movements based on Laban space

Movement	**Laban space**
HAPPY	Extremely spreading, ascending, and advancing
ANGRY	Somewhat spreading, ascending, and advancing
SAD	Enclosing, descending, and retiring
CONFIDENT	Enclosing, descending, and advancing
SHY	Spreading, ascending, and retiring

2.2 Laban Movement Analysis in Robotic Application

LMA has been applied with varied methodologies in the field of robotics. Zhu et al. [64] used a camera and LMA detection algorithms to extract movement information for the NAO robot, allowing it to act based on detected emotions in a reactive approach. Similarly, in Lourens et al. [71], the system categorized different waving patterns following Laban Efforts definitions. Professional actors in [32] interpreted emotions, recorded, classified, and reproduced them on a simulated skeleton. Another approach is demonstrated in [69], where a wheeled robot was teleoperated following LMA, and user experiences were subsequently rated.

Direct modeling of movements is evident in [67, 68, 72], where movement is designed, and participants are asked to rate it. Others adopted a co-creation session for movement design [66, 65], gathering opinions from a control group to evaluate movements based on various parameters. Questionnaires are prevalently used for validating movements in related works [67, 69, 73, 11]. Emotion and movement interpretation are recognized as highly dependent on cultural and personal backgrounds, environmental factors, and context [74]. M. A. Salichs et al. [73] propose considering puppetry for studying movement in social robots, drawing parallels between puppeteers enabling puppets to express emotions and the role of social robots. Companies like Paro, Aibo, Nao, and Keepon (Figure 2.2) already offer puppet-like robot companions in the market.

This paper builds upon these previous studies, extracting LMA parameters and

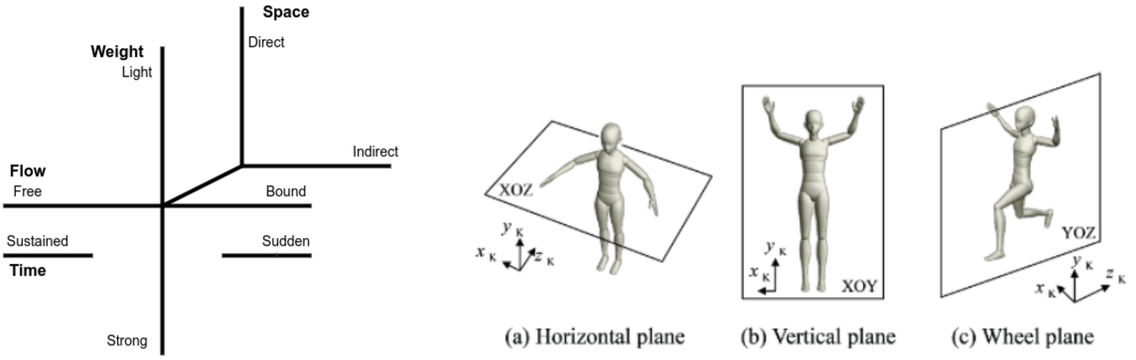


Figure 2.1: a) Depiction of Laban effort Graph representation system, b) Depiction of Laban Space representation, from Zhu et al.

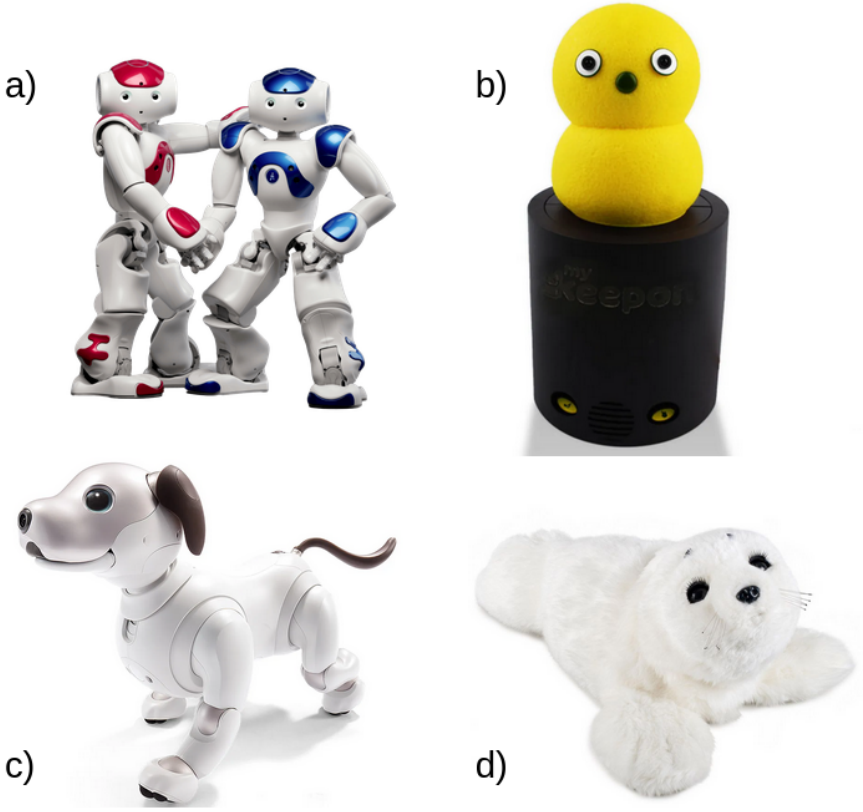


Figure 2.2: Puppet like social robots: a) Nao, b) Keepon, c) Aibo, d) Paro.

applying them to a robotic arm. Notably, this work introduces a novel application by employing a robotic arm with Laban movements for HRI, incorporating physical interaction (e.g., handover) with social and emotional elements; on a further evolution, also the cognitive stimulation of people is introduced in our HRI paradigm. To test and validate the LMA approach, various experiments were conceived, of increasing difficulty but similar objectves, aimed at the discovery of how to apply LMA to robotic arms and how to build rehabilitation sessions that make patients benefit from the emotional movement approach.

In the following paragraph the movements will be described using mathematical formula that aim to univocally explain the possible implementation of Laban movements carrying an emotional load on a robotic arm.

2.3 Development and Implementation of Laban-Inspired Robotic Movements

The robotic arm movements were formalized based on evidence from the literature and the intention to adapt them to a robotic scenario, with the main robot being a robotic arm.

The movements, described in their Laban configuration in this work, can be categorized into two groups of micro-movements. Micro-movements are defined as small-scale displacements with a singular purpose, such as picking up or releasing an object, or performing a Laban movement. On the other hand, all handover tasks, encompassing both picking and placing or other successions of actions, are considered macro-movements. A macro-movement is characterized by a unitary succession of micro-movements, each contributing to the overall task. The correspondence of each Laban movement used in this Ph.D. work and the related micro-movement group is depicted in Table 2.1.

Each of these movements will be subsequently described with formulas, corresponding to the implementation performed using dedicated control software for the robots. These movements were generated through the combination of LS and LE parameters, and the respective Laban components and their transposition into robotic actions are summarized in Table 2.3 for LS and Table 2.2 for LE. The main elements of the movements are the waypoints (WPs), representing the points in the space where the trajectory evolves. The other elements are the speed of transition between two consecutive waypoints, and the rotations of the joints while moving. The curved or straight movement lines were modeled taking into account the position of the observer. This implementation of the two movements can be formalized, to allow repeatability and to standardize the movement behavior based on LMA. Being the WPs the main element, the formalization will be based on them.

A set of n WPs represents a trajectory and can be defined as:

$$WP = \{P_1, P_2, \cdots, P_n\} \tag{2.1}$$

Each waypoint i can be defined as the combination of 3 terms, one for each axis; therefore, a trajectory is created by combining a set of waypoints. As the waypoints are defined on the three spatial axes, the general formula for any trajectory will be:

$$WP_{type} = \left\{ \begin{array}{c} \sum_i p_i \cdot X_i \\ \sum_i q_i \cdot Y_i \\ \sum_i r_i \cdot Z_i \end{array} \right\} \tag{2.2}$$

where:

- p_i, q_i, r_i: Coefficient values indicating the amount of displacement of the *i-th* waypoint in centimetres. It could be positive or negative based on the direction of movement, according to the reference system of the robot;
- X_i, Y_i, Z_i: The movement axis of the considered *i-th* WP.

Therefore, the final formula that defines a happy Laban Movement implemented on a robotic arm is:

$$WP_{HAPPY} = \left\{ \begin{array}{c} -qY_1 + 2qY_3 - qY_5 \\ rZ_1 - rZ_2 + rZ_3 - rZ_4 \end{array} \right\} \tag{2.3}$$

The formula 2.3 describes the Laban movement for the happy movement, that develops around the Y and Z axis of the robot; no movement on the X axis is planned. In the first line of the formula, it is possible to see that the Y coordinate value changes once every two waypoints (i.e.; q coefficient value is 0 for WP_2 and WP_4). Being Y the movement on the horizontal axis according to the robot reference system, the movement goes first to the left for two waypoints ($-qY_1 + 0Y_2$), then moves to the right of double the previous distance and stays in this new horizontal position for the duration of two waypoints ($2qY_3 + 0Y_4$), and finally goes back to the starting position to the left of a coefficient one ($-qY_5$). The Z axis, the one dedicated to the vertical movement, follows a different pattern: moves up and down twice, with the same coefficient. So the LMA on the Z axis will move the robot up and down ($rZ_1 - rZ_2$) twice.

Similarly, the angry movement can be expressed as:

$$WP_{ANGRY} = \left\{ \begin{array}{c} -pX_1 + 2pX_2 - 2pX_3 + pX_4 \\ rZ_1 - 2rZ_2 + 2rZ_3 - rZ_4 \end{array} \right\} \tag{2.4}$$

The angry movement follows a different pattern when compared to the happy one and it is described in formula 2.4. This movement evolves around the X and Z axis and does not plan any movement on the Y axis. Both the lines of the formula encompass 4 waypoints. This means that each of the robotic movements will displace the robot on two axes. This kind of pattern results in a robotic movement that is similar to a wave-like movement back and forth.

Relatively to the sad movement, its formalization is:

$$WP_{SAD} = \left\{ \begin{array}{c} -pX_1 \\ -rZ_1 - rZ_2 \end{array} \right\} \tag{2.5}$$

It follows a shorter trajectory (only two WPs) compared to the other two movements, and it is characterized by a retiring movement and a downward motion, as suggested in the LMA definition. Moreover, the speed factor of this movement should be low.

The formalization of movement presented in this section should serve as inspiration for creating additional Laban movements, consistently based on the original formalization. The one outlined in this section is an adaptation of techniques from the dancing world to the realm of robotics, addressing the necessity of quantifying differences and encoding effective and precise robotic behaviors with well-defined dimensions, such as trajectory and speed.

The following chapter is dedicated to the description of the software system to discover how to apply LMA to robotic arms and how to build rehabilitation sessions that make patients benefit from this approach; then the work will focus on the thorough description on how the experiment were conducted and what results were evinced by their unfoldment.

Chapter 3

Architectural Insights: Unveiling Technological Choices in Project Implementation

This chapter is dedicated to the detailed description of the technology used in this work, and in the ROS framework that was developed to achieve the objectives of this research. The great aim of this chapter is to introduce a technological environment that accurately describes the use of an integrated system for robotic rehabilitation, with high level of adaptability and customizability. The system presented is called ROS-based Manipulation for Cognitive and Physical Rehabilitation (ROS-MCPyRe) and contains all the elements to build and customize a robotic rehabilitation; the core of this work is based on Robot Operating System (ROS), but there are also elements independent from it. All the details will be explained in Section 3.3.2

3.1 Actors in the Environment

There are three main actors in this system (Figure 3.1), that guided the development and the structural choices made so far; their specific tasks in this system and their needs are described in this section.

3.1.1 The therapist

The therapist assumes the role of the agent responsible for defining the rehabilitation strategy and determining the difficulty level of each exercise in both cognitive and physical aspects. Additionally, the therapist has the authority to terminate or extend a rehabilitation session based on the patient's needs. With control over the system, the therapist receives real-time information on the ongoing interaction, including the patient's current scoring and performance. This data empowers the therapist to make informed decisions to optimize the rehabilitation process.

3.1.2 The robot

The robot functions as the agent responsible for conducting rehabilitation sessions, recording data, adjusting the surrounding environment for exercises with patients, and managing exercise repetitions based on the initial rehabilitation plan defined by the therapist. The key advantage of employing a robot over a human therapist lies in its consistent and objective execution of exercises, unaffected by human limitations such as stress, fatigue, or emotions. Furthermore, the use of multiple robots allows for simultaneous exercise execution with the supervision of only one therapist, optimizing efficiency in patient care.

3.1.3 The patient/user

In this rehabilitation framework, the patient assumes a central role as the recipient of personalized care facilitated by the robot and overseen by the therapist. The patient's experience is meticulously tailored, with the robot recording and adapting to individual performance data. Moreover, patients benefit from the adaptability of the system, allowing for personalized rehabilitation plans while promoting engagement and adherence to prescribed exercises. The integration of technology thus empowers the patient in their rehabilitation journey, providing a structured and objective approach to enhance overall well-being. Furthermore, this work aims to enable patients to socially interact with the robot, utilizing LMA, and also communicate with the therapist in case they have any questions they wish to pose to a human.

3.2 Human-Centric Approach

This section aims at explaining why and how the whole software and hardware system development was thought, always keeping in mind a human-centric approach, where the system is dedicated to improve human capabilities rather than replace them. This analysis will be carried on from the point of view of the therapist and of the patient, or the two human actors involved in the system.

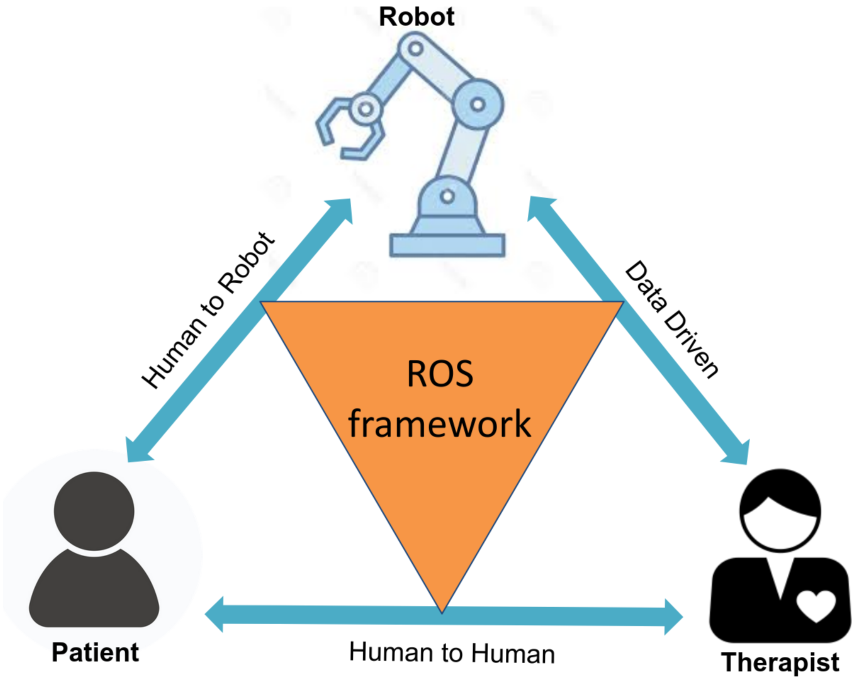


Figure 3.1: The three actors and the interactions that connect them. In the center there is the ROS-MCPyRe.

3.2.1 Therapist point of view

One of the primary goals of the ROS-MCPyRe system is to assist therapists in their duties, which include visiting patients, formulating diagnoses, defining rehabilitation strategies, and implementing them. Certain aspects of this work, such as making diagnoses or directly interacting with patients, cannot be delegated to a robot due to their complexity. However, repetitive tasks and actions requiring consistent execution can be effectively handled by robots. Additionally, robots serve as valuable agents for collecting objective data through dedicated sensors and biosensors. Introducing robotic assistance can alleviate some of the therapist's workload, allowing them to focus on defining optimal rehabilitation strategies independently of technological constraints. This work adopts a human-centric approach, providing therapists with the flexibility to use different hardware (via the *Robot controller* module), vary rehabilitation exercises (via the *Exercise manager* module), or customize system actions (via the *Therapist interface* component). These features emphasize the therapist's autonomy and aim to avoid imposing any limits on their choices.

3.2.2 Patient point of view

The ROS-MCPyRe system's another primary objective is to engage with patients on physical, cognitive, and social levels, tailoring interactions specifically to each individual. Recognizing the uniqueness of each patient, the system aims to offer a personalized experience—an evolution of modern medicine's trend towards customized therapies [20]. Considering a patient's physical capabilities, the robot should dynamically adjust its workspace to align with the patient's abilities. This entails modifying the *Robot controller* module. For cognitive stimulation, the system proposes rehabilitation exercises of varying difficulty levels based on therapist diagnoses or previous performance, sourced from the database. This adaptability is achieved by replacing the *Exercise manager* module. The gamification aspect, using a scoring system reflecting user performance, serves as an additional motivator during exercises [75]. Adjusting this aspect involves changing the *Score manager* module. Furthermore, integrating social HRI enhances interaction quality, positioning the robot as a genuine social agent capable of performing tasks with humans and triggering appropriate stimuli. Adapting social interaction to the patient's characteristics, such as through a personality assessment, enhances the robot's ability to behave optimally for each user. These modules are designed to adapt to diverse patients and enhance their rehabilitation session experience.

3.3 System Architecture

The overall system can be conceptualized as a triangle, where each vertex corresponds to one of the actors. Consequently, each actor is connected to the other two, and these connections can take various forms, as illustrated in Figure 3.1. At the center of the figure, the ROS-MCPyRe serves as a nexus facilitating interactions among the three actors and managing the majority of their engagements. The therapist and the robot are linked by a *Data-Driven* connection, exchanging data through the system interface to influence each other's behavior. The robot interprets the data received from the therapist—whether in real-time or historical—and adjusts its movements accordingly, modifying features such as speed and trajectory. Conversely, the therapist is influenced by robotic data, providing real-time insights into the patient's performance and enabling the therapist to decide whether to halt the rehabilitation session or increase the difficulty level based on the patient's performance.

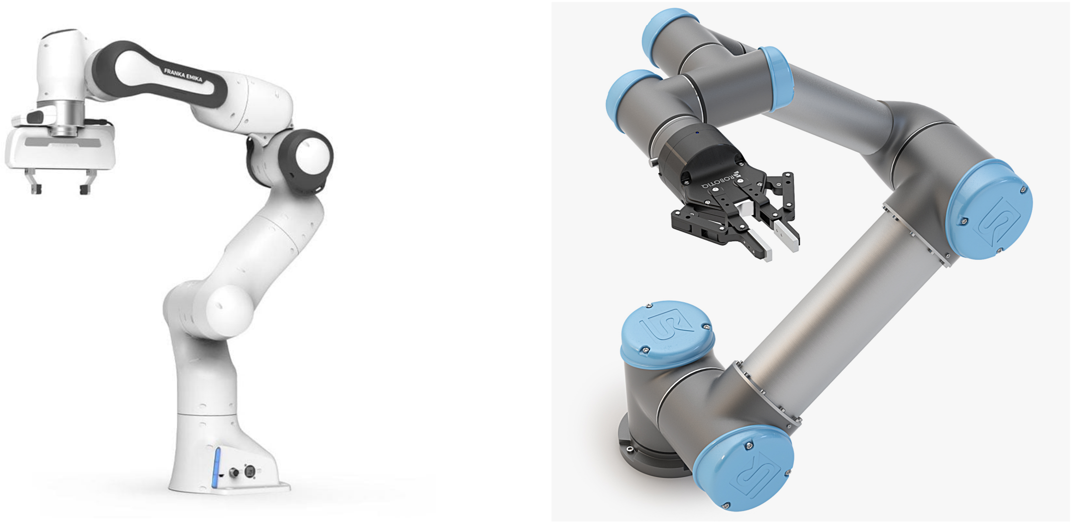
From the robot to the patient, there exists HRI, which has a triple nature: i) physical, involving the exchange of objects between the robot and the patient, stimulating the upper limbs of the patient to reach for the object at a well-defined position in space; ii) cognitive, where the system instructs the patient to place objects in a specific location or organize them following a pattern of varying complexity; iii) social, with the robot performing movements according to LMA, programmed specifically to convey an emotional state. These movements may react to the patient's actions or serve as stimuli for a patient response, such as a joyful movement to signal success in carrying out the exercise.

Finally, the therapist and the patient engage in a direct human-to-human interaction, unmediated by the system. Maintaining this human connection serves the purpose of enabling the therapist to always have the capability to intervene in the rehabilitation session and provides the patient with more time to familiarize themselves with the robot. Not all individuals are receptive to solely robotic interactions. The advantage of incorporating a framework and a robotic helper is evident in alleviating the therapist's burden during rehabilitation. However, in this work, we emphasize that the ultimate decision-making authority always rests with the therapist. We aim to preserve the human element in the interaction, crucial for patients to feel heard, and for therapists to establish a clear connection, enabling the development of rehabilitation therapies tailored to the specific needs of each patient. Further details on this approach will be provided in Section 3.2.

3.3.1 Hardware Components

The main hardware components of this project are the two robotic arms used in the experiments, namely the Panda and the UR5. The Franka Emika Panda robot (Figure 3.2a) is a collaborative robot (cobot) designed and manufactured by the German robotics company Franka Emika. Known for its sleek design and human-like dexterity, the Panda robot is specifically built for collaborative tasks, working alongside humans in shared workspaces. The robot features seven degrees of freedom in its lightweight robotic arms, providing it with a high level of flexibility and agility. Equipped with sensitive torque sensors in each joint, the Panda ensures safe interaction with humans, promptly responding to external forces to prevent accidents. Its advanced control system allows for precise and smooth movements, making it suitable for a wide range of applications, including assembly, research, and light manufacturing. The Universal Robots UR5 (Figure 3.2b) is a widely recognized and versatile robotic arm produced by Universal Robots, a pioneering company in collaborative robot technology. With a payload capacity of 5 kilograms and a reach of 850 millimeters, the UR5 is designed for various collaborative applications, offering flexibility in industrial settings. Like other robots in the Universal Robots' lineup, the UR5 is known for its user-friendly programming interface, allowing users with minimal programming experience to set up and operate the robot efficiently. Equipped with force/torque sensors, the UR5 ensures safe collaboration by detecting unexpected contact and promptly reacting to prevent accidents. Its modular design and adaptability make it suitable for tasks such as material handling, assembly, and machine tending, contributing to the evolution of human-robot collaboration in industry.

The technological goal of this project is to construct a portable system that enables component interchangeability, and robotic hardware is no exception. Thanks to the layer of abstraction introduced by ROS and the MoveIt library [70], a module has been developed that facilitates the use of either robot with minimal effort. In the future, this system could be expanded to encompass not only robotic arms but also various other platforms. Presently, the integration of a different robot involves coding; however, there are plans to create a dedicated customizer in the future. This customizer will enable non-expert users, such as therapists, to reconfigure the ROS-MCPyRe system.



(a) Franka Emika, Panda

(b) Universal Robots, UR5

Figure 3.2: The two robotic arms used in this work.

Other hardware components of the system include the computer responsible for controlling the robot and providing a high-level interface for therapist control. Additionally, a tablet is utilized to present information to the user. This information may take the form of facial social features related to the robot or display exercise-related details, such as cognitive stimuli that influence the execution of the current rehabilitation exercise.

3.3.2 Software Components

The software architecture developed for this study (Figure 3.3) corresponds to ROS-MCPyRe. The main software is written in Python and utilizes the ROS catkin-based build system. ROS nodes communicate through publish/subscribe mechanisms and services, exchanging information via custom messages.

The connection from ROS to external systems is facilitated by ROS-Bridge, which uses its JavaScript libraries for interfacing. This connection enables seamless integration with the web-based frontend, which is written in HTML and CSS. The reactive aspects of the frontend are managed using plain JavaScript, while the graphical elements are enhanced using the Bootstrap CSS framework.

All software is version-controlled using GIT, ensuring robust management and tracking of changes. Additionally, the system employs various ROS libraries, such as Moveit2, which is utilized for robotic movements, providing advanced capabilities for motion planning and execution.

In summary, the whole software is composed of three main elements, described in the following paragraphs.

3.3.2.1 The ROS based software

This component is in charge of controlling the robotic arm, managing the exercise and performing the needed tasks for the HRI. The ROS based software is composed of different nodes, each of them in charge of specific tasks; each node belongs to a specific module that has one responsibility for the execution of the robotic rehabilitation task. In the first place there is the *Exercise manager* module, that manages the various part of the interaction, reads the data from the user and coordinates the robot actions. This module is crucial to the well execution of the exercise because it acts as a planner of the different actions. Looking at the reusability, in case the therapist decides to change exercise, it will be necessary to act and modify a few of the nodes belonging to this module; this limits the impact of a new exercise to this module, leaving the other nodes unaffected. The module *Score manager* is connected with the interface and the DB, and collects all the information on the ongoing session. All the scores are saved in the working memory of this module and then dispatched to the DB module when the session is finished. In this module is also focused the logic to evaluate the participant's performance with a score, to psuh forward the concept of gamification of the rehabilitation exercise that increases the engagement and satisfaction in the participants [75]. This module can be updated in case there is need to modify the scoring system (e.g., to measure different features of the patient's performance). The *Exercise manager* and the *Score manager* modules are part of the *Reasoning* unit of the ROS-MCPyRe system.

Next, the *Robot controller* module is delegated to perform the hardware control; using the Moveit library [70] it can send commands to the robot to perform a specific part of the rehabilitation exercise and can also read the robot status to perform a continuous monitoring ot its state, in order to avoid failures and ensure the safety of who is using the robot. This module can be modified according to which robot is connected to the ssystem, and a simple rewriting of the main functions would allow the whole ROS-MCPyRe to easily work with another robot. The *Robot controller* module belongs to the *Action* unit.

To allow the ROS-MCPyRe to take into account external stimuli, the system is endowed with the *Robot sensing* module that collects input from the outside world and can modify the behavior of the robot itself using these information. This module is part of the *Perception* unit.

The communication task is performed by the module *ROS-bridge*, that comes from the work of Crick *et al.* [76]. ROSbridge is a middleware that acts as a communication bridge between the ROS and external programs or systems. It facilitates bidirectional communication through WebSocket, providing a JSON API for non-ROS applications to interact with and control robots. Commonly used in robotics, ROSbridge supports features like publishing and subscribing to topics, calling services, and accessing the ROS parameter server. It is language-agnostic and can be extended with plugins, making it versatile for integrating diverse robotic platforms and applications.

The *DB interface* module is one of the simplest parts, but performs an important task. It is composed of connectors to the DB (in this implementation MongoDB, described further), and is in charge of saving and loading the data from the DB. Through chankging this module would be possible to switch to an SQL DB instead of a document based one, or extending this module insted of replacing it would allow the system to use multiple databases, according to the needs of the specific project.

3.3.2.2 The therapist interface

The therapist interface, a pivotal component of the system, allows a therapist (or the researcher in this study) to control the system and trigger the robot to perform the needed tasks. It is constructed within a Flask container leveraging Docker technology [77]. Docker, a powerful containerization platform, plays a crucial role in enhancing the system's portability, scalability, and efficiency. By encapsulating the therapist interface within a Docker container, the application gains the ability to run consistently across various computing environments. This ensures that dependencies and configurations are isolated, minimizing compatibility issues and streamlining deployment processes. Docker's lightweight and fast containerization make it an ideal choice for packaging applications and their dependencies, fostering an environment where the therapist interface can seamlessly operate across different systems without concerns about underlying infrastructure variations. Furthermore, Docker facilitates efficient collaboration and development workflows, as the containerized application can be easily shared and replicated, simplifying the deployment of the therapist interface in diverse settings.

This container hosts four interconnected web pages seamlessly linked to the ROS system through ROS-libjs [76]. The adoption of this approach stems from a deliberate focus on portability and reusability, serving as a guiding paradigm throughout the entire system development process. These four web pages empower therapists to perform key functions: i) input user data and save workspace waypoints based on user arm extensions; ii) generate random points of interaction for the robotic arm, factoring in user-specific data; iii) determine the type of HRI, whether it be Standard or Inverted; iv) allocate points during the interaction using dedicated buttons on the web GUI. This user-friendly interface not only enhances the therapist's control over the robotic system but also aligns with the overarching goals of portability and adaptability, ensuring a seamless integration into various environments and therapeutic scenarios.

3.3.2.3 The database (DB)

This component stores user specific data and performance, to keep track of the various sessions of the participants and perform future data analysis on them. Data persistence is a critical aspect in robotics, ensuring that a robot's memory extends beyond individual operations. This capability allows a robot to accumulate knowledge and experiences over time, enhancing its adaptability, decision-making, and overall efficiency. With persistent data storage, robots can learn from past interactions, refine their responses, and maintain a coherent understanding of their environment. MongoDB [78], a prominent NoSQL database, serves as a robust solution for data persistence in robotics. Its schema-free structure accommodates diverse data types generated by robots, such as sensor readings, navigation maps, and historical task information. MongoDB's scalability, flexibility, and ability to handle large volumes

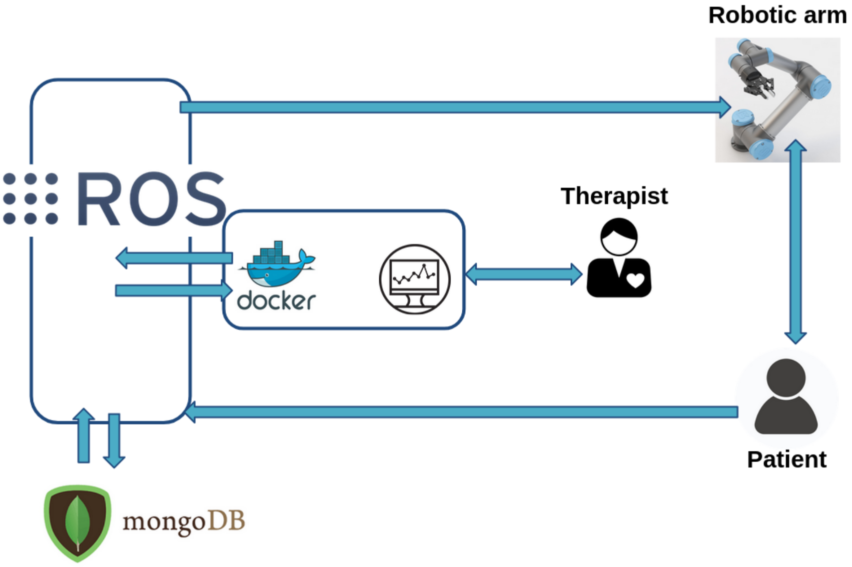


Figure 3.3: Software architecture representation at a high level.

of unstructured data make it a suitable choice for supporting the evolving and dynamic nature of robotic applications. By leveraging MongoDB's features, robots can effectively manage and retrieve valuable information, paving the way for continual learning and improvement in their operational capabilities.

3.4 Evolution of Software: A Chronological Journey through Development Milestones

The software architecture presented in this chapter poses multiple challenges that need to be decomposed into minimal blocks to allow successful implementation and ensure accurate testing. In this section, all the development will be presented in the form of a timeline, and all the development features will be connected with the corresponding experiment in which they were tested. The overall evolution is available in Figure 3.4.

3.4.1 Perception Unit

The initial capability developed for this system is perception. In the context of ROS-MCPyRe, vital information is derived directly from the patient. The analysis of posture, gaze, and facial expressions enables the understanding of various elements, including stress levels, current emotional status, frustration, or fatigue during exercise performance. Consequently, the primary developmental focus was on creating a

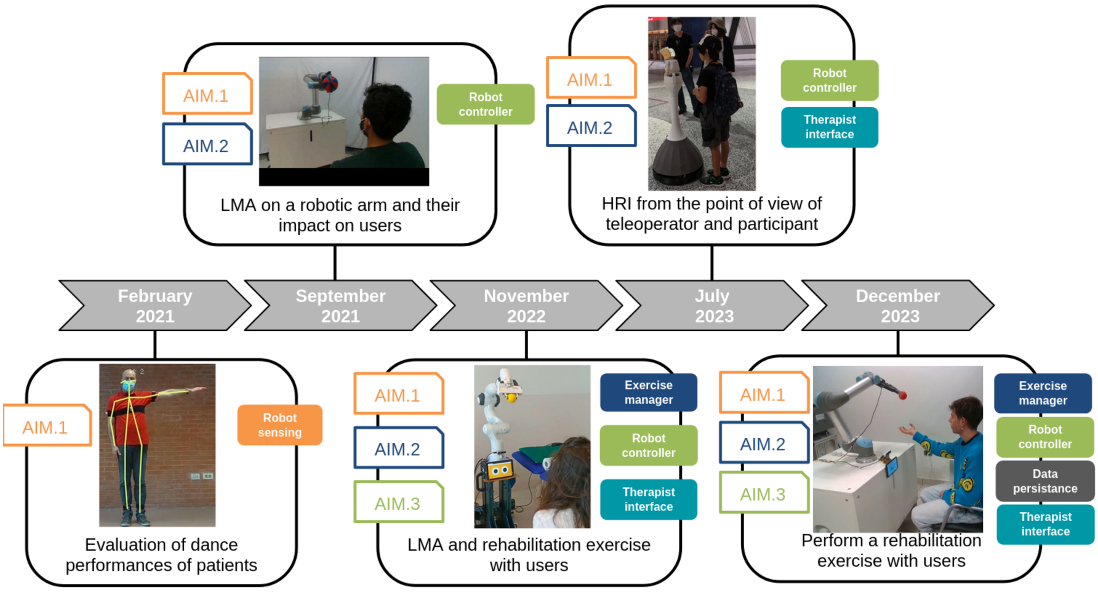


Figure 3.4: The timeline of development. Each block is connected to the aim and the robotic task tested in the related experiment.

perception module for detecting the human skeleton and measuring movement parameters such as symmetry, velocity, and accuracy in the displacement of arms and legs. This module underwent testing under the SI-Robotics project [1]. In this project, the perception module was employed to assess the dance performances of individuals affected by Parkinson's Disease. The measuring system aimed to provide therapists with an objective evaluation tool for understanding patient performance. Developed in collaboration with other partners, the system also sought to customize rehabilitation sessions based on parameters extracted from the evaluation.

The sensing component of the ROS-MCPyRe system is crucial for monitoring patient movements and providing real-time feedback. Figure 3.5 illustrates the architecture of the perception unit, which includes skeleton tracking, posture analysis, and facial expression recognition. This system leverages the X-Sense IMU and the Intel RealSense Camera for capturing body pose and movement data. The IMU data acquisition is handled through proprietary software, while the Intel RealSense Camera utilizes ROS drivers for seamless integration.

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[1] Published in *"Dancing with a robot: an inner view on technology for rehabilitation and support to therapists in the stimulation of Parkinson's disease patients". F.G. Cornacchia Loizzo, C. La Viola, L. Fiorini, R. Bevilacqua, M. Benadduci, L. Rossi, E. Maranesi, G. R. Riccardi, G. Pelliccioni, G. Melone, A. La Forgia, N. Macchiarulo, L. Rossetti, A. Potenza, A. Leone, G. Rescio, A. Caroppo, A. Manni, A. Cesta, G. Cortellessa, F. Fracasso, A. Orlandini, A. Umbrico, R. De Benedictis, Y. Gentili, A. Puglisi, G. Pioggia, M. Tritto, A. Merla, C. Porfirione, N. Casiddu, F. Burlando, A. Vacanti and F. Cavallo, 2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2022, APHRODITE Workshop (Oral Presentation)*

RGB images from the camera are processed using Cubemos, an inference model that aligns with the COCO human pose estimation. The integration of these sensors enables comprehensive data collection, which is then processed to determine movement accuracy, symmetry, and emotional states. The analysis focuses on geometrical features derived from the IMU and body pose estimations, allowing the system to make decisions on features such as body balance, trunk inclination, and movement symmetry.

These data are processed in real-time, and based on geometrical evaluations, the system can make informed decisions, such as assessing body balance and movement symmetry. This dynamic adjustment of rehabilitation exercises ensures that the therapy is tailored to the patient's needs, enhancing the overall effectiveness of the rehabilitation process.

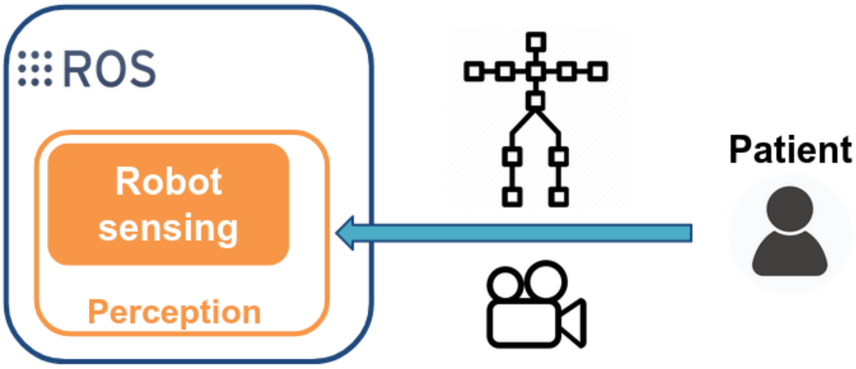

Figure 3.5: Schema of the perception unit with skeleton tracking

3.4.2 Action Unit

The second focus in the development of ROS-MCPyRe was the creation of the action unit, establishing a bidirectional connection with the robotic component of the system to monitor the robot's status and send commands. Monitoring the robot's status is crucial to ensure that everything functions as expected, and in case of suspected misbehavior, the system can be halted to guarantee the safety of the therapist, patient, and technological equipment. The command component enables the definition of movement strategies on the robot, in this case, based on LMA or the execution of emotional movements described in the strategy outlined in Chapter 2. This aspect of the ROS-MCPyRe implementation underwent testing through the recording of videos showcasing the robot's movements in front of a researcher. The results gathered from questionnaires informed the development's progression to more advanced stages.

Additional details about this experiment can be found in Chapter 4. A schematic representation of this aspect of the system is depicted in Figure 3.6.

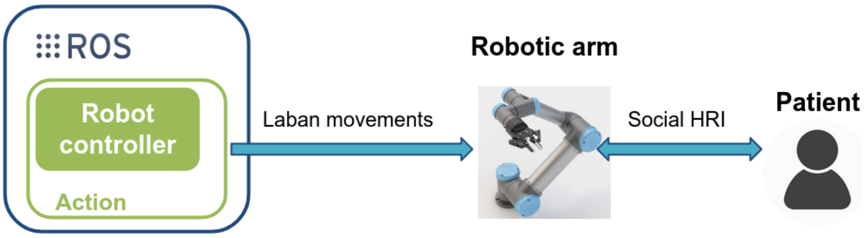

Figure 3.6: Schema of the action unit implemented for the first experiment.

3.4.3 Reasoning Unit and Therapist Interface

Advancing to the next stage, the system progresses towards the completion of all essential modules. In this evolutionary phase, additional elements were incorporated. Specifically, within the ROS-MCPyRe, the reasoning unit was introduced, encapsulated in the *Execution manager* module. This module is now capable of sending commands to the robot based on a plan derived from a rehabilitation exercise. The interconnection of these elements is facilitated through ROS, and a comprehensive exploration of the experiment can be found in Chapter 5. Another module integrated into the ROS system is the ROS-bridge, serving as a translation layer that exposes ROS messages on a TCP protocol. This invaluable ROS module facilitated the development of an external interface, utilized for exchanging simple commands with the reasoning unit. In its initial stage, the interface allowed the therapist to initiate and conclude the exercise, with further functionalities to be explored. However, this inaugural implementation of the *Therapist interface* played a crucial role in experimenting with the integration of ROS with a web-based Flask app hosted on a Docker container.

An additional noteworthy element in this phase of the experiment is the substitution of the robotic arm. For this test, the UR5 model was replaced with the Panda. Beyond expanding the system's scale with the introduction of the reasoning unit and the user interface component, this transition allowed the first assessment of the ROS-MCPyRe's adaptability, necessitating modifications to the *Robot controller* component. A schematic representation of this aspect of the system is depicted in Figure 3.7.

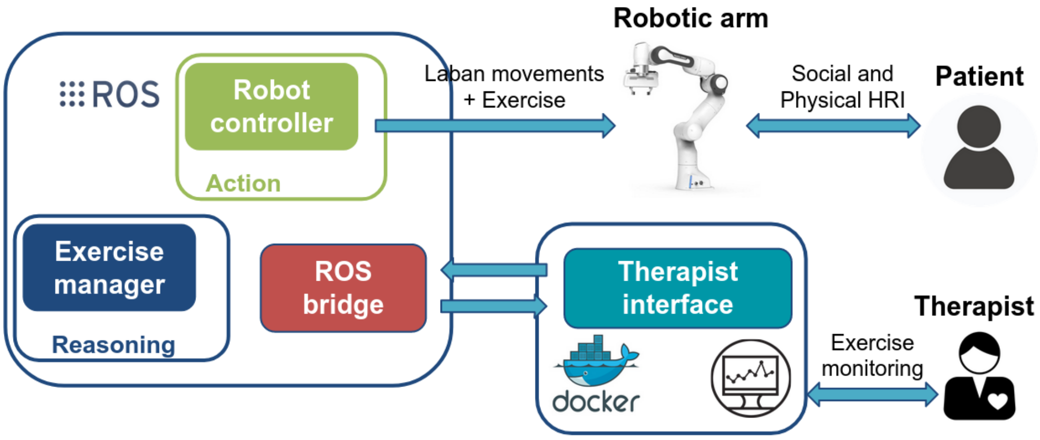

Figure 3.7: Schema of the modules integrated in the second experiment.

3.4.4 Final design of ROS-MCPyRe

The final step in creating ROS-MCPyRe involves introducing the missing components and connecting them. In this initial stage, the modules added include the *Score manager* within the reasoning unit and the *DB interface*. The former is introduced to enhance engagement and patient satisfaction during the rehabilitation process through a gamification approach. The scoring can be evaluated according to a policy decided by therapists or psychologists, allowing flexibility for different tasks or patient cohorts. The latter is a small module responsible for exchanging data with the persistence base, specifically MongoDB. Using a persistence module for saving user data is crucial for creating patient-tailored therapy and preserving a historical record of patient performances, aiding therapists in adjusting therapy for each patient. Consequently, the DB module has also been incorporated into ROS-MCPyRe. Regarding the *Therapist interface*, it has been reinforced through the creation of more interfaces, thoroughly described in Section 3.3.2.2. The difference from the previous implementation lies in the interface's capability to allow the monitoring of exercises, scoring performances, and creating patient profiles for the persistence of relevant data.

The reintroduction of the perception module in this configuration allows the robot to also have information on the user, rather than simply executing its tasks. One notable aspect in this last implementation is the interconnection among the actors; in this test, the loop robot-patient is closed through the modules of action and perception. At this stage of implementation, the interconnection between perception and action is missing, meaning that the robot is not able to apply reactive behavior based on the patient's actions. Nonetheless, the infrastructural work has been completed with this version of ROS-MCPyRe, and in the future, it will be possible to complete this loop through the implementation of reactive behavior and its easy integration into the system. The testing scenario for this version of the system is described in chapter 7 The complete picture of the ROS-MCPyRe system is available in Figure 3.8.

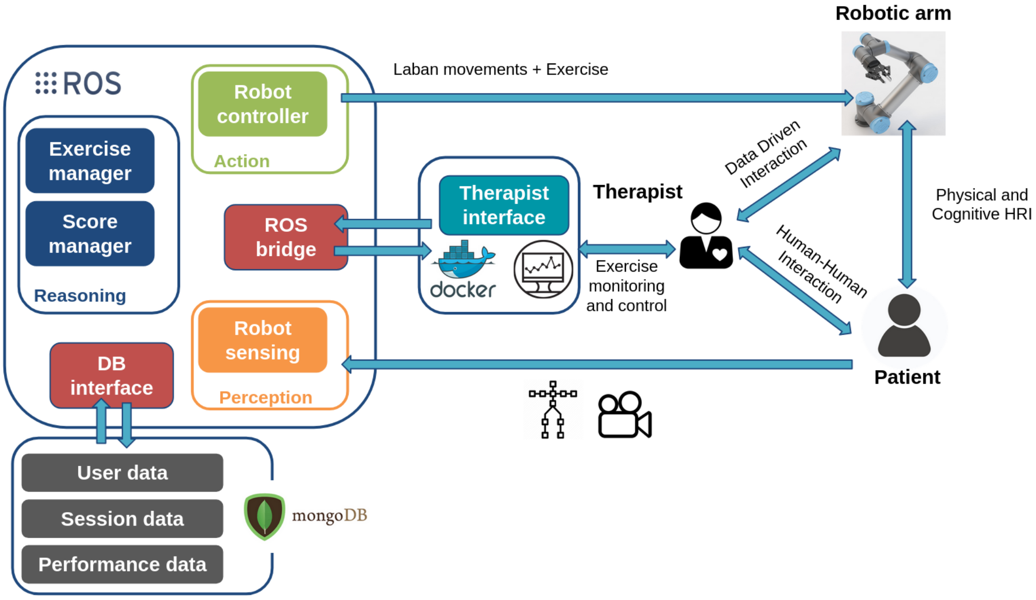

Figure 3.8: Schema of the modules integrated in the last experiment.

3.4.5 Extension of ROS-MCPyRe: Intelligent Space

An "intelligent space" in the context of robotic automation refers to an environment equipped with a network of sensors, actuators, and interconnected devices that facilitate real-time monitoring, data collection, and autonomous decision-making. This setup allows robots and automated systems to interact seamlessly with their surroundings, adapt to changes, and perform complex tasks with minimal human intervention.

Intelligent spaces enhance efficiency, accuracy, and safety in various applications, such as manufacturing, logistics, and smart homes, by leveraging technologies like artificial intelligence (AI), machine learning, and the Internet of Things (IoT). These technologies enable robots to dynamically understand and respond to their environment, thereby improving overall productivity and operational effectiveness.

Due to the architectural choices made for implementing ROS-MCPyRe, extending the system's behavior through new ROS-based elements is straightforward. One significant future development is the inclusion of intelligent spaces.

Integrating intelligent space technology into the ROS-MCPyRe system could significantly enhance its capabilities. Environmental sensors and interconnected devices would create a responsive environment that smartly adapts to the needs of both the patient and the therapist. By incorporating intelligent spaces, the system can offer more precise tracking of patient movements, provide real-time feedback, and dynamically adjust rehabilitation exercises based on patient progress. This integration could potentially improve patient outcomes by offering a more immersive and interactive rehabilitation experience. Moreover, the enhanced monitoring facilitated by multiple environmental sensors can fine-tune rehabilitation therapy according to patient inputs, prevent dangerous behaviors, and adjust the therapy with greater accuracy. This aims to improve patient well-being by managing stress situations and exercise difficulty more effectively.

Chapter 4

Enhancing the Analysis of Robotic Arm Micro-movements for Rehabilitative Purposes through Laban Theory

This chapter [1] explains the first experiment carried on to achieve a part of the objectives. The conception of this experiment started from the literature awareness about the possibility of using LMA for robotics movement to convey a social interaction to participants. The lack in literature that was found regarding the robots used for these approach paved the way for this specific work, that was aimed at the resolution of the following research questions.

4.1 Reasons for the study and research questions

In recent years, studies on social robotics in rehabilitation underscore the benefits of enhancing patients' quality of life through physical and cognitive stimulation. Robots assist clinicians by handling repetitive tasks. Real-time measurements of parameters during interaction provide valuable data for assessing clinical status and the quality of interaction. Despite these advantages, there are gaps in research regarding robots expressing emotions and adapting behavior with advanced social intelligence, especially

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[1] adapted from *"Humans and Robotic Arm: Laban Movement Theory to create Emotional Connection", **C. La Viola**, L. Fiorini, G. Mancioppi, J. Kim and F. Cavallo, 2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2022, pp. 566-571, doi: 10.1109/RO-MAN53752.2022.9900708. (Oral Presentation)* and *"Enhancing the analysis of a Robotic Arm Micro-movements using Laban Theory for Rehabilitative Purpose." **Carlo La Viola**, Laura Fiorini, Gianmaria Mancioppi, Leopoldina Fortunati, Filippo Cavallo, 2022, Robotic and Automation Letter (SUBMITTED)*

in handover tasks. This chapter highlights the absence of robotic arms, such as UR5 and Panda, integrating Laban Movement Analysis (LMA) for expressive interaction with humans, especially in the context of rehabilitation or assessment. Unlike the commonly used puppet-like or wheeled robots, there is a dearth of literature on robot arms attempting to convey emotions through movement. This work aims to bridge this gap by drawing inspiration from LMA to control robot manipulation for expressing emotions, thereby enhancing the social capabilities of robot arms and improving HRI. There are two primary reasons for this integration: firstly, it stimulates patients both physically and emotionally, enhancing their engagement during rehabilitation sessions; secondly, it addresses emotional interaction tasks necessary for frail populations like those with Mild Cognitive Impairment, Alzheimer's Disease, or post-stroke patients. Additionally, it emphasizes the potential application of this approach in addressing pathologies involving the social sphere, such as autism spectrum disorder or dementia.

The research questions emanating from this exploration are threefold. Firstly, the study aims to ascertain the feasibility of a robot arm communicating an emotional state through macro and micro-movements (RQ.1). Secondly, it delves into the variability of human perception and likability of different robot arm movements, exploring patterns based on sociological data and past experiences (RQ.2). Finally, it explores the impact of users' personality traits on the perception of a robotic arm's micro-movements (RQ.3). The proposed methodology involves developing robot manipulator movements according to LMA principles and evaluating participant responses to videos depicting the moving robot expressing emotions. The methodology is furtherly explained in the next section.

4.2 Materials and Methods

4.2.1 Experimental setup

The UR5 robot from Universal Robots, Denmark (Figure 1, b), served as the robotic manipulator for this study. Featuring 6 rotational joints and a maximum action range of 850mm, the UR5 was chosen primarily for its availability and compatibility with ROS (Robot Operating System). The study's hardware implementation is designed to be portable to other robot arms with similar capabilities. On the software side, the main implementation leveraged ROS, the motion planning library Moveit, and the Python coding language.

The control strategy involved direct kinematic control for setting up the initial pose and joints position. Subsequently, Cartesian movement functions were utilized, enabling parametrization of the movement by acting on the end-effector pose, resolved using inverse kinematics. Moveit's simulation capabilities were employed to verify trajectories before execution, and the library facilitated the prevention of unreachable states, blocking the execution of incorrect or hazardous trajectories.

The robotic arm was positioned in a room, and a researcher, acting as a participant, interacted with the robot, performing three groups of interactions, described in the next section. Each interaction was recorded from lateral and frontal views relative to the robot (Figure 4.1). The integration of ROS and MoveIt allowed precise control over the robotic arm's movements, enhancing the study's experimental design.

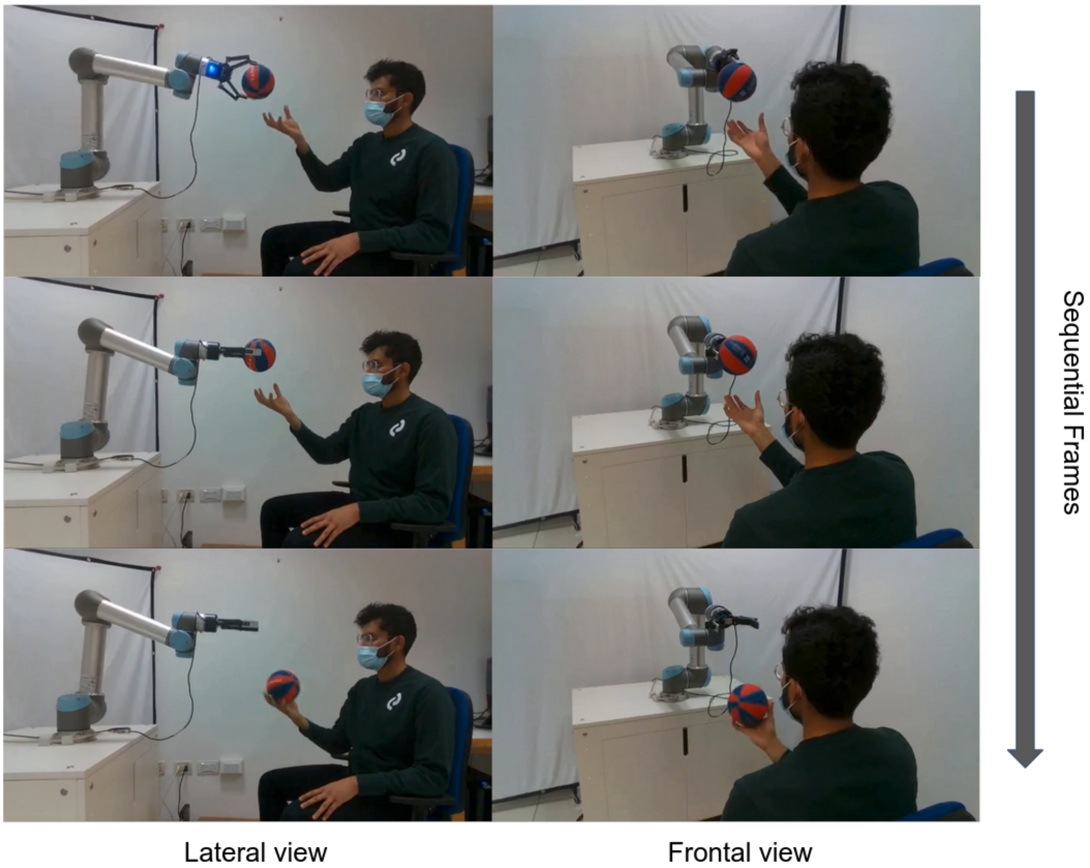

Figure 4.1: Visual perspective captured by sequential frames from both lateral and frontal cameras.

4.2.2 Questionnaire design and experimental procedure

To conduct the study, an online questionnaire was administered and three groups of videos (with no audio) were recorded using the UR5 robot. These groups comprised emotional videos (labeled as M1 in 2.1) featuring micro-movements depicting happiness, sadness, and anger; handover videos (labeled as M2) focusing on confident and shy handover movements; and combined videos that merged micro-movements to create macro-movements (3 M1 x 2 M2 combinations). Additionally, it was implemented a neutral movement using the robot's planning software, resulting in a total of seven videos. The questionnaire begins with a brief video introduction explaining the work and its objectives. The questionnaire is then divided into five main sections (Figure 4.2).

The Section 1 collects personal information related to emotional perception, including education, pet ownership, experience in dance, puppetry acting, digital animation, and level of experience with robots. The Section 2 includes a brief personality assessment based on the Big Five Personality Test (BFI) test [79]. The BFI-10 is a 10-item scale assessing the Big Five personality traits. Section 3 presents the seven macro-movement videos, and participants are asked to rate the emotions elicited using a 7-point Likert scale. The emotions align with those summarized in Table 2.1. In addition to these scales, an extract from the Self Assessment Manikin (SAM) questionnaire [80] measures each micro-movement. The SAM assesses emotional response across three dimensions: Valence, Arousal, and Dominance. This experiment focuses on SAM's Valence and Arousal dimensions to investigate emotional perception of the robotic arm macro-movements. Section 4 presents three videos of micro-movements from the emotional group M1. Participants are instructed to choose one label from five possibilities (happy, sad, angry, fearful, and neutral), with a text box provided for spontaneous comments. In Section 5, two videos from the handover group M2 are shown, and participants rate the extent to which they perceive the videos as 'confident' or 'shy' using a 7-point Likert scale. After S4 and S5, participants have the opportunity to express a preference for one micro-movement video in each section, along with an open question about the reason for their preference. Clear textual instructions on how to respond to each section are provided before participants engage with the content.

4.2.3 Participants

A total of 142 individuals participated in the online survey through snowball sampling [81]. No specific inclusion criteria were set, allowing anyone to respond. Participants were briefed about the survey's purpose, duration, and asked to provide consent before proceeding. However, 13 subjects were excluded from the statistical analysis due to missing data, resulting in a final inclusion of 129 subjects for analysis.

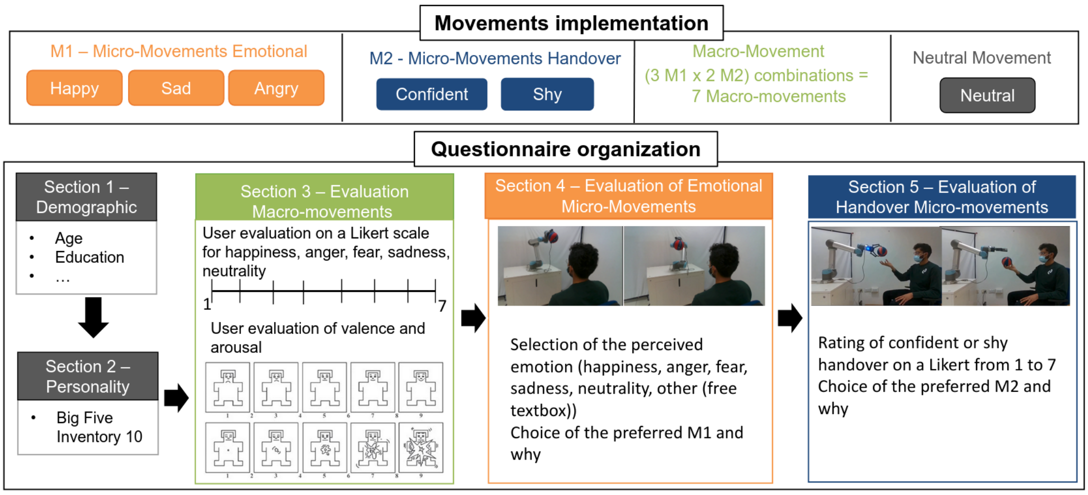

Figure 4.2: Evolution of the first experiment, with details of the different phases.

Sociodemographic details are outlined in Table 4.1. It's noteworthy that, to prevent bias, participants were kept unaware of the emotion associated with the videos they viewed. The survey, as per pre-test results, took approximately 15 minutes to complete, though participants had the flexibility to take as much time as needed. The questionnaire was presented in both English and Italian, allowing participants to choose their preferred language for responses. For the survey completed in Italian, all the information collected was processed and translated into English for data analysis.

The study received approval from the Ethics and Research Committee of the University of Florence (protocol number 0077883 dated 06.04.2023)

Table 4.1: Socio-Demographic Distribution of Participants for the First Experiment(%)

Gender	Male 52.1		Female 45.8		Not Said 2.1
Age Range	(15-25) 19.1	(25-35) 40.4	(35-45) 21.3	(45-55) 9.9	(>55) 9.2
Education	Primary School 1.4 Master's degree 48.6		High School 16.2 Bachelor's degree 12.7		Ph.D. 21.1
Pets experience	Has experience 69.0		Has not experience 31.0		
Dance experience	Has experience 36.6		Has not experience 63.4		
Robot experience	Has experience 40.1		Has not experience 59.9		

4.2.4 Data Analysis

The sample of participants was considered and analyzed to address the research questions posed at the beginning of this chapter. The response to RQ1 was derived from the findings of Sections 3, 4, and 5, employing specific analytical approaches. In Section 3, SAM questionnaire values were averaged and normalized between -1 and 1, assigning each macro-movement a value for Valence and Arousal, and these results were plotted on Russell's circumplex model [82], a two-dimensional representation organizing emotions based on valence and arousal dimensions. In Section 4, emotions expressed through labeling were manually analyzed, categorized into three polarized feelings according to Russell's circumplex model—'positive' for positive valence, 'negative' for negative valence, and 'other' for emotions with low arousal and valence close to 0 (e.g., labels like "satisfied," "relaxed," "calm," "sleepy," "bored," "tired"). For Section 5, mean values related to the perception of confident and shy micro-movements were computed. In both Sections 4 and 5, responses about the preferred video were grouped, and participants' spontaneous comments in the open text box were subjected to content analysis [83]. All open comments were manually coded and categorized into macro-categories by three researchers based on the meaning of the comments.

Research Question 2 (RQ.2) aimed to explore correlations between demographic data (gender, age range, education) or social data (previous experience with pets, dance, acting, digital animation, puppetry, or other robots) and the Likert-scale scores obtained in Section 3. To achieve this, the different distributions were compared using both the χ^2 test and Cohen's D effect size measure.

Investigating RQ.3, the five BFI-10 final scores for each participant were employed to group them using the K-means clustering technique [84]. This technique aims to partition the five dimensions of personality into clusters with the nearest mean value from a centroid, minimizing within-cluster variance. The distribution of questionnaire responses related to the BFI-10 scale was subsequently analyzed within these clusters. Moreover, the Kruskal-Wallis non-parametric test by ranks was applied to each of the BFI-10 dimensions to confirm significant differences among the clusters. The reported results include Kruskal-Wallis p-values, associated H-test, effect size computed by η^2, and post-hoc analysis corrected using the Bonferroni method. Additionally, preferences for the videos were examined both cluster-wise and across the entire sample (as a reference). To explore potential differences among personality groups, the χ^2 test was employed for analyzing video preferences.

4.3 Results

The first part of the results answers to RQ.1: can the robot communicate an emotional state only through movement? In Section 3, participants were asked to evaluate the macro-movements and the neutral movement based on the SAM dimensions of

Valence and Arousal. Mean values for each video's Valence and Arousal dimensions were computed. According to these mean values, each macro-movement was plotted on Russell's Circumplex of emotions, as presented in Figure 4.3. Each point on the plot corresponds to a macro-movement and is labeled using the first letters of the micro-movements involved in its definition: HC for happy and confident, AS for angry and shy, SS for sad and shy, N for neutral, and so on. The HC, AC, SC, and N points are farthest from the origin axis, while the others are almost placed at the origin.

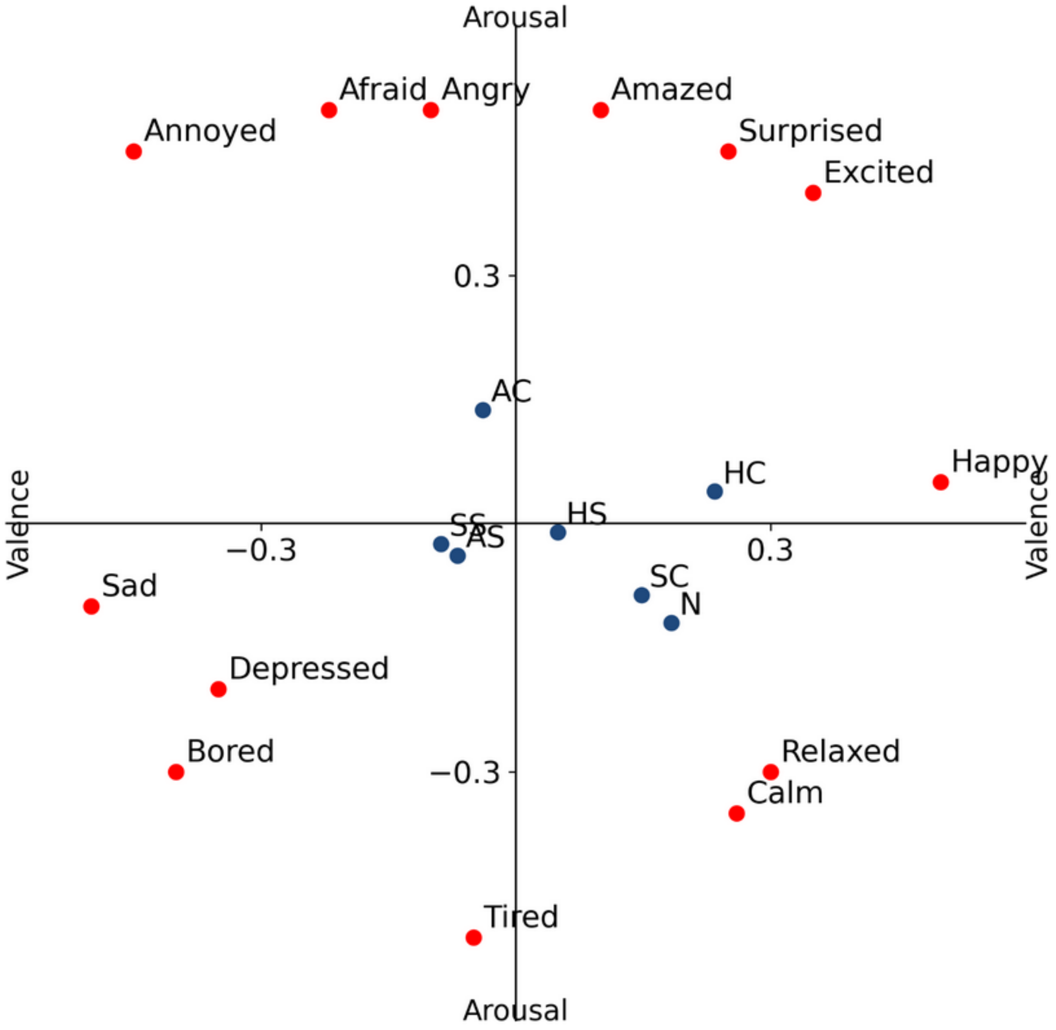

Figure 4.3: Russell's circumplex model of emotion depicting macro-movements in blue dots and standard emotions in red.

In Section 4, according to the results (Table 4.2), only 51.0% of respondents perceived the HAPPY video with a positive valence. Regarding the SAD micro-movement, 50.0% of participants attributed a negative valence to it. Participants

Table 4.2: Percentage of Polarized Emotions associated to Micro-Movements Videos (Happy, Sad and Angry)

Polarized emotions	**HAPPY**	**SAD**	**ANGRY**
Positive	51.0	7.0	19.0
Negative	32.0	50.0	58.0
Other	17.0	43.0	23.0

Table 4.3: Micro-Movements videos preferences by personality clusters and overall population (%)

	HAPPY	**SAD**	**ANGRY**	**None of them**
L-NEU	44.7	26.3	18.4	10.5
L-OPE	29.0	32.3	9.7	29.0
H-CON	56.3	6.3	21.9	15.6
L-CON	46.4	14.3	17.9	21.4
Overall population	44.0	20.0	17.0	19.0

assigned a negative valence to the ANGRY micro-movement in 58.0% of cases. Notably, 43.0% of respondents chose the answer option 'other.'

For the handover micro-movements in Section 5, the CONFIDENT video was rated as confident (M=5.2), and the SHY video was rated as shy (M=5.6) on the relative Likert scales. Video preferences are detailed in Table 4.3 (last row), with the HAPPY micro-movement receiving the most votes at 44.0%. From the analysis of open answers, 30.3% of participants commented to explain their choice of the preferred video (i.e., HAPPY, SAD, ANGRY). The majority of comments (59.7%) were made by participants who preferred the HAPPY video (44.0%).

At the end of the content analysis of the open answers for Section 4, it was possible to extract a total of six macro-categories regarding the micro-movements of HAPPY, SAD, and ANGRY videos, namely: i) "it expresses or conveys emotion," where the comments were more focused on describing emotion (e.g., Participant (P)63, "I choose it because it is more emphatic"); ii) "Faster or more direct," where the comments given were about the time efficiency to achieve the handover result (e.g., P16 "I prefer this video because I perceived the robotic arm as most straightforward"); iii) "Playful," where the comments highlighted the sensation that the robot was inviting them to play a game (e.g., P40, "It is more playful"); iv) "Positive or human-like movement," where participants liked the similarity to human behavior (e.g., P95 "The movement is more articulated"); v) "Predictability of movement," where participants liked the easy movement and the fact that they could predict what the robot was going to do next (e.g., P9 “Clearer movement that avoids fear in the user”); vi) “Similar to a pet,” where participants liked the similarity of the movement to the behavior of a pet (e.g., P42 “It seemed to wag its tail”). Among the people who preferred the ANGRY video (17.0%), the main reasons were the clear emotional content, the fact that it was contradictorily identified as more playful than the other videos, and the more human-like movement of the robotic arm. Finally, those who preferred the SAD video (20.0%) mainly liked it because it was perceived as more direct and faster in terms of duration; indeed, this was the shortest micro-movement. Regarding considerations from the participants that are worth highlighting, P10 liked the ANGRY video because of unexpectedly perceiving it as happier and more human-like than the other videos. On the contrary, P66 preferred ANGRY, associating it with the behavior of an animal, even though perceiving it as slightly creepy.

The percentage of comments received for the handover strategy in Section 5 is 47.2%. The people who preferred the shy attitude perceived the robotic arm micro-movements as being more friendly (27.3%) and easier to empathize with (36.7%). For the confident preference, the focus was on the perception of the micro-movement as being more confident and direct (44.4%), on the shorter duration of this video (13.3%), and on the fact that the action was perceived as predictable (13.3%). Figure 4.4 reports the percentages of the categorizations of the comments made by the participants.

As concerns the handover movements, six macro-categories were identified: i) “Could empathize,” with the robot, where participants felt that the robot carried a higher social load (e.g., P12 “Emotions are more clearly expressed”); ii) “Duration,” where the preference was based on the time constraint for the movement (e.g., P30 “The goal is more rapidly reached”); iii) “Friendly,” where participants felt the robot to be kind and with a positive attitude (e.g., P38 “I prefer this because it’s sweeter”); iv) “More confident and direct,” where the movement made to achieve the task is the most direct (e.g., P35 “More confident, fast and safe”); v) “Perceived safety,” where participants liked the robot for not invading their space (e.g., P0 “It is more in my comfort zone”); vi) “Predictable action,” where the participants liked the fact of being able to predict the trajectory of the robotic arm (e.g., P14 “More efficient and predictable”).

Subsequently, the analysis focuses on RQ.2: is the perception of the robot influenced by sociodemographic information and/or past experiences? For the three groups of past experiences, the Cohen’s D value is lower than 0.2 (small effect size), and p-values are non-significant. Therefore, it is possible to affirm that exposure

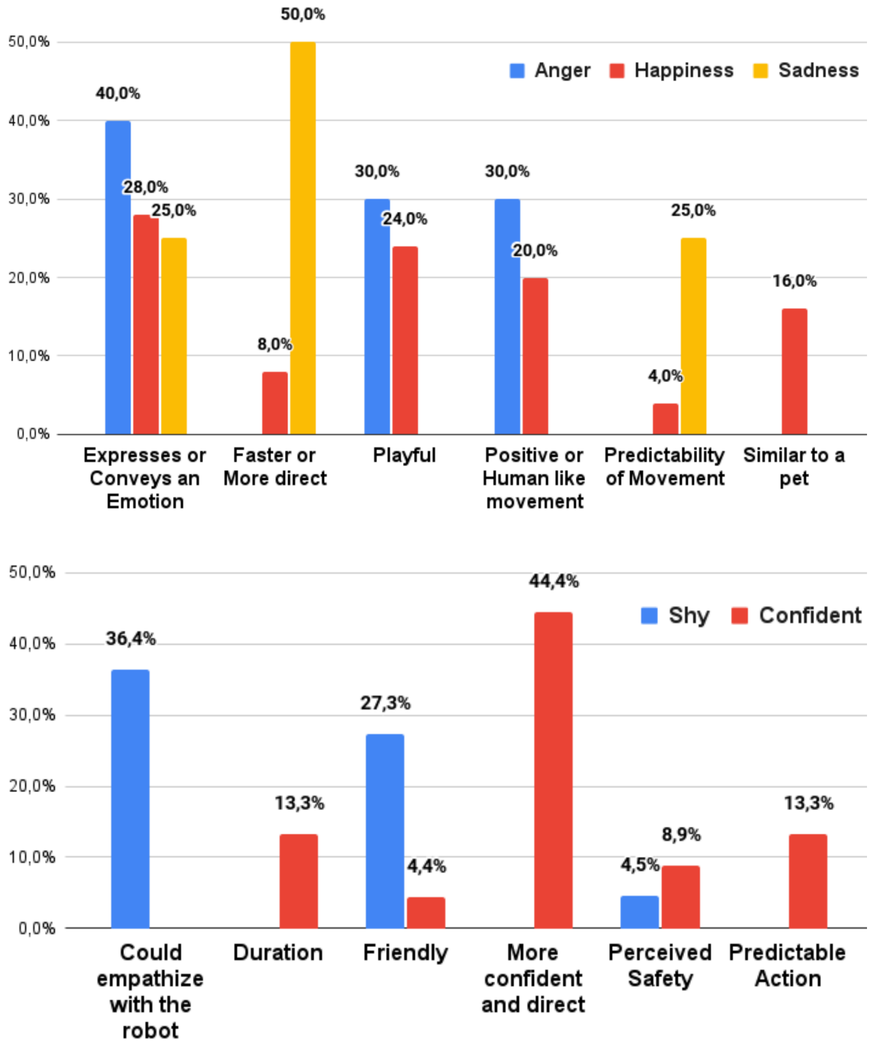

Figure 4.4: a) Categories extracted after cluster analysis of open answers in S4, b) categories from open answers in S5.

to particular life experiences (e.g., owning a pet or not, having experience in dance or not, etc.) does not influence the perception of the emotion elicited by the robot arm. A similar study was performed on sociodemographic data, where the answers related to the macro-movements of Section 3 were examined . This analysis also did not highlight any significant values. Therefore, in this context, the results suggest that past experiences and sociodemographic features do not impact the perception of robotic movement in this study.

Finally, the results related to RQ.3: is the perception of the robot influenced by different personality traits? The K-Means clustering technique allowed the extraction of four clusters of participants' personalities. Each cluster was named after the pre-

Table 4.4: BFI dimensions mean values for each of the clusters: Extroversion (EXT), Agreeableness (AGR), Conscientiousness (CON), Neuroticism (NEU), Openness (OPE)

	EXT	**AGR**	**CON**	**NEU**	**OPE**
L-NEU	7.6	8.1	7.6	4.4	8.6
L-OPE	5.8	6.9	7.8	5.7	5.9
H-CON	8.0	8.3	8.7	7.4	8.5
L-CON	6.0	6.0	6.4	7.0	8.3

dominant difference in mean values for the 5 BFI dimensions, with the suffix low (L) and high (H), depending on the most relevant dimension (Table 4.4). The first cluster, characterized by low neuroticism and high mean values for the other dimensions (Cluster L-NEU), proved to be the most numerous (38 participants). The second cluster showed particularly low openness (Cluster L-OPE) and comprised 31 participants. The third cluster, which attracted 32 participants, had high mean values for all personality dimensions and more specifically higher conscientiousness (Cluster H-CON), while Cluster L-CON (28 people) is differentiated from the others by low conscientiousness. The names given to the different clusters exemplify their personality traits. The Kruskal–Wallis test by ranks confirmed ($p < .001$) that this is the optimal number of clusters to consider. Results of this analysis are reported in Table 4.5, while in Table 4.6, it is possible to check the post-hoc analysis.

Table 4.3 depicts the video preferences for each personality cluster. Statistical analysis did not highlight any significant difference against a random distribution, neither cluster-wise nor for the overall sample of participants. The percentage of people that assigned one of the possible labels (“positive,” “negative,” or “other”) for each micro-movement according to the personality cluster is reported in Tables 4.7, 4.8, and 4.9 for HAPPY, ANGRY, and SAD micro-movement videos, respectively. Cluster L-OPE was the only one that did not show significant differences with respect to a random distribution of answers for any of the micro-movements. Another point to note is that participants characterized by L-NEU and H-CON were able to identify the ”negative” feeling with high accuracy (Tables 4.7, 4.8, 4.9), but were not able to distinguish the HAPPY micro-movement (”positive” feeling).

4.4 Discussion

The primary aim of this paper was to investigate the user’s perception of emotion linked to the movement of a robotic arm during a handover task. This study confirms

Table 4.5: Results of the Kruskal-Wallis test on the 4 clusters

	df	**H test**	**Effect size (η^2)**
EXT	128	37.49 [1]	0.32
AGR	128	53.30 [1]	0.41
CON	128	37.29 [1]	0.33
NEU	128	70.62 [1]	0.49
OPE	128	57.61 [1]	0.52

[1] represents $p < .001$, Extroversion (EXT), Agreeableness (AGR), Conscientiousness (CON), Neuroticism (NEU), Openness (OPE)

Table 4.6: Post-hoc analysis of Kruskal-Wallis test for Extroversion (EXT), Agreeableness (AGR), Conscientiousness (CON), Neuroticism (NEU), Openness (OPE) dimensions.

	EXT	**AGR**	**CON**	**NEU**	**OPE**
L-OPE vs L-NEU	$< .001$	*n.s*	$< .001$	.007	$< .001$
L-OPE vs H-CON	*n.s*	$< .001$	$< .001$	*n.s*	*n.s*
L-OPE vs L-CON	*n.s*	$< .001$	$< .001$	$< .001$	*n.s*
L-NEU vs H-CON	$< .001$	$< .001$	*n.s*	$< .001$	$< .001$
L-NEU vs L-CON	$< .001$	$< .001$	*n.s*	$< .001$	$< .001$
H-CON vs L-CON	*n.s*	*n.s*	*n.s*	$< .001$	*n.s*

All the p-values are corrected by Bonferroni. n.s. is for non-significant values.

that Laban movement theory can be very useful if applied to the robotic field since it offers a formalization of movements that allows the creation of emotional movement, even on agents of unusual shape (in this case, a robotic arm), traditionally not used for social and emotional purposes. However, the results point out that the perception of the robotic arm emotional micro-movements by users is slightly inconsistent.

From Figure 4.3, it is possible to notice how the macro-movements that are composed using the SHY micro-movement are affected by a leveling effect that makes the users rate these movements with very low arousal and low valence. Contrarily,

Table 4.7: Polarized emotion by Cluster for HAPPY Video (%)

	L-NEU	**L-OPE**	**H-CON**	**L-CON**
Positive	44.7	45.2	62.5	60.7
Negative	36.8	29.0	21.9	32.1
Other	18.4	25.8	15.6	7.1
	$\chi^2_2 = 2.69$	$\chi^2_2 = 1.19$	$\chi^2_2 = 5.39$	$\chi^2_2 = 6.97$
	p *n.s.*	p *n.s.*	p *n.s.*	$p = .031$
	$\varphi_c = 0.19$	$\varphi_c = 0.14$	$\varphi_c = 0.29$	$\varphi_c = 0.35$

Table 4.8: Polarized emotion by Cluster for ANGRY Video (%)

	L-NEU	L-OPE	H-CON	L-CON
Positive	7.9	25.8	15.6	25.0
Negative	73.7	41.9	68.8	46.4
Other	18.4	32.3	15.6	28.6
	$\chi^2_2 = 14.45$	$\chi^2_2 = 0.66$	$\chi^2_2 = 9.00$	$\chi^2_2 = 0.70$
	$p < .001$	p *n.s.*	$p = .011$	p *n.s.*
	$\varphi_c = 0.32$	$\varphi_c = 0.10$	$\varphi_c = 0.38$	$\varphi_c = 0.11$

the CONFIDENT micro-movement increases such measures. This can guide to the conclusion that the straight and fast movement is preferable because people perceive it with more strength (regardless of perceiving it positively or not). Furthermore, the AC macro-movement seems the one more aligned with expected values of valence and arousal, being placed on the line that connects the origin of the circumplex with the angry emotion coded by Russel. Similarly, also the HC macro-movement looks well-placed; to summarize, people's perception is increased by confident-like moves, and happy or angry behavior impacts the perception of robotic movements in terms of the strength of valence and arousal.

It is worth highlighting the N macro-movement, which is close to the "Bored" and "Calm" emotions of Russel; this is explained by people relating an automatic movement without any emotional intention to a relaxing movement.

Examining the results for Sections 4 and 5, users demonstrated the capability to recognize all the micro-movements with limited accuracy (Table 4.2), slightly surpassing fifty percent, and individuals did not exhibit a clear preference for the movement modeled as positive (Table 4.3). This suggests that micro-movements based on Laban's theory are not unambiguously perceived by participants. The ANGRY micro-movement was recognized as "negative" by 58.0% of participants (Table 4.2),

Table 4.9: Polarized emotion by Cluster for SAD Video (%)

	L-NEU	L-OPE	H-CON	L-CON
Positive	2.6	12.9	6.3	7.1
Negative	50.0	38.7	50.0	57.1
Other	47.4	48.4	43.8	35.7
	$\chi^2_2 = 12.67$	$\chi^2_2 = 3.36$	$\chi^2_2 = 7.97$	$\chi^2_2 = 5.89$
	$p = .002$	p *n.s.*	$p = .019$	p *n.s.*
	$\varphi_c = 0.41$	$\varphi_c = 0.23$	$\varphi_c = 0.35$	$\varphi_c = 0.32$

indicating that this movement is the most easily understood. This result suggests that participants were better able to discern the LMA features of this movement. Generalizing this finding, it is possible to assume that negative emotional movements are easier to understand. Notably, a high proportion of participants grouped their answers as 'other' (Table 4.2). This result suggests that when individuals encounter new technology, their initial impressions don't tend to lean distinctly towards a positive or negative perception, as explained in [85].

Regarding the evaluation of ratings to define the CONFIDENT or SHY movement, participants correctly identified the information in the two videos. Indeed, participants preferred the confident movement because it is more direct and shorter (4.4). This finding reinforces the concept that straight micro-movements of short duration are preferred by participants in experiments and should be used in future studies and implementations. This finding contrasts with the LMA theory, which typically associates straight trajectories with negative feelings, such as anger and sadness. This perspective on future development for social movement in a robotic arm suggests that relying solely on LMA may not be sufficient to encode social features. Other features to be considered are certainly the duration of the interaction and the final robotic task (i.e., handover) that will affect the perception of movement; it is possible to summarize this topic as the *context-problem*. For practical purposes, or for tasks that involve a clear objective (e.g., handover, manipulation), people prefer the efficacy of movement over social features. In impractical tasks (e.g., social interaction, entertainment), movements that are not straightforward might be equally appreciated by the participants.

The results of the personality study indicate that individuals characterized by different personality traits are influenced in varying ways by the robotic arm micro-movements (RQ.2). The findings align with other studies that have underscored the impact of openness or neuroticism on human perception of robots [57, 86]. Openness refers to the capacity for creativity and receptiveness to new ideas, while neuroticism pertains to the tendency toward stress and anxiety.

The results highlight how the L-OPE group, characterized by low openness, is less likely to perceive a robotic arm as capable of expressing an emotional load. According to personality descriptions, individuals with low openness tend to have less preference for variety and novelty. For this reason, this group is the only one with a randomized answer pattern for all three videos (see Tab.4.9). Another notable point is that the L-CON group is the only one that has significantly identified the HAPPY video compared to a random distribution. L-CON is characterized by low conscientiousness (low diligence and seriousness), combined with a high level of openness in this cluster. This seems to amplify the impact of openness, increasing the perception of positive movement while not significantly impacting the perception of negative ones. The last finding is that in this study, neuroticism is not a factor affecting how emotions are perceived. In fact, the groups L-NEU and H-CON gave similar ratings to the videos and obtained significant differences against a random distribution for the SAD and ANGRY videos. Their main difference lies in the value of neuroticism; therefore, this result suggests that this dimension is not relevant in the perception of the robotic arm moving according to LMA.

According to the state of the art, user profiling is crucial to providing effective social robot intervention. In the future, robots should consider demographic data, user preferences, and clinical profiles to offer tailored services. In this sense, based on the current findings, it is important to also consider human personality traits in the definition of the user profile, as they seem to affect the perception of robots.

Furthermore, according to the overall findings, it appears that when dealing with the emotional perception of robots, openness and conscientiousness personality traits are the most influential.

As for the study's limitations, the sample utilized was a convenient sample. Secondly, it would have been beneficial to include patients engaged in the rehabilitation process or those with cognitive disabilities or lower educational levels. Generic users were chosen, as a compromise due to the difficulty in finding patients available for such a study, making the generalization of these results challenging.

Third, the qualitative component of the questionnaire was limited compared to the quantitative part, despite yielding very interesting findings. Finally, the questionnaire was conducted online, limiting users from interacting with the robot in a real context.

Future research should focus on developing and validating dedicated open-ended questions to collect relevant information and serve as a control tool for close-ended survey responses. To achieve this, establishing stronger collaborations with psychologists and sociologists for the design and interpretation of open-ended answers would be beneficial.

Further studies should delve into identifying the factors that trigger conflicting perceptions and contribute to shaping coherence in understanding robotic arm movements. It's important to note that these findings could be valuable references for future studies involving individuals with cognitive and physical impairments, as certain conditions may significantly influence interactions with robots.

Additionally, future research should validate this study by conducting long-term tests of Laban Movement Analysis (LMA) through repeated in-person interactions between individuals and robotic arms. This validation process should observe how people's perceptions evolve during these interactions.

4.5 Conclusion

In summary, this paper delved into the exploration of utilizing a robotic arm to express emotions, substantiating the applicability of Laban Movement Theory in modeling emotional expressions and enhancing human-robot interaction. Notably, participants exhibited a preference for faster and more direct movements, indicating a favorable inclination towards the mobile robotic arm. This study has also illuminated the significant influence of participants' personalities on the perception of emotional movements in a robotic arm. This underscores the imperative of customizing rehabilitative therapies to align with individual patient personalities, biological factors, and cognitive characteristics.

However, the study brought to light that beyond Laban's theory, the context and the specific robotic task significantly influence movement perception, encapsulating what can be termed the *context-problem*. The findings suggest the feasibility of implementing emotionally loaded movements in a robotic arm, providing insights for designing rehabilitative robots that can foster social interactions during physical exercises. While different movements trigger diverse responses, the absence of a singular interpretation emphasizes the importance of meticulous movement design. Consideration of Laban dimensions, application context, and participants' personality traits should be integral in this process.

In conclusion, this investigation demonstrated that the personality of participants shapes their perception of the emotional movement in the robotic arm. This reinforces the necessity of tailoring rehabilitative therapies to individual personalities, as well as accounting for biological and cognitive characteristics in patient-centric interventions. The ensuing chapter will delve into specific challenges that remain in the implementation of emotionally expressive robotic movements and propose avenues for addressing these complexities in future research.

Chapter 5

On the Optimal Configuration of Social Cues for a Robotic Arm in Rehabilitation and Human-Robot Interaction

This chapter [1] provides a critical examination of the concepts revealed in the preceding results, focusing particularly on the theme of robotic movement and HRI. Given the intricacies associated with this pivotal theme, a meticulous exploration and comprehensive elucidation are imperative. The objective is to extend the prior work by presenting a thorough analysis, thereby contributing significantly to the overall comprehension of the optimal strategies for defining Laban movements on a robotic arm and the desirable combination of social cues. The chapter concludes by unveiling the most effective social configuration for a robotic arm and outlining guidelines for further development in that direction.

5.1 Reasons for the study and research question

In the previous chapter it was possible to establish that participants exhibited a preference for faster and more direct movements, indicating a favorable inclination towards the mobile robotic arm. Moreover, there was evidence of the significant influence of participants' personalities on the perception of emotional movements in

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[1] adapted from *"On the Optimal Configuration of Social Cues for a Robotic Arm in Rehabilitation and Human-Robot Interaction." **Carlo La Viola**, Laura Fiorini, Gianmaria Mancioppi, Filippo Cavallo, 2024, International Journal of Social Robotics (SUBMITTED)* and *"Investigating the role of different social cues in the human perception of a social robotic arm." **C. La Viola**, L. Fiorini, G. Mancioppi, and F. Cavallo, 2022 14th Springer International Conference on Social Robotics (ICSR), 2022, ALTRUIST Workshop (Oral Presentation)*

a robotic arm. This underscores the need for customizing rehabilitative therapies to align with individual patient personalities. However, the previous study presented some limitations, namely the fact that the HRI was not physical but only achieved thorugh videos, and that the only involved robotic social feature was movement.

From these considerations, the study present in this chapter was conceived and its basic components are posed on the previous results. In fact, the Laban movements used in this stydu are the ones mostly preferred in the prevous one. Starting from the previous limitations, this study aims at understandingn how social cues can impact the overall physical HRI with a robotic arm, what are the preferred combinations of social cues, and finally, to verify that different personality traits influence the overall perception of the robot. Therefore, the first research question (RQ.1) is: "How the robotic arm movement is perceived when the participant is physically in front of the robot?". Next, the second research question (RQ.2) is "What is the preferred social cues configuration on the robotic arm, for users that interact with it?". The third question (RQ.3) is focused on the personality differences, so it will be: "What correlation is there between the personality of participants and their responses to the experiment to understand?".

5.2 Matherials and Methods

5.2.1 Design of Social Cues

This study aims to determine optimal combinations of social cues for effective human-robot interaction (HRI) and task achievement. Three social cues are considered in the study.

The first implemented cue is the face/gaze social cue, recognized for its crucial role in HRI [87]. Drawing from the work of Sorrentino *et al.* [28], the chosen face/gaze presentation incorporates eye expressions, including blinking and movement. The positive evaluation of this presentation in a previous field test involving a wheeled social robot for interaction with older adults and disabled individuals influenced its inclusion in the current study.

The second considered social cue is non-verbal sound, acknowledged for its impact on perceptual and objective measures in HRI, as detailed in Zhang *et al.* [30]. In this study, the sound is inspired by the sonification of UR5 movements. Programmed using the pygame library, the sound features an initial descending C Major arpeggio, followed by a G Major chord (5th), an F Major chord (4th), and concludes with an ascending C Major arpeggio. Chord changes are triggered by specific events in the robot's movement, such as ball picking, handover, session start, and session end.

The third social cue incorporated in this work is robotic movement, which characterizes human body movements based on the Laban Movement Analysis (LMA) components of effort and space. The movements are developed as outlined in Section 2.3 and depicted in Figure 5.1. This study distinguishes itself from previous research for two main reasons: i) it selectively employs the most preferred movements from prior studies; ii) it systematically tests these movements with different social cues to determine the most effective combination for HRI.

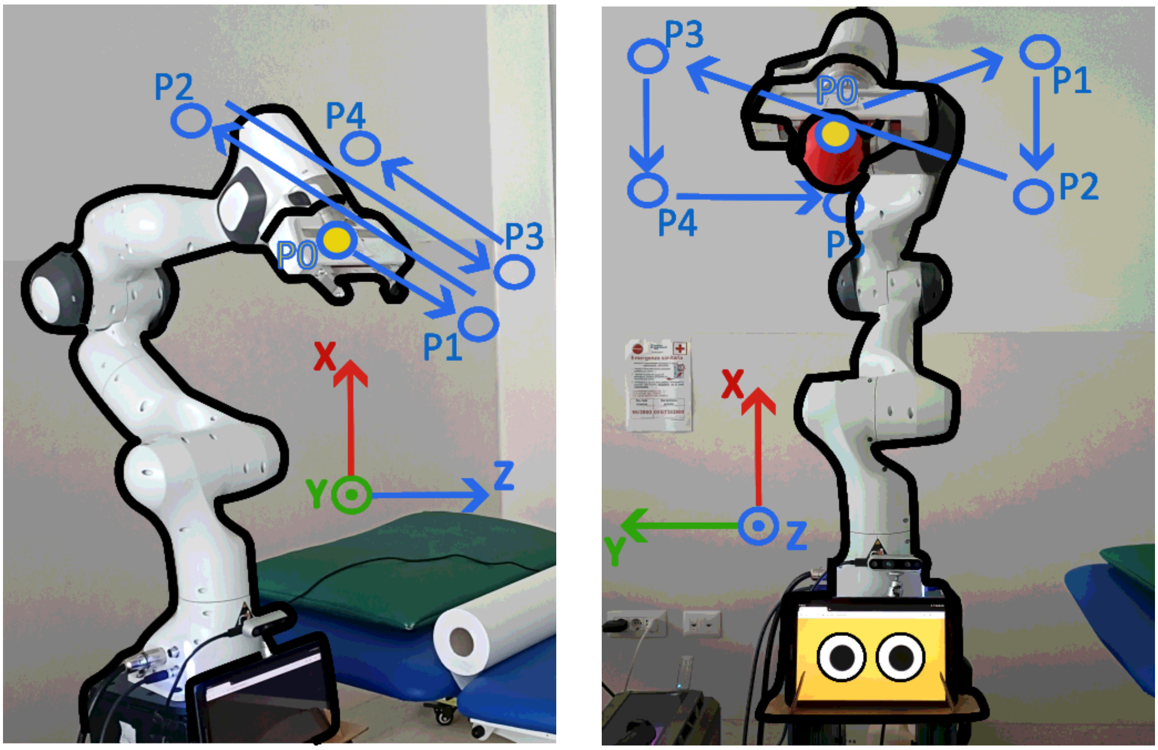

Figure 5.1: Depiction of the robotic arm movements. a) direct movement, b) indirect movement.

5.2.2 Participants

A study was conducted with a total of 31 healthy young individuals, comprising researchers, medical doctors, psychologists, and nurses, who voluntarily participated in the experiment. One participant, who encountered technological setup failure, was subsequently excluded from the study. The remaining thirty participants consisted of 61The mean age of the participants was 30.4 years, with a standard deviation of 3.7. Prior to the experiment, participants received comprehensive information about the test and a written description of the experiment. All participants provided their informed consent for participation. The study received approval from the Ethical Committee for Research of the University of Florence (prot. 0077883 of 06.04.2023).

5.2.3 Experimental Procedure

The participants are tasked with performing a task that involves receiving a colored ball from the robotic arm and placing it in a box of the same color. Social cues will be tested in four possible conditions: movement only (M), movement and face (MF), movement and sound (MS), and movement, sound, and face (MFS). Each condition will be tested with two types of movements, direct and indirect, resulting in eight trials for each participant.

The experiment comprises four main phases (Fig.5.2): i) collection of socio-demographic data; ii) robotic arm movement; iii) human-robot ball release; iv) questionnaire about the interaction. The robotic arm movement phase (ii) consists of five main blocks: i) turning toward the colored balls; ii) approaching and picking up a ball; iii) turning toward the user; iv) approaching and releasing the ball; v) returning to the idle position. Following the completion of the robotic arm movement phase, the human-robot ball release phase (iii) begins. During this phase, participants receive a ball from the robot and place it in a dedicated box matching the ball's color. At the end of each interaction, participants are asked to complete a questionnaire to assess their experience during that session.

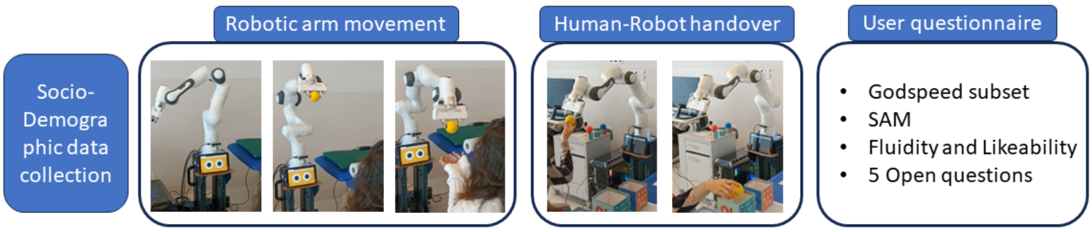

Figure 5.2: Experimental procedure for the second experiment.

The system randomly determines the combination of social cues, movement, and the color of the ball to pick until all possible combinations are exhausted.

The questionnaire consists of two parts: in the first part, participants rate the interaction based on six parameters. Two parameters are defined from the Self-Assessment Manikin (SAM) [80], specifically valence and arousal; other two parameters are components of the Godspeed questionnaire [88], namely animacy and safety. The last two parameters, relative to fluidity and likability of the movement, were purposefully designed for this experiment. Data are collected on a scale of 1 to 9 for SAM values and a scale of 1 to 5 for fluidity, likability, and the Godspeed questionnaire questions. In the second part of the questionnaire, participants are asked five open-ended questions to obtain qualitative feedback. The questions include: 1) Your opinion on the movements. 2) Your opinion on the sound. 3) Your opinion on the face. 4) Did the movements evoke any emotion or sensation? 5) If you were to bring the robot home for personal use, which configuration of sound, face, and movement would you prefer? This study will only examine the answers to question 5.

5.2.4 Data Analysis

The Godspeed responses for animacy and safety were combined into a single value, which was then reported on a scale from 1 to 5. Similarly, values for fluidity and likeability were reported on the same scales. The SAM values, representing valence and arousal, were maintained on a scale from 1 to 9 following the standard test protocol.

To assess statistical significance, a Wilcoxon test was conducted for pairwise comparisons among different social cue configurations for each of the two movements.

Personality information gathered at the start of the experiment was utilized to categorize participants into two clusters based on levels of openness: one with high openness (HO) and another with low openness (LO). Openness is one of the Big Five personality traits and is associated with characteristics such as creativity, curiosity, and a preference for novelty. This categorization was achieved through the application of a K-Mean clustering technique, as previously employed in the preceding chapter.

Once the personality groups were identified, the results were correlated with open-ended responses. Context analysis, as per Krippendorff's method [89], was employed to extract preferences related to preferred movement and condition from the open-ended responses. The results of the open-ended answers were then visualized and discussed based on their distribution within the respective personality clusters.

5.3 Results

All the questionnaire scores are presented in Table 5.2 for the direct movement and Table 5.4 for the indirect movement. Each column in these tables corresponds to a specific parameter from the questionnaire, and for each parameter, the conditions are listed, starting with the condition involving only movement (M) and concluding with

Table 5.1: BFI scores for the two clusters of people. The columns named with the initials represent the BFI dimensions of Openness (O), Extroversion (E), Agreeableness (A), Conscientiousness (C), and Neuroticism (N)

	O	**E**	**A**	**C**	**N**
LO	5.4	6.0	7.1	7.0	5.2
HO	8.8	5.9	6.4	7.1	6.4

the condition incorporating face, sound, and movement (MFS). Significant values are highlighted in Table 5.3 and in Table 5.5 for the two movements.

Analyzing the direct movement, statistical significance is observed for the features of valence, fluidity, and animacy. In the first two cases, the MFS condition exhibits the highest mean values, while the latter has a value equal to the other conditions. Significant differences can be found in comparisons between M and MFS for the first two features and between MF and MFS for fluidity.

Turning to the indirect movement, statistical significance is noted for the arousal and fluidity features. The MS condition has the highest mean value for arousal and is statistically significant when compared against the N and SF conditions. For fluidity, the SF condition is rated the highest, and statistical significance is observed when comparing this condition against M and MF.

Utilizing the K-means clustering technique, the authors identified two clusters based on participants' BFI scores. The primary distinction between the two groups lies in the openness component, designating the clusters as High Openness (HO) and Low Openness (LO). These groups comprise 13 and 17 individuals, respectively, with Openness values of 8.82 and 5.36 on a scale from 2 to 10 (Table 5.1). Subsequently, a comparative analysis was conducted for all conditions of each feature, considering the division into HO and LO clusters.

The examination of preferences derived from the open-ended responses, as depicted in Figure 5.3, indicates a prevailing inclination towards the MFS condition and the indirect movement for both clusters. Specifically, the MFS condition emerges as the most preferred choice for participants in their interactions with the robot, as illustrated in Figure 5.3, and this trend holds true for both the HO and LO clusters. A notable majority favored the MFS condition, with a small percentage showing preference for the MS condition (17.7% LO and 7.7% HO) or the MF condition (11.8% LO and 38.5% HO). The indirect movement garnered preference from the majority of participants (52.9% LO and 46.1% HO), with only a minor percentage expressing a preference for the direct movement. Additionally, a considerable portion of participants (40.0%) did not specify a preference for a particular movement.

Table 5.2: Mean values for all the answers of participants for the DIRECT Movement. The columns represent the answers regarding Valence (V), Arousal (Ar), Likeability (L), Fluidity (F), Animacy (An), and Safety (S)

Condition	**V**	**Ar**	**L**	**F**	**An**	**S**
M	6.3 ± 1.5	4.7 ± 1.4	3.8 ± 0.8	3.7 ± 0.8	1.5 ± 0.4	3.0 ± 0.7
MF	6.6 ± 1.5	4.9 ± 1.7	3.7 ± 0.9	3.3 ± 1.0	1.6 ± 0.4	3.1 ± 0.7
MS	6.4 ± 1.3	4.6 ± 1.4	3.9 ± 0.8	3.7 ± 0.8	1.6 ± 0.2	3.1 ± 0.6
MFS	6.7 ± 1.3	4.9 ± 1.8	4.0 ± 0.7	3.7 ± 0.9	1.7 ± 0.3	3.1 ± 0.7

Table 5.3: Significant *ps* from the comparison of the different conditions for each dimension of the questionnaire for the Direct movement

Conditions	**Dimension**	***ps***
M vs MFS	Valence	.043
MF vs MFS	Fluidity	.032
M vs MFS	Animacy	.015

Table 5.4: Mean values for all the answers of participants for the INDIRECT Movement.

Condition	**V**	**Ar**	**L**	**F**	**An**	**S**
M	6.5 ± 1.5	4.6 ± 1.7	3.9 ± 0.9	3.8 ± 0.8	1.6 ± 0.4	3.1 ± 0.8
MF	6.5 ± 1.5	4.9 ± 1.6	3.9 ± 0.6	3.6 ± 0.8	1.7 ± 0.3	3.2 ± 0.6
MS	6.5 ± 1.4	5.4 ± 1.6	4.0 ± 0.7	3.9 ± 0.8	1.7 ± 0.3	3.4 ± 0.9
MFS	7.0 ± 1.2	5.0 ± 1.6	4.1 ± 0.7	4.1 ± 0.6	1.7 ± 0.3	3.3 ± 0.7

Table 5.5: Significant *ps* for the Indirect movement

Conditions	**Dimension**	***ps***
M vs MS	Arousal	.033
Ms vs MFS	Arousal	.041
M vs MFS	Fluidity	.011
MF vs MFS	Fluidity	.005

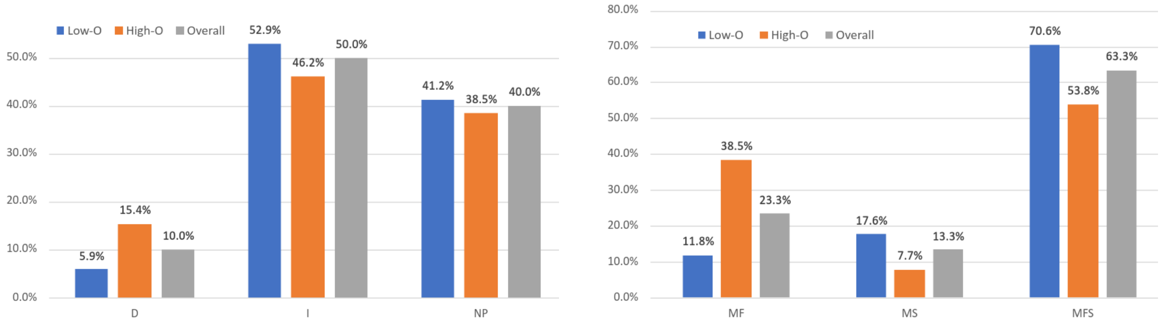

Figure 5.3: Preferences of participants by the overall sample and the by the two groups for a) Movement and b) Condition. In histogram **b**, no preference was assigned to the condition with only movement (M).

5.4 Discussion

The primary objective of this paper was to determine the optimal social cue configuration for a robotic arm and explore whether specific personality traits influence the robot's perception. The study concludes that the most effective configuration involves the simultaneous presence of all social cues, namely movement, face, and sound. In the case of indirect movement, the dimensions most influenced by varying social cue combinations are arousal and fluidity. Arousal, representing the perceived emotional intensity, exhibits the highest mean value in the MS condition, with statistical significance compared to M and MFS. This suggests that nonverbal sound plays a crucial role in communicating the intensity of an emotion expressed through a Laban movement. The fluidity dimension attains maximum significance in the MFS condition, indicating that the combined presence of face and sound is essential for enhancing movement perception. The inclusion of face and sound potentially renders the robot more lifelike, contributing to a superior perception by participants who attribute more biological-like features to the robot. Despite this, responses regarding animacy do not reveal variations, implying that such perceptions might be unconscious. Similar patterns emerge in the direct movement, where the significance of valence, fluidity, and arousal dimensions consistently appears against the MFS condition. This underscores the importance of a comprehensive set of social cues for improved perception across these dimensions. Notably, the fluidity dimension exhibits the same pattern for both movements, reinforcing the earlier observations. The quantitative analysis strongly supports the relevance of the MFS social cue condition in influencing diverse perceptual dimensions. These findings align with qualitative analysis outcomes obtained through open-ended questions.

The second key outcome of this study underscores the preferred social cues configuration and movement based on personality traits, defined as the MFS condition and the indirect movement. This result aligns with the findings of a prior investigation, reinforcing the idea that participants favor indirect movements and a broader set of social cues for improved human-robot interaction (HRI) and user acceptability. This consistency across studies enhances the reliability and robustness of the identified patterns. However, several noteworthy points deserve attention. Regarding the preference for the best condition, an opposing pattern emerges between the LO and HO groups. The LO group places significant importance on sound as a social cue, as reflected in their preferences for conditions containing it. Individuals with lower openness may find non-verbal sounds more comfortable or familiar, perceiving them as less complex or overwhelming than facial expressions. This sense of familiarity may contribute to a feeling of predictability and reduced anxiety during interactions. Conversely, the HO group exhibits a strong preference for the MF condition and a very low preference for MS. Faces serve as powerful conveyors of emotions and expressions, and those with high openness may appreciate the complexity and richness of emotional expression conveyed through facial features. A robot with a face can offer a broader range of emotional cues, thereby enhancing the overall interactive experience.

Regarding the preferred movement, the majority opts for the indirect movement, although a significant number of people do not select a specific option. In this case, personality does not seem to exert a significant impact on perception. This lack of influence can be due to the "context-problem"; the movement, despite being designed with social features, is closely tied to task execution. Thus, it becomes challenging to evaluate it independently of this task-related context. Recognizing this as a limitation of the study, future research will explore alternation between social movement and task-related movement within the HRI context.

The limited sample size that gave us a limited statistical power can be addressed as another limitation; the aim in future studies will be to recruit more people and to test further the influence of personality in the perception, taking into account the other points of variability of the system (context, personal information, interaction scenario).

5.5 Conclusion

This experiment aimed to observe human reactions when interacting with a robotic arm performing Laban movements in close proximity. It also sought to identify the optimal combination of social cues for achieving effective HRI. Additionally, the most preferred movement was determined among the two modeled for this experiment. In conclusion, it was investigated the feasibility of incorporating social interaction into a rehabilitation task involving a handover between a robotic arm and a human. The findings of this study confirm and build upon previous results [31], providing insights for future experiments. The focus will shift towards exploring the best combinations of movement and social cues in various tasks.

While this work contributes valuable insights, it has some limitations, such as the relatively small sample size and the inclusion of only healthy subjects for testing the proposed task. Future research will leverage the configurations and characteristics defined in this study as the foundation for developing innovative HRI scenarios in the field of rehabilitation.

Chapter 6

Insights into Social Robotics: A Journey through Japanese Innovation

[1] During this PhD work there was the possibility to undergo a period as a visiting student in the Advanced Telecomunication Reserch Institute International (ATR). ATR is a leading research institute in the field of information and communication technologies, headquartered in Kyoto, Japan. Established in 1986, ATR is a private organization that focuses on cutting-edge research and development to advance telecommunications, robotics, and various interdisciplinary areas. ATR is known for fostering collaboration between academia, industry, and government agencies. The institute conducts both basic and applied research with the aim of contributing to technological advancements and societal well-being.

ATR has made significant contributions to the field of robotics, particularly in the development of innovative technologies and systems. The institute's robotics research spans various domains, including social robotics, human-robot interaction, and artificial intelligence. ATR's robotics initiatives often aim to create intelligent and adaptive robotic systems that can seamlessly integrate into human environments. Researchers at ATR have been involved in projects ranging from humanoid robots to assistive devices, exploring the potential of robotics to enhance human lives. The institute's multidisciplinary approach, combining expertise in telecommunications, artificial intelligence, and robotics, positions ATR at the forefront of technological innovation in the realm of robotics. The collaborative and forward-thinking environment at ATR

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[1] Adapted from *"Teleoperation and Human-Robot Interaction in Public Spaces: Insights from a Field Study at the Avatar Festival.",* ***Carlo La Viola****, Laura Fiorini, Gianmaria Mancioppi, Shogo Nishimura, Arne Hitzmann, Yukiko Horikawa, Filippo Cavallo and Takahiro Miyashita,(IN PREPARATION)*

continues to drive advancements in the field, making it a hub for cutting-edge robotics research and development.

During the visiting period, the focus was on achieving a milestone within the Moonshot project [90], specifically targeting Goal 1, which aims to "Overcome limitations of body, brain, space, and time." This objective revolves around leveraging technologies to surpass human limitations. In this context, robotics assumes a paramount role, being the only technology capable of emulating human capabilities in terms of action, reasoning, and perception. As a result, it has the potential to provide a human-like experience even when physically separated from the human body. Moreover, contemporary technologies enable individuals to work in different locations and utilize networks for remote presence, such as telepresence or videopresence. According to this project, the integration of these capabilities represents a transformative value that will redefine the fabric of future society.

Located in Goal 1, this PhD work was performed inside the Interaction Technology Bank (ITB) team, and focused on the deployment of a social robot in real world environments (e.g., shopping mall, museums). Similarly to the main aim of this PhD thesis, the system developed in ITB has three main actors: the participants that socially interact with the robot, the robot itself, and the teleoperator. While the participant can be related to the patient in the big picture of this work, the teleoperator can be related to the therapist, that has the role of supervision and control over the overall HRI.

6.1 Reasons for the study and research question

This research centers on deploying social robots for brief Human-Robot Interaction (HRI) in public spaces. Thrun *et al.* [91] pioneered the introduction of social robots for HRI, emphasizing the significance of social features in enhancing human experiences with robots. Recent studies, such as the work by Babel *et al.* [92], deployed an autonomous robot in a metro station, highlighting the importance of user-centered behavior and adaptability for improving robot acceptability and mission accomplishment.

Horikawa *et al.* [93] identified limitations of fully autonomous robots for HRI, proposing a solution through teleoperation and introducing the Collaborative Avatar Performance Framework (Cybernetic Avatar Platform (CAPF)). They presented a smart teleoperation platform capable of controlling multiple avatars, easing the burden on operators and enabling effective interactions with various users.

Challenges arise in teleoperation, necessitating valid interfaces for operators. Rea et al. [94] tackled teleoperation issues by drawing insights from video games, which excel in avatar control through social techniques. Additionally, Warta et al. [95] demonstrated that a higher level of human likeness positively influences the perception of social features in HRI scenarios.

This study addresses two research questions: 1) What are the strengths and weaknesses of deploying a robotic avatar in a public environment? and 2) What robotic capabilities influence human perception? Both questions are examined from the perspectives of operators and individuals interacting with the robot in a public setting.

The research methodology involves integrating the system implementation of a robotic avatar and the CAPF, executing tasks, and collecting feedback from operators and participants. The study, conducted over 10 days in a shopping mall, concludes with observations drawn from the experimentation.

6.1.1 Teleco Robot features

The robot used in this study was Teleco (VStone, Japan). This robot is composed of two main elements: the rover part and the humanoid part, as depicted in 6.1.

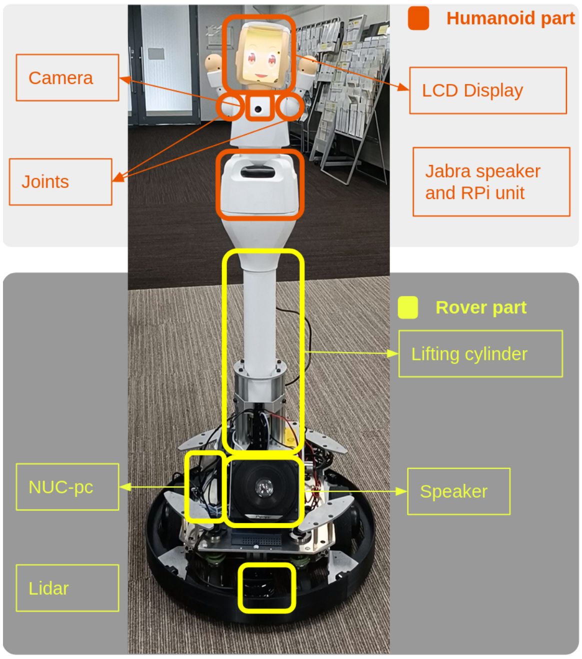

Figure 6.1: Depiction of the Teleco robot and its two main parts.

6.1.1.1 Rover part

This part is composed of a differential drive platform equipped with a 2D Lidar sensor that allows the perception of surroundings and autonomous navigation in unknown environments. In the rover it is also placed the main computing unit of the robot (NUC-pc, Intel, USA), that is in charge of the robotic tasks, and manages the communication with the remote elements (the CAPF and the humanoid part). It also contains the motor drivers which are connected to the NUC unit using USB interfaces. Finally, in this part it is mounted a lifting mechanism that uses a dedicated brushless motor to lift a cylinder and modify the total height of the robot itself. This cylinder has a dedicated driver and it is connected using the USB interface to the NUC unit. The rover is also provided of a speaker unit that allows the NUC to reproduce any sound; in this implementation, the speakers plays non-verbal sounds or reproduces the voice of the teleoperator . Finally, a panic button is provided to stop the robot in case of unexpected behavior and ensure the safety of the people surrounding it.

6.1.1.2 Humanoid part

The humanoid component of Teleco is situated atop the lifting mechanism. It consists of a doll-like humanoid figure crafted from white plastic, featuring an LCD curved screen capable of displaying the Teleco face. The humanoid parts possess various degrees of freedom (DoF): each shoulder has 2 DoF, the base has 2 DoF, and the neck has 3 DoF. The study authors harnessed different combinations of rotations for each DoF to create diverse movements for the humanoid section. An RGB camera embedded in Teleco's torso serves as the sensing component, enabling real-time video streaming of the robot's surroundings. The humanoid is under the control of a Raspberry Pi, that manages the motors for joint movement, and communicates with the central unit via Ethernet connection . Additionally, a Jabra speaker is integrated into the design for playing Teleco's pre-defined sentences with the Teleco synthesized voice.

6.1.2 Social Cues implemented on the Teleco Robot

To facilitate social interaction, the Teleco robot was programmed to exhibit social behavior by leveraging its various capabilities. The facial expressions were displayed on the screen positioned on the face of the humanoid section, synchronized with non-verbal sounds played through the dedicated speaker of the rover. Additionally, the joints of the humanoid part were programmed to move in harmony with the facial expressions and sounds, creating a cohesive social behavior. The subsequent paragraph will delve into a detailed description of the three social cues.

6.1.2.1 Facial expression

The facial expressions were crafted using the functions embedded in the Teleco robot. This editor enables to change the Teleco faces, through a TCP connection, using JSON format messages. Modifying the JSON message allows the adjustment of several facial features, including eye shape, iris position, iris type, mouth shape, face color, cheeks type, eyebrows shape, and eyebrows position. The researchers in this study created a repertoire of faces representing fundamental facial emotions for Teleco by combining various configurations of these elements. As a foundational reference, the study by Casiddu et al. [87] served as a base for developing the unique facial expressions for this work. Drawing inspiration from Ekman et al. [96], their insights were adapted in this work, according to the technological capabilities of this system. Aligning with the aforementioned emphasis on simplicity in interface usage, it is adopted a subset of emotions deemed most suitable for this work's specific usage scenario. Figure 6.2 illustrates the selected emotions.

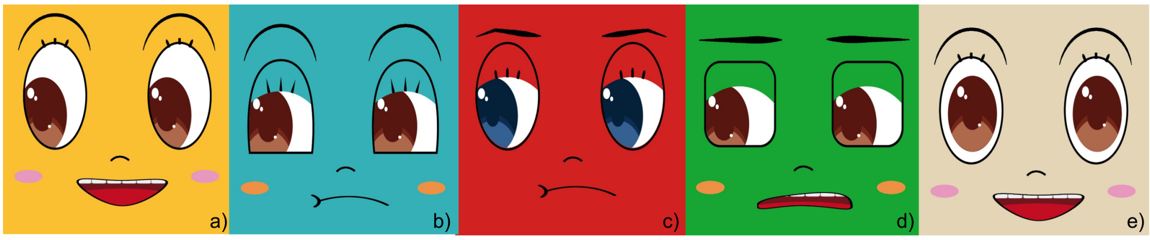

Figure 6.2: Faces developed for the Teleco robot. a) Happy, b) Sad, c) Angry, d) Nervous, e) Neutral

6.1.2.2 Non-verbal sound

The sounds were not individually created for this project but were sourced from an online repository[2]. A specific subset of this collection was utilized, and all sounds were coordinated with changes in facial expressions and joint movements. In determining which sound to associate with each expression, the authors thoroughly listened to the downloaded sound package and carefully selected sounds that complemented the desired behavior of the Teleco robot. Four distinct sounds were chosen and assigned to accompany different facial expressions and movements. Notably, the neutral expression did not have an associated non-verbal sound.

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[2] https://freesound.org/people/Audionauten

6.1.2.3 Joints Movement

The joint movements were built on top of Laban Movements Analysis (LMA), which was introduced in Chapter 2. Based on the information provided in the table, the Teleco's movements were programmed to adjust the various joints accordingly. Specifically, in the case of direct space, the shoulder was rotated only vertically, whereas in the case of indirect space, it was rotated both vertically and horizontally. The speed was determined based on the maximum movement capability of the motors and then adjusted for sad and nervous movements by reducing it. As for weight, it was manipulated by limiting the rotation of the joints: more joints were allowed to move for lighter movements, while only the shoulder (vertical) and the base (horizontal) were allowed to move for heavy movements. Introducing additional intermediate points for the movement of the head and arms achieved different flow. Other than the humanoid part, the social interaction movement was realized by changing the height of the robot using the lifting cylinder featured in the robot. Different emotional conditions were connected to different heights, based on the descending or ascending component of the Laban space feature, present in the last column of Table 2.1.

6.1.3 Robot control: the Cybernetic Avatar Platform (CAPF)

The CAPF platform, hosted on AWS, facilitates remote operation of the Teleco robot. teleoperators can access the dedicated URL from any location, gaining real-time control over the Teleco robotic avatar. Acting as a vital component of the proposed system, the platform handles all information exchange between teleoperators and participants (Figure 6.3). It houses the interconnection code between the interface and the robot, along with the logic for video streaming and command forwarding. The platform's standout feature is its global accessibility, allowing any teleoperator to remotely control the Teleco robot, aligning with this project's emphasis on distribution and independence from temporal and spatial constraints.

Beyond its infrastructural advantages, CAPF provides a custom-coded interface tailored for Teleco robot control. The interface, illustrated in Figure 6.4, encompasses several key areas: A) Real-time Video Streaming Panels: these panels display videos from both the robotic avatar's camera (left) and the operator's camera (right). The teleoperator can use it as a standard video conferencing software. The video feed is unidirectional, available only on the teleoperator 's end, while the audio is bidirectional; B) Control Panel: The top panel features basic movements and standard

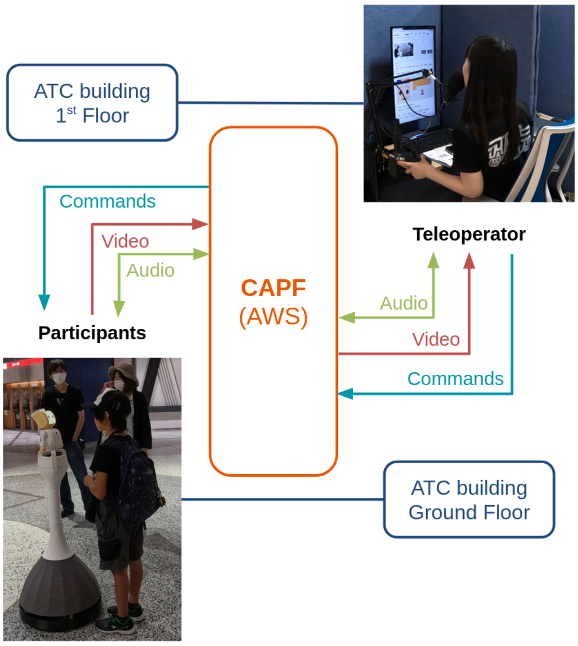


Figure 6.3: Schema of information exchange between teleoperators and Teleco through the CAPF.

greeting sentences for effortless interaction. The bottom panel contains buttons specific to mission interactions, tailored to meet specific needs; C) Social Expression Panel: users can choose and display facial expressions on the robot from a selection presented in Figure 6.2; D) Waypoints Panel: populated with navigation waypoints defined during the robot's setup, these are based on geographical location and mission objectives; E) Text-to-Speech Panel: dedicated to converting written text to speech, allowing teleoperators to hear what participants say, even if they face hearing difficulties; F) Warning Messages Panel: this section displays warning messages in case of danger or malfunction, alerting teleoperators to take corrective action.

6.1.4 Experimental settings

The experiment took place at the Asia and Pacific Trade Center (ATC) in the Osaka Bay area, specifically on the ground floor, which is a shopping mall where Teleco was deployed for public interaction. Spanning 10 days from July 10th to July 20th, 2023, the experiment coincided with the Avatar Festival. Teleco's operation time was set to 3 hours in the morning and 3 hours in the afternoon, according to the battery capacity. The ATC setting allowed free interaction with the deployed robots for all passersby, irrespective of age, gender, or any socio-demographic constraints. The teleoperators and the participants were the key actors in this experiment. The former had the responsibility of controlling Teleco through the dedicated interface, while the latter

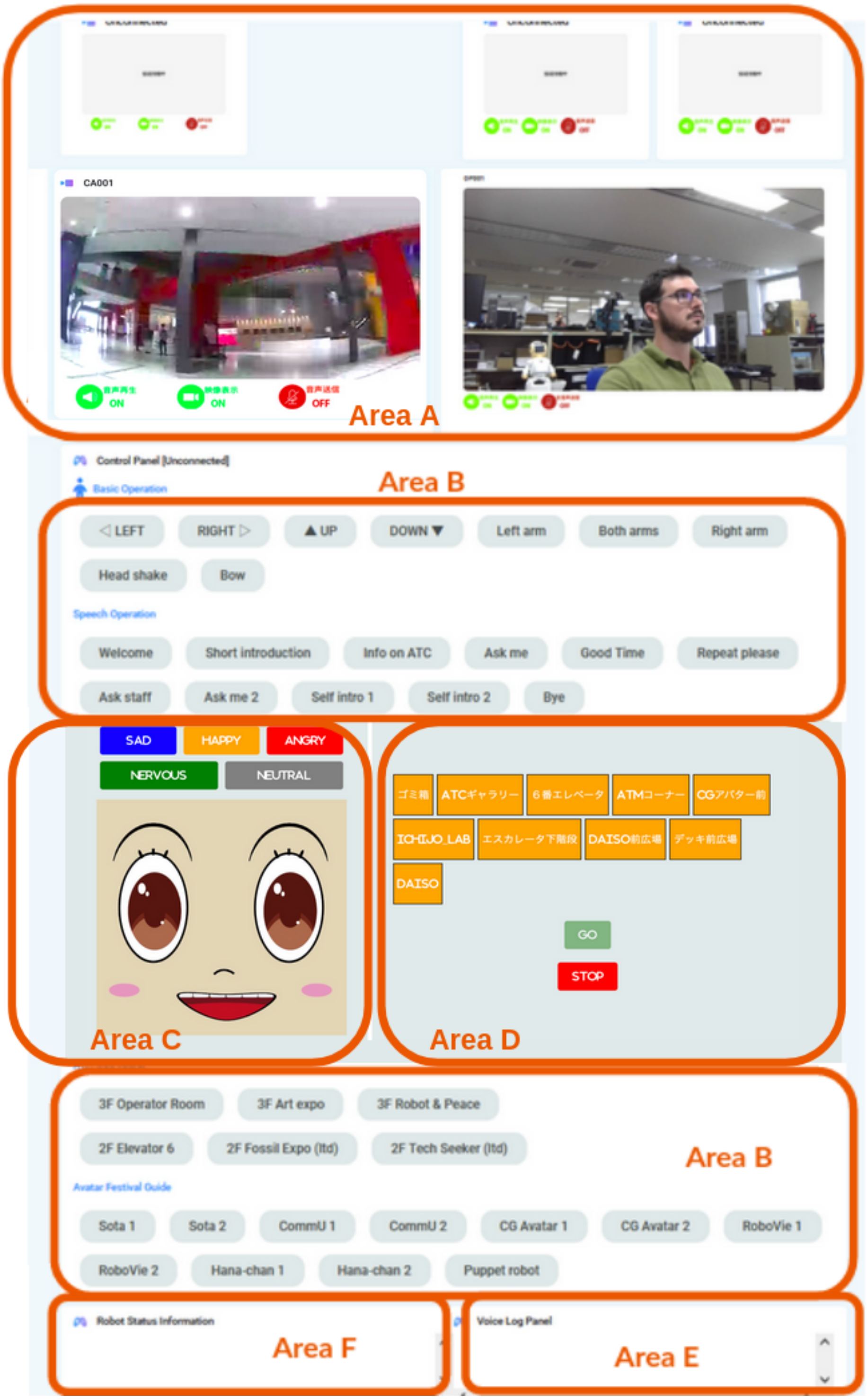


Figure 6.4: The interface implemented for this work, with the different areas highlighted.

were physically distant and located in different areas. Teleoperators operated from a control room on the first floor of the ATC building, having a limited view of the teleoperation area through Teleco's sensing capabilities. Interactions occurred over a predetermined time interval, enabling teleoperators to engage with participants using the interface buttons or their voice.

The interface featured buttons for playing predefined sentences (e.g., event descriptions, information on other robots in ATC, general greetings) and autonomous navigation options using predetermined waypoints. The autonomous movement utilized Teleco's navigation stack, and teleoperators could adjust Teleco's emotional behavior through the dedicated panel. Additionally, teleoperators had the option to use their own voice for interaction, activating and deactivating the microphone at the control position. To enhance their operational familiarity, teleoperators received a 20-minute instructional session covering the Teleco interface and navigation space for safer and more aware operation.

Participants comprised individuals passing by the ATC building during the experiment. Teleoperators were instructed to engage with them using any interface feature. Participants could freely respond to Teleco or choose to ignore it based on their preferences and duties. In cases of interaction, participants were approached by the team and invited to complete a questionnaire, with the freedom to accept or refuse.

6.1.5 Participants

As previously introduced, in this study two primary roles were identified: the teleoperators and the participants . teleoperators were recruited from the student body of Osaka University, as well as from individuals passing by ATC who expressed interest in Teleco. The lack of specific criteria for teleoperator participation aimed to investigate the diverse interactions and control approaches across individuals with varying backgrounds and experiences. This approach also facilitated an assessment of how well-received the designed interface was among both technical and non-technical users. A total of 21 teleoperators engaged in Teleco teleoperation over the 10-day experimental period.

On the contrary, participants were not actively recruited; instead, they were invited to fill out interaction questionnaires after participating voluntarily with Teleco. Due to the public nature of the experiment and the difficulty in managing participant involvement, an open interaction approach was adopted , gathering feedback from individuals who willingly engaged with Teleco. It's noteworthy that, due to time constraints or other reasons, multiple participants did not provide information about their interaction. Nevertheless, a total of 31 participants decides to fill-in the questionnaires, detailing interactions with Teleco were obtained.

Table 6.1: The questions posed to teleoperators (QT), and the ones posed to participants (QP)

ID	Question
QT.1	How did you feel while operating the Teleco robot?
QT.2	What do you think about the features of the Teleco interface?
QT.3	What part of the Teleco interface did you prefer?
QP.1	What do you think of your interaction with the Teleco robot?
QP.2	What did you prefer about your interaction with the Teleco robot?
QP.3	Do you think that your interaction was natural?

6.1.6 Evaluation Tools

The data collection was performed using a set of questionnaires that were taken from literature and used as standard in the context of robotics HRI (for Teleco) and user interfaces (CAPF). Both the participants and the teleoperators , after their interaction with the robot, had to complete the Godspeed Questionnaire [88]. This tool is designed to assess users' perceptions and attitudes towards robots. It evaluates various dimensions, including anthropomorphism, animacy, likeability, perceived intelligence, and user comfort, providing valuable insights into the social and emotional aspects of human-robot relationships. After this questionnaire three open questions (reported in Table 6.1), were administered to both participants and teleoperators, to assess their feedback about the HRI.

Lastly, for the teleoperators only, it was administered the System Usability Scale questionnaire (SUS) [97]. SUS is a widely employed questionnaire for assessing the perceived usability of a system or product. It consists of ten straightforward questions, providing a quick and reliable measure of users' subjective opinions on the usability and user-friendliness of the evaluated system. The SUS score is calculated to gauge overall usability, making it a popular tool in user experience research. The experiment conducted in Japan involved administering questions in Japanese. Two native speakers were responsible for translating both the questions and answers in the questionnaires. Additionally, a Japanese-speaking individual was consistently present while users completed the questionnaires to provide any necessary explanations.

6.1.7 Data Analysis

The initial step involved calculating descriptive statistics, specifically median and interquartile range (IQR), for the Godspeed questionnaire within both groups (teleoperators and participants). These measures were chosen as they provide a robust representation of central tendency and statistical dispersion, particularly suited for this study's relatively small sample size.

Following this, a pairwise Spearman correlation analysis was executed to examine the correlation among the Godspeed domains within each group. These findings will offer valuable insights into the perception of the robot from both perspectives (teleoperators and participants) and illuminate any notable differences.

Subsequently, the teleoperators' group's cumulative score for the System Usability Scale (SUS) questionnaire was computed. This cumulative score serves as a metric to assess the usability of the system.

The open-ended responses from both teleoperators and participants have been organized into word clouds, offering a visual representation of the most frequently occurring words in the dataset. These word clouds provide an immediate visual summary of prominent terms, with varying sizes reflecting their frequency. Additionally, researchers have carefully reviewed the responses, extracting suggestions from user comments.

Furthermore, this paper will delve into the empirical observations made during the experiment. Over the entire 10-day period, two researchers were consistently present in both the participants ' and teleoperators ' areas. This ongoing observation allowed us to monitor the behavior of individuals on both sides. The collected observations are presented as a set of guidelines derived from this experience, aimed at enhancing the success of deploying a semi-autonomous robot in a real environment and fostering effective HRI. The open answers let us have a deeper understanding of the limitations of this work and the user perception of Teleco and the CAPF.

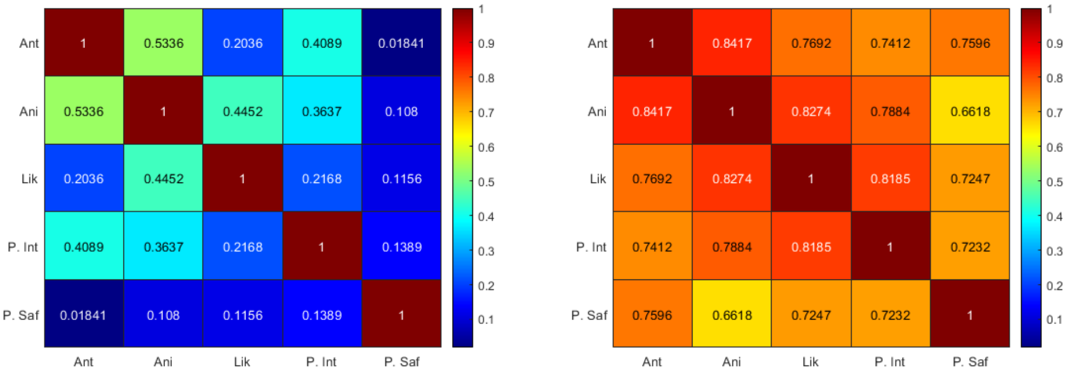
6.2 Results

Descriptive statistics pertaining to the Godspeed questionnaire, specifically the median and IQR scores for each of the five domains, have been computed and are presented in Table 6.2.

Table 6.2: Descriptive Statistics for Godspeed Questionnaire

		Ant	**Ani**	**Lik**	**P. Int**	**P. Saf**
Teleoperators	**Median**	3.00	3.67	4.20	3.40	3.67
	IQR	0.40	0.50	0.60	0.60	0.67
Participants	**Median**	2.60	3.33	4.20	3.20	3.33
	IQR	1.50	1.04	0.75	1.05	1.08

The correlation matrix related to the Godspeed questionnaire are depicted in Figure 6.5 for both the teleoperators and the participants . The first evidence is the difference between the two, with the teleoperators matrix that has substantially lower values than the one of the participants . While the maximum correlation value for the former is 0.53, the latter has the highest value set at 0.84. For both the matrices though, the last row shows the lowest levels of correlation, indicating a difference in that specific question.



	Ant	Ani	Lik	P. Int	P. Saf
Ant	1	0.5336	0.2036	0.4089	0.01841
Ani	0.5336	1	0.4452	0.3637	0.108
Lik	0.2036	0.4452	1	0.2168	0.1156
P. Int	0.4089	0.3637	0.2168	1	0.1389
P. Saf	0.01841	0.108	0.1156	0.1389	1

(a)

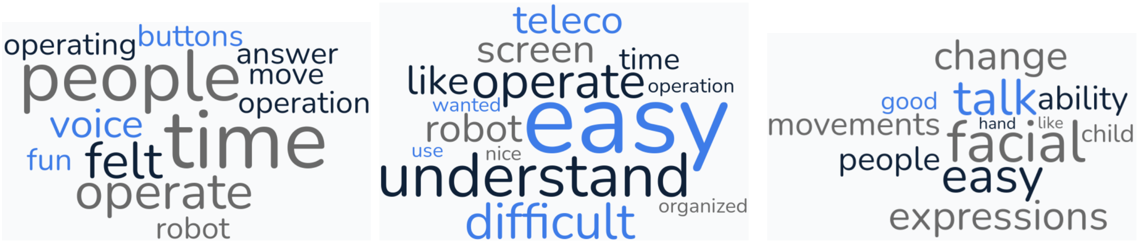
	Ant	Ani	Lik	P. Int	P. Saf
Ant	1	0.8417	0.7692	0.7412	0.7596
Ani	0.8417	1	0.8274	0.7884	0.6618
Lik	0.7692	0.8274	1	0.8185	0.7247
P. Int	0.7412	0.7884	0.8185	1	0.7232
P. Saf	0.7596	0.6618	0.7247	0.7232	1

(b)

Figure 6.5: Cross correlation matrix of a) teleoperators , and b) participants for the 5 Godspeed dimensions.

The examination of the SUS questionnaire, exclusively administered to the teleoperators group, revealed a predominantly favourable rating exceeding the acceptability threshold (51.7) associated with the descriptor "Ok." Only one participant provided a score below this threshold. Specifically, lower scores were assigned to items 6, 8, and 9, corresponding to the statements "I thought there was too much inconsistency in this system," "I found the system very cumbersome to use," and "I felt very confident using the system," respectively. Remarkably, insights gleaned from the participants' responses to open-ended questions did not underscore any noteworthy issues. Notably, five out of seventeen participants rated the system above 71.1, corresponding to the descriptor "Good," while four participants assigned scores surpassing 84.1, denoting the highest tier on the SUS questionnaire and aligning with the descriptor "Best Imaginable" [98].

The word clouds summarizing the teleoperators responses (Figure 6.6) emphasize 'people' and 'time' for QT.1, then highlight words related to teleoperation in response to QT.2, such as 'easy,' 'difficult,' 'operate,' and 'understand.' Finally, they focus on the best features for QT.3, emphasizing ’facial,’ ’change,’ ’easy,’ and ’talk.’ For the participants ’ responses (Figure 6.7), QP.1’s most prominent comments include ’voice,’ ’cute,’ and ’human.’ In QP.2, prominent words are ’facial,’ ’change,’ ’height,’ ’cute,’ and ’voice.’ Lastly, QP.3 features a significant number of comments containing ’natural,’ with fewer mentions of ’voice,’ ’movement,’ and ’people.’



(a) (b) (c)

Figure 6.6: The word-clouds originated from the answers of the teleoperators .

(a) (b) (c)

Figure 6.7: The word-clouds originated from the answers of the participants .

The manual analysis of the open-ended responses allowed the authors of this work to extract several suggestions from users (Table 6.3. These suggestions clearly outline future improvements necessary to enhance usability and satisfaction in subsequent experiments and real-world HRI scenarios. Two teleoperators emphasized the need for a navigation map on the interface rather than a simple waypoints list, marking it as a crucial enhancement. Additionally, nine participants highlighted the issue of voice change when transitioning from the synthetic robotic voice to the operator’s speech, while three participants also pointed out a problem of lag during the interaction.

Table 6.3: Suggestions given by the teleoperators (T) and the participants (P) to improve the HRI experience

Users	**Suggestion for Improvement**
T4, T7	Navigation map should be on the UI
T8	Incorporate a feature to project the teleoperator’s face onto the Teleco display.
T18	Control the robot not only with a mouse, but with a joystick too
P3, P5, P6, P7, P8, P11, P19, P25, P28	The switch from human to mechanical voice and vice-versa is troublesome and uncomfortable
P18, P21, P28	The time-lag during the conversation should be avoided

Finally, this section incorporates the empirical observations gathered during the 10-day experiment, as detailed in Table 6.4. Two distinct behaviors among the teleoperators were identified: one where the teleoperator attempts to conceal their presence, refraining from using the microphone and avoiding direct interaction with the other interlocutor. This behavior was summarized as the *"I am the robot"* behavior. On the contrary, there were teleoperators who were indifferent about being revealed behind the robot, consistently opting for the speech interface as it is more natural and intuitive. This group was labeled as *"The robot is me"*.

Table 6.4: Behaviors observed for the teleoperators (T) and the participants (P) during their interaction with Teleco

Group	Observation	Summary
T	Refrain from revealing the human presence behind the robot by avoiding any control features that may expose the truth.	I am the robot
	Leverage any feature of the robot to subtly convey the human presence behind it, engaging with the participant through direct communication.	The robot is me
P	Treat the robot as if it were intelligent. When the operator communicates through the dedicated speaker, people became frightened and withdrew.	Unaware of human
	Speak to the robot but don't anticipate a response. When it does reply, they become surprised and start looking around to verify how they could have been heard or seen	Aware of human, unaware of remote control
	Ask directly if somebody was controlling the robot. This group was the smallest and composed of individuals with technical expertise.	Completely Aware

Similarly, three behaviors were evident among the participants , based on their approach to interacting with the robot. In one scenario, individuals freely engaged with the robot, attributing a sort of personality to it and interacting seamlessly. When the teleoperator dispelled the illusion, these individuals became confused and/or scared, typically terminating their interaction with Teleco. This group was named *"Unaware of human"*. Another behavior mirrored the previous one, but when the robot spoke with teleoperator 's voice, participants were not scared by the human speech but appeared perplexed, immediately searching for the teleoperator controlling the robot. This group was termed *"Aware of human, unaware of remote control"*. Finally, the least observed behavior was among more technically inclined individuals who directly inquired about teleoperation, showcasing a higher level of technical maturity. This behavior was classified as *"Completely aware"*.

6.3 Discussion

The results have provided valuable insights for future developments and experiments of this nature, particularly when situated in a real-world scenario that incorporates

HRI. This experiment has allowed us to steer the direction of upcoming projects and establish guidelines that should be adhered to for achieving successful HRI, facilitated by platform-aided robotic teleoperation.

6.3.1 Quantitative Results and Observations

Firstly, it is worth differentiating between two types of interactions with the robot. On one side is passive interaction, where the user cannot change the behavior of the robot; this is related to participants . On the other side is active interaction, where the robotic behavior is directly influenced by the user; this is related to teleoperators.

The noticeable disparity in the correlation among the Godspeed dimensions indicates that the perception of those with passive interactions and those with active ones differs. Participants tend to provide responses with similar scores. In other words, if their impression of the Teleco robot is positive, it applies to all Godspeed questions; similarly, a negative impression extends across all dimensions. In contrast, for teleoperators , a high score in one dimension does not correlate with a high score in another. Consequently, their response distribution is more varied. It is speculated that this is intrinsically linked to the different interaction types, but it is also possible to analyze this feature on the social level.

The participants interact with the robot as if it were another person, assigning a positive or negative connotation based on their interaction—similar to how one would with a new acquaintance. In contrast, teleoperators project themselves onto the robot, rating its features based on their allowed actions; they assess the robot's capability to grant them the freedom to guide the interaction.

The data from the SUS questionnaire indicate an acceptable level of usability for the interface, but it requires multiple improvements. Future implementations of the interface should consider the comments provided by teleoperators and incorporate the suggestions left in the comments.

6.3.2 Behavioral Considerations and Interpretations

The word clouds of teleoperators highlight the concepts of 'people' and 'time'. 'People' is derived from the interaction, and teleoperators seem to appreciate this way of interacting with others. Unfortunately, the topic of time lag and delay was raised more than once, significantly impacting the successful completion of the teleoperation task. Future system implementations must ensure minimal lag time and an effective connection to avoid frustration for the person controlling the robot.

General feedback on the interface is reflected in words like ’easy’ and ’understand’, emphasizing the intuitive and user-friendly nature of the interface for the majority of users. However, there are some responses that include the term ’difficult’ in their feedback. Finally, the preferred features are highlighted by the words ’facial’, ’easy’, and ’talk’. Users appreciated the ability to change facial expressions, interact using human speech in a natural way, and the ease of executing Teleco controls. The first two preferred elements were also favored by the participants , indicating the importance of retaining these features in future developments of this project and in other projects focusing on robotic interaction and control through dedicated interfaces.

The word clouds from the participants emphasize how the cuteness of Teleco was appreciated, along with the use of human voice for natural interaction (participants interacted with Teleco solely through speech). When detailing the preferred features of Human-Robot Interaction (HRI), respondents focused on the change of facial expressions and height adjustment. Height change was specifically highlighted for its adaptability to both adults and kids. Combining this information, the conclusion is that the key elements for successful HRI in this environment are the ability to use human voice for communication, changing facial expressions to convey social information, and adjusting the height or point of view of the robot. Finally, ’natural’ is the most frequently used word in response to the last question, indicating that most people accepted the robot as natural, or at least welcomed the interaction with Teleco.

The concepts extracted from the suggestions in Table 6.3 align with the word clouds, enriching them with valuable content needed for the next development phase. The idea of integrating the real map of the location where the robot interacts and providing localization information is of great interest. In this work, however, this feature was not included because of the sought balance between the number of functions and ease of control. Apparently, incorporating this feature is necessary for teleoperators to enhance their experience and should be considered in future works, bearing in mind that it might increase the interface’s complexity.

While the idea of projecting the teleoperator face onto the Teleco display is intriguing, it is in contrast with the concept of abstraction and the use of the robotic avatar. From this work’s perspective, the avatar itself should be the primary element of interaction, rather than serving as a mere intermediary between the teleoperator and the participant. Lastly, the idea of using a joystick as a replacement or support for the GUI is interesting. It could provide teleoperators with faster access to a palette of possible actions, enhancing their enjoyment and aligning with modern Human-Robot Interaction (HRI) scenarios that incorporate gamification principles.

The suggestions from the participants are significantly focused on two key points. The first, and most crucial, is the switch between human and synthetic voice. This feature was the least favored by participants and proved to be the most cumbersome during interactions, often eliciting reactions close to fear and surprise. In many cases, these reactions led to the premature end of the interaction. To address this, the technical solution should involve using a synthesizer that takes the teleoperator voice as input and outputs the exact synthetic voice of Teleco used for predetermined buttons.

The second point concerns the infrastructure of CAPF, which currently demonstrates good performance, but in some instances, the lag is too significant, resulting in a negative perception of the interaction from both teleoperators and participants 6.3. This issue can be mitigated by investing in a reliable infrastructure and enhancing the system's performance through appropriate caching policies and other strategies.

Finally, concerning the observed behaviors, it is possible to anticipate two different strategies for the two actors.

In one case, the teleoperators adopt either the paradigm *I am the robot* or *The robot is me*. They use the interface differently, and therefore, in the next versions of CAPF, it should be possible to choose one of these two approaches. This way, the interface itself would adapt to what the teleoperator wants to do, allowing for the greatest level of customization and enhancing the teleoperation experience.

As for participants ' behavior, it will possibly be influenced by multiple factors. First and foremost, the increasing use of robotic technologies will establish well-defined usage scenarios, and people will become more familiar with interacting with a robotic avatar. This familiarity will prevent situations of fear or surprise and focus the interaction on the task to be achieved (e.g., a museum tour) rather than on the robotic appearance and features. Basically, the supposition is that all the users will fall into the *"Completely aware"* category. Additionally, technological improvements will mitigate problems experienced in this experiment, such as the sudden change between human voice and synthetic voice. Therefore, it is asserted that the different behaviors observed during the experiment are linked to people's technological knowledge and will become more stable as robotic avatar technologies permeate everyday life.

6.3.3 Comparison of CAPF with SIGVERSE Simulator

SIGVerse [99] is a sophisticated simulation environment designed to study and develop social intelligence in robots by combining dynamics, perception, and communication simulations. Built on the Unity game engine, SIGVerse supports the use of various VR devices to mirror real-world human behavior in a virtual setting. It leverages ROS to control virtual robots, allowing researchers to apply existing ROS-based software seamlessly. SIGVerse facilitates interdisciplinary research by integrating insights from cognitive science, developmental psychology, brain science, evolutionary biology, and robotics to explore the genesis of social intelligence.

The CAPF platform and SIGVerse serve distinct purposes and operate in different domains of robotic interaction and simulation. CAPF is primarily focused on enabling remote control of the Teleco robot through a globally accessible platform hosted on AWS, emphasizing real-time control, video streaming, and command forwarding. Its features include real-time video panels, control and social expression panels, navigation waypoints, text-to-speech capabilities, and warning messages. This platform allows teleoperators to manage the robot from any location, facilitating distributed and independent operations across various missions.

In contrast, SIGVerse is a virtual simulation environment designed to explore the development of social intelligence in robots by integrating dynamics, perception, and communication simulations. Using Unity as its foundation, SIGVerse allows for the simulation of physical and social interactions in a virtual world. It supports a range of VR devices to reflect real-world human behaviors and utilizes ROS to control virtual robots, making it possible to apply existing ROS-based software without modification. SIGVerse facilitates interdisciplinary research by combining elements from cognitive science, developmental psychology, brain science, evolutionary biology, and robotics to study the genesis of social intelligence through virtual interactions.

In summary, while CAPF is centered on the practical application of remote robotic control with real-time interaction capabilities, SIGVerse focuses on theoretical and experimental research in social intelligence through virtual simulations, providing a platform for interdisciplinary studies and the development of intelligent robotic systems.

6.4 Conclusion

This work drew guidelines and best practices to deploy a robotic avatar in a real-world scenario. Moreover, this work highlights what features are necessary in a robotic teleoperation system, and what are their limits. It was possible to analyze how people that interact with the robot as participants perceive the interaction and what are the capabilities and limits to be aware of, when designing this kind of HRI scenario. Even though the data collected for this work did not refer to a big sample size, the experiment went on for various days and multiple people could interact and control Teleco. The experience tells that this kind of deployment is possible, and that there is great room for improvements.

Chapter 7

ROS-based Manipulation for Cognitive and Physical Rehabilitation

This chapter[1] elucidates the concluding phase of the Ph.D. work, focusing on the ultimate goal of constructing a comprehensive rehabilitation procedure. This segment represents the culmination of various efforts converging to shape the final HRI scenario. The integration of cognitive and physical rehabilitation was tested in this context, and the results affirm that the path pursued by this work is indeed promising, holding the potential to significantly enhance rehabilitation for both patients and therapists. The title "Manipulation for Cognitive and Physical Rehabilitation" refers to the use of robotic arms to perform tasks that require both physical interaction and cognitive engagement. In this context, manipulation involves the robot guiding the patient through exercises that challenge their motor skills as well as cognitive functions, such as memory, attention, and problem-solving. This dual approach aims to provide a holistic rehabilitation experience that addresses multiple aspects of the patient's recovery.

7.1 Reasons for the study and research questions

Recent studies have considered the advantages of using technology to enhance the quality of life for patients through physical and cognitive stimulation [100]. Li *et al.* [101] highlighted the benefits of having a physical robot in front of patients, emphasizing its advantages over virtual agents or telepresence systems. Other studies

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[1] Adapted from *"ROS-MCPyRe: ROS-based Manipulation for Cognitive and Physical Rehabilitation," **C. La Viola**, L. Fiorini, and F. Cavallo, 2024 (IN PREPARATION)*

underscore the positive impact of robots on medical practice, particularly in automating repetitive tasks. For instance, in Krebs *et al.* [102], robot-aided therapy is shown to enhance brain recovery, while Lo *et al.* [103] demonstrate that a 36-week therapy with robots can improve upper limb post-stroke recovery compared to conventional care. On top of this, the ability of robots to objectively record physical measures, such as limb movements and exerted forces, adds significant value to robotic-aided rehabilitation. In this chapter, it is hypothesized the use of a robotic arm as an agent to perform well-defined exercises with patients, aiding in the stimulation of both the physical and cognitive spheres.

The use of an agent performing exercises with a patient was previously explored by Manera *et al.* [23] in a human-human interaction context. Eizicovits *et al.* [11] conducted a comparable exercise, utilizing a robotic arm to design a tic-tac-toe game and evaluate its efficacy, specifically focusing on the physical execution of the task with a user against the robotic arm. In this scenario, patients were tasked with solving a cognitive exercise. On these premises, this chapter introduces the use in operation of ROS-MCPyRe, where a robotic arm is programmed to perform exercises with clinical relevance, targeting the physical and cognitive stimulation of patients. In this specific implementation, the robotic arm selects a colored ball, releases it in a specific position in space, and the user must then grab and place it in a colored box. This exercise is adapted from the Token Test [104], which is a neuropsychological assessment tool used to evaluate language and cognitive functions, focusing on auditory comprehension and processing. In this test, participants manipulate tokens based on spoken instructions, assessing skills like auditory comprehension, working memory, and sequential processing. It helps identify language and cognitive impairments in conditions like stroke or traumatic brain injury, providing valuable insights into an individual's ability to follow complex verbal instructions. In this work it is declined differently, by using visual information and by incorporating physical stimulation through an object handover task between the robot and users. The goal is to verify how users react to two different exercise difficulties, and perform data collection. In the future, such data will be use as information to customize future rehabilitation session. This approach is aimed at enhancing rehabilitation outcomes and personalizing therapy, aligning with the current trend of therapy customization, as highlighted in Yuan *et al.* [105]. In essence, this chapter seeks to ascertain the viability of conducting a robot-aided rehabilitation exercise that effectively stimulates participants both physically and cognitively through the utilization of ROS-MCPyRe.

7.2 Materials and Method

7.2.1 Participants

The study involved 31 healthy young individuals, including researchers and students who volunteered for the experiment. Participants were recruited from the University of Florence, specifically from the Department of Industrial Engineering (DIEF). The group comprised 51.6% females and 48.4% males, with a mean age of 27.3 years and a standard deviation of 5.3. Before the experiment, participants received information about the test, a description of the experiment, and provided their informed consent. The study received approval from the Ethical Committee for Research at the University of Florence (protocol 0077883 of 06.04.2023).

7.2.2 Experimental Procedure

Participants were initially welcomed to the experimental room and asked to read and sign the informed consent. Subsequently, a brief socio-demographic data collection took place on a dedicated computer. Personality data were also recorded using the Big Five Inventory (BFI-10) test [79], which assesses participants on five personality categories with scores ranging from 1 to 10. Following these initial procedures, the actual experiment commenced. Participants were provided with instructions regarding the exercise's general purpose: the robot would pick a colored ball (red, yellow, or blue), move to a random point in space, and release the ball. The participant's task was to then grab the colored ball and place it in a corresponding colored box (red, yellow, or blue). With a total of two balls per color, each human-robot interaction (HRI) session included six balls. The participant is briefed about two different modes of human-robot interaction (HRI) that will alter their task. In the standard (S) mode, the participant is instructed to place the colored ball inside the box that matches its color. Conversely, in the inverted (I) mode, the participant is required to follow instructions displayed on a tablet in front of them. The tablet will show text in one of the three color names, but the actual color of the text will be random. The participant is instructed to focus solely on the text and accordingly place the ball in the box that corresponds to the color mentioned in the writing. In summary, the sequence of robot actions comprises: i) turning towards the known position of the ball and picking it up; ii) turning toward the participant; iii) moving to the ball release position; iv) releasing the ball; v) returning to the starting position. User actions differ based on the mode: in the standard case, participants pick the ball and place it in the box of the same color; in this case the table always shows the facial expression of the robot. In the inverted case, participants pick the ball, read the tablet, and place the ball in the color written on the tablet; the tablet displays firstly the facial expression and then the color information, as depicted in Figure 7.1. The order of S and I sessions was randomly assigned to ensure an equal distribution of participants starting with I or S.

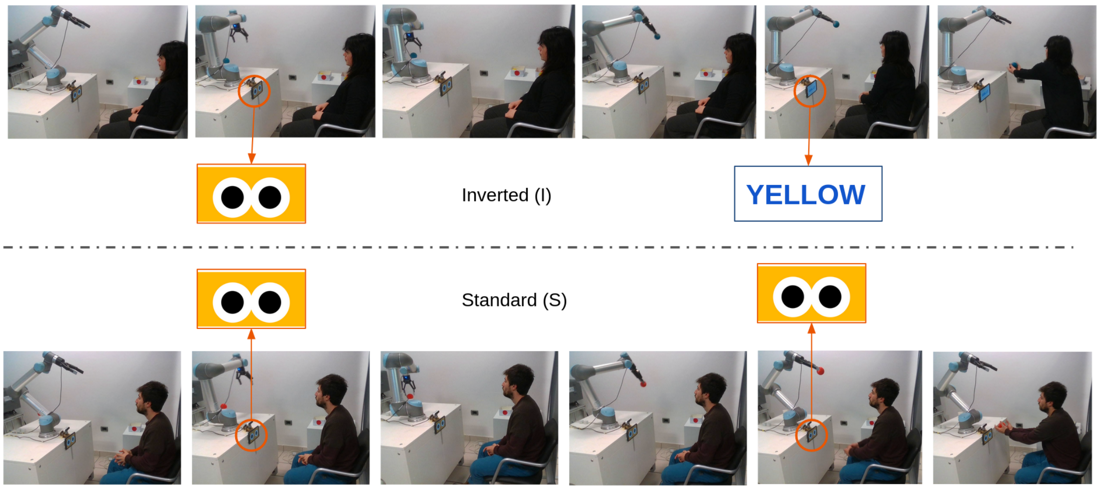

Figure 7.1: Difference between the Standard (S) mode, and the Inverted (I) mode.

Following each session, participants were directed to a dedicated webpage to complete a questionnaire structured with six questions. Respondents interacted with sliders, positioning them between opposing values (e.g., "not at all" to "a lot"). The questions were: i) Do you consider this activity as physically challenging; ii) Do you consider this activity as mentally challenging; iii) Do you think that the position where the robot was releasing the balls were appropriate; iv) Did you have fun; v) Were you comfortable during the test; vi) What would you rate the overall experience?

In the role of a simulated therapist, the experimenter utilized an interface to initiate various actions and record participant performance. The interface facilitated recording the time taken for each ball placement and selecting the exercise outcome. Participants' performances were categorized as "success" if they correctly placed the ball in the designated box, "mistake" if the ball was caught but placed in the wrong box, and "failure" if either the ball or the box was missed.

7.2.3 Data Analysis

The participants' responses were categorized based on the interaction mode (S or I). The questionnaire utilized a 1 to 5 scale, and the summarized responses, including median values and interquartile range (IQR), are presented in Table 7.1. These

Table 7.1: Statistical results from the comparison of the Standard (S) and the Inverted (I) condition

Question	**Med. S**	**IQR S**	**Med I**	**IQR I**	**p**	**Effect size**
Q1	1.12	0.54	1.58	0.97	ns	15.81
Q2	1.53	1.18	3.00	1.87	$< .001$	3.95
Q3	3.62	1.52	3.85	1.93	ns	29.81
Q4	4.30	1.36	4.63	1.09	$< .001$	9.16
Q5	4.61	0.59	4.67	0.82	ns	21.55
Q6	4.68	0.99	4.84	0.65	$< .001$	7.54

Table 7.2: Different duration for placing each ball (seconds) for the two condition S and I (Means and Standard deviations)

Ball Number	Placing time S	Placing time I
Ball 1	2.56 ± 1.67	3.11 ± 1.78
Ball 2	1.93 ± 0.54	2.75 ± 1.68
Ball 3	1.73 ± 0.44	2.57 ± 1.55
Ball 4	2.12 ± 0.64	2.52 ± 1.42
Ball 5	1.86 ± 0.62	2.32 ± 1.03
Ball 6	1.93 ± 0.43	2.41 ± 1.19

measures were chosen as they provide a robust representation of central tendency and statistical dispersion, particularly suited for this study's relatively small sample size. To assess the distinction in response distributions between the modes S and I, a statistical analysis was conducted using the Wilcoxon signed-rank test, suitable for paired non-parametric data. The outcomes underwent the Bonferroni correction, and the adjusted results are outlined in Table 7.1.

Additionally, the reaction times of participants in both interaction modes are detailed in Table 7.2. These values denote the average duration in seconds for each ball exchange between the participant and the robotic arm during the exercise. The gameification ratings, specifically the scoring assigned during the exercise, are presented in Table 7.3. The values represent the percentage of "success", "mistake", and "failure" throughout the entire interaction.

Table 7.3: Percentage of Success, Mistake and Failure for the two condition S and I (%)

Score type	Occurrence for S	Occurrence for I
Success	92.5	93.6
Mistake	7.5	3.8
Failure	0.00	2.7

7.3 Results

The results reveal notable differences in mean and standard deviation between modes S and I. Responses to Q3 and Q5 show relatively minor distinctions, while the mean values for all other answers are higher in the I session. This trend is supported by significant p-values for responses Q2, Q4, and Q6. Particularly noteworthy is the substantial difference in mean values between S and I for Q2, which pertains to mental load during the exercise.

In Table 7.2, it is detailed the time participants took to place the ball in the designated box. For the S mode, the first ball exhibits a longer placing time and greater standard deviation, while subsequent balls have comparable measures. In the I mode, all placing times and standard deviations are larger compared to session S, indicating greater variability in task execution.

Lastly, Table 7.3 illustrates the percentage of occurrences for the three possible scores. The ”success” score has a high percentage for both S and I (92.5 and 93.6), while the ”mistake” percentage is slightly higher for the S mode, contrary to expectations. Notably, the S mode did not result in any failures, while the I mode's failure percentage slightly increases, aligning with the expectation of a more challenging exercise.

7.4 Discussion

The presented results provide insights into the application of a robotic arm in a rehabilitation scenario, highlighting the validity of the ROS-MCPyRe framework in relation to the integration of physical and cognitive rehabilitation. The experiment aimed to validate the hypothesis that a robotic arm could effectively contribute to both physical and cognitive aspects of rehabilitation simultaneously. The results for Q1 indicate that the physical effort required in both S and I modes was comparable. This aligns with the experimental design, where the balls were placed randomly within the predefined workspace for both modes. It is hypothesized that, for individuals with motor disabilities, the scores related to physical stimulation will significantly improve, but this necessitates dedicated testing on a specific sample, a consideration reserved for future studies.

Q2 results emphasize that the exercise devised in the experiment provides a genuine stimulus for cognitive rehabilitation. The contrast between the S and I sessions demonstrates that even with a non-human agent, it is feasible to design exercises that effectively stimulate users or patients on the cognitive level. The statistical significance underscores the efficacy of a fully automated rehabilitation procedure capable of stimulating participants. By entrusting this task to the robotic arm, therapists can potentially supervise and manage the rehabilitation treatment for multiple individuals concurrently.

Analyzing the non-significant results for Q3, and Q5 suggests that the comfort level and the positions where the robot releases the ball are independent of the specific task. This implies that the robotic arm can perform similar tasks with different participants without negatively impacting the overall human-robot interaction (HRI) perception. In essence, the robotic arm's versatility allows it to engage in various tasks with participants while maintaining a positive perception.

On the contrary, the counterintuitive results for Q4 and Q6, where an increase in task difficulty positively correlates with higher enjoyment and an improved overall experience, are promising for future experiments. This finding suggests that introducing more challenging tasks, especially on the cognitive level, with a robotic arm can enhance participant satisfaction. This phenomenon might be attributed to the non-human nature of the robot, alleviating potential anxiety associated with judgment from another human. The overall experience benefits from this unique dynamic.

The placing time data presented in Table 7.2 provide positive insights into this work's objectives. The increased time for all balls in mode I compared to mode S supports the effectiveness of the cognitive load on participants. The notable standard deviation values, indicating higher variability, emphasize individual differences in task execution. While this experiment involved healthy participants, the observed differences suggest that similar tasks with not-healthy adults could offer a substantial cognitive stimulus for rehabilitation.

Additionally, the increased occurrences of "failure" in Table 7.3 underscore the heightened difficulty of mode I, further affirming the efficacy of cognitive stimuli introduced by the system (via the tablet). The higher percentage of "mistake" in mode S can be attributed to participant confusion and initial difficulties in executing the task correctly that triggered the "mistake" for the S mode and the "failure" for the I mode. These findings collectively support the notion that the cognitive challenges introduced by the system contribute significantly to the rehabilitation stimulation effectiveness.

While these results provide a positive outlook for future studies, it's essential to acknowledge the limitations of this experiment, which involved healthy and young participants in a short-duration interaction. Future studies should replicate these findings with real patients to validate their applicability. Additionally, assessing the interface's usability and system validity from a therapist's perspective is crucial. Increasing the sample size and incorporating a more diverse participant pool will further enhance the study's validity and establish the proposed robotic rehabilitation system as a robust and effective tool.

7.5 Conclusion

The successful completion of the experiment and the coherence of the collected data, along with the absence of technical failures, allow us to conclude that ROS-MCPyRe is an appropriate software architecture to support physical and cognitive rehabilitation. One of the future objectives is to customize this framework, testing it on different tasks to ensure its design for adaptability.

The obtained results are promising for the development of this robotic arm-based rehabilitation system designed for HRI in post-stroke rehabilitation. These findings suggest that a robotic arm can effectively replace human involvement in performing repetitive tasks aimed at both physical and cognitive stimulation in individuals. The positive feedback on the overall likability of the exercise and the participants' favorable experiences envision a successful future for rehabilitation systems incorporating robotics.

The success of this approach holds significant implications for addressing current health challenges, particularly the shortage of personnel and the growing demand for personalized rehabilitation treatments. The robotic arm's ability to engage users in repetitive yet cognitively stimulating exercises offers a scalable and adaptable solution, potentially alleviating the strain on healthcare resources. The positive response from participants underscores the potential for incorporating robotics in rehabilitation to enhance accessibility and effectiveness, marking a promising step toward addressing the evolving needs of patients in rehabilitation settings.

Chapter 8

General Discussion

This work anayzed various aspects related to robotic rehabilitation, and went through a set of 4 experiment to effectively evaluate the initial hypotheses and achieve AIM.1, AIM.2 and AIM.3, and the related objectives.

The experimentation based on an iterative set of experiment, aimed at verifying small portions of the overall picture, allowed a focused testing and to obtain a set of results that supports the initial idea in all its parts. The discussions will be analyzed by research aim, as the ones presented in Chapter 1, and put in relation to the various experiments and results. A summary is available in Table 8.1

8.0.1 AIM.1: A robotic system that adapts to therapists and patients needs

The software design and implementation revolved around the iterative testing and validation of various components within the final software, examining their intercorrelation in a real rehabilitation scenario. In the initial two experiments, successful confirmation was achieved regarding the adaptability of the "Robot controller" module to distinct robots—specifically, the UR5 and the Franka Emika Panda robotic arms. By leveraging the Moveit ROS-library and carefully adjusting select portions of the code, the reuse of this module was facilitated and its correlation with two different robots was permitted. These minor code adjustments ensured the retention of the adaptability paradigm, a central focus in the overall implementation, and allowed the achievement of OB.1.

Subsequently, the development of the rehabilitation exercise underwent iterative refinement, particularly during experiment two, where the actual rehabilitation exercise involving colored balls began implementation. Experiment four marked the

Table 8.1: Summary of the results in relation to each objective.

		Result achieved
AIM.1	**OB.1**	Successful testing with UR5 and Panda robotic arms
	OB.2	Integration of UI for real-time management of the interaction
	OB.3	Use of database to define specific parameters of the rehabilitation
AIM.2	**OB.4**	Created 5 social movements based on LMA
	OB.5	Analyzed the robot perception based on past experiences and personality traits
	OB.6	Found the optimal social configuration for a robotic arm with movement, non-verbal sound and facial expression
AIM.3	**OB.7**	Development of a rehabilitation task to perform physical stimulation of the upper limb
	OB.8	Development of a cognitive exercise, integrated in the system and coordinated with the physical interaction

completion of this exercise, validating its effectiveness at both cognitive and physical levels. This validation solidified the strength of the ”Exercise manager” module within the ROS-MCPyRe system.

Continuing in the same iterative fashion, the system incorporated elements such as the database and therapist interface, which were tested and validated in the same set of experiments. Their inclusion in the system provides control on the therapist’s side and adapts to patient needs. This paradigm also offers possibility to actively modify the rehabilitation session through adequate inputs. Similarly, experimentation with the ”Score manager” confirmed its potential for data aggregation and supported the pursuit of gamification, enhancing participant engagement. The capability to modify the esercise and to use score data and other information to tune the treatement are the basis for the dynamic management and the data-driven therapy for the achievement of OB.2 and OB.3.

The versatility and customization potential of all these modules for rehabilitation therapy needs have been demonstrated, and the full extent of the ROS-MCPyRe system’s capabilities was tested throughout all the experiments performed. Nontheless, there is room for improvements and interesting aspect that are left for the investigation of future researchers. Primarily, the system’s usage should be adapted to accommodate at least another rehabilitation exercise and a different robotic arm, verifying its efficacy in a diverse range of scenarios. Additionally, while all the modules are interconnected, the absence of closed-loop control currently limits the management of robotic behavior. Presently, the robotic arm operates based on therapist commands and historical data without utilizing the perception module to provide feedback to the system.

Closed-loop control, a pivotal aspect in robotics, represents a challenging yet crucial goal. This Ph.D. work has laid the groundwork for its inclusion in the system and has laid the basic infrastructure for its seamless integration. Nonetheless, future advancement should use this preparation work and finilize the integration of the closed-loop control. The utilization of the perception unit in tandem with the reasoning unit holds the potential to significantly enhance the overall experience, propelling the system to a higher level of maturity. Implementing Machine Learning techniques could effectively manage perception data and develop robust robotic behaviors in response to human movements.

Upon achieving closed-loop functionality, the system would definitively adapt to both users and therapists, transforming into a comprehensive rehabilitation tool applicable in various care facilities and adaptable to diverse contexts.

8.0.2 AIM.2: Pursue social engagement for the success of the rehabilitation session

In the broader context of this work, a crucial element influencing social engagement is the imperative to establish a robust connection between humans and robots. This connection transcends mere task accomplishment, extending into the realm of social interaction. A pivotal aspect in fostering this connection is the incorporation of social cues into the design of robotic systems. The initial exploration focused on the social cue of movement, yielding positive results that conclusively demonstrated a robotic arm's capacity to convey emotional information solely through movement. This discovery holds paramount significance as, to the best of the author's knowledge, there is a dearth of literature investigating the exclusive impact of social movement on a robotic arm.

Therefore, social movements, inspired by LMA, were defined to communicate social information, elucidating the specific movement features that influence human perception. Building on the foundation of social movement, the exploration sought to identify additional relevant social cues in the context of HRI with a robotic arm. The findings underscored the importance of incorporating a face, social movements, and non-verbal sound to convey the essence of a social robot. Consequently, a fundamental configuration comprising these three social cues was defined as the cornerstone for effective HRI in a robotic context, reaching OB.4 and OB.6.

The involvement of real participants in all the experiments played a crucial role in the progression of this Ph.D. work. Over 200 participants were successfully recruited across the experiments, and the insights gained throughout these studies provided valuable information on user engagement in HRI. In the experiment detailed in Chapter 4, no correlation was identified between robotic perception and past experiences, specifically pet ownership and experience in dance or theater.

However, when delving into personality traits, notable differences emerged, suggesting a tangible impact of personality on robotic perception. While acknowledging that sample sizes in all experiments should be substantial for conclusive findings, this work managed to discern patterns and offer guidelines for considering personality in HRI. Furthermore, the combined findings from both Chapter 4 and 5 enable the definition of guidelines for future interaction scenarios. In these scenarios, robotic actions are not solely based on historical performance data but are also tailored to personality traits. For instance, individuals characterized by higher openness might prefer a robot with direct movements, while those with conscientiousness tendencies might favor more curved motions. These considerations warrant further analysis and integration into rehabilitation sessions due to their proven impact on social perception and, consequently, human engagement. Exploring this topic, this work accomplished the goal of OB.5.

Finally, an additional outcome emerged from the experimentation detailed in Chapter 7, a result not directly anticipated but logically consequential to the exercise design. The incorporation of a cognitively challenging element into the exercise revealed an observable increase in entertainment value associated with the task, indicative of heightened engagement. It appears that introducing cognitive stimulation during interactions with the robotic arm is not only beneficial for rehabilitation and the stimulation of specific cognitive functions but also contributes to enhancing overall engagement and attention toward the robotic arm. This aligns with the principles of gamification, suggesting that elevating the difficulty level and implementing a rewarding system during a rehabilitation exercise not only facilitates the intended rehabilitation task but also amplifies interest and engagement levels among patients.

In the realm of engagement, a parallel study, detailed in Chapter 6, was conducted to assess the level of engagement from the therapist's perspective. This investigation also delved into the experiences of participants and users encountering social robots in public spaces, shedding light on their reactions and management of social interactions. The study focused on identifying key elements for an effective control interface, yielding promising insights for the implementation of a therapist-controlled robot. The findings will steer the development of the next version of the ROS-MCPyRe system, aiming to establish a robust interface that enhances usability and engagement for therapists. Additionally, plans to incorporate the control of multiple robots into the *Therapist interface* will be crucial for achieving a mature and versatile system. From the user standpoint, this experience holds significance in introducing social actions and interactions during rehabilitation therapy. Through this experiment it was possible to reinforce the realization of OB.3, OB.5, OB.6 This addition allows for a segment where patients can momentarily detach from the specific rehabilitation task, engaging in more social interactions. This approach enhances overall engagement and satisfaction during the therapy session.

8.0.3 AIM.3: Commistion of cognitive and physical rehabilitation in the same system

The integration of physical and cognitive stimulation into the overall system was carried out iteratively to individually validate components and stress the adaptation capabilities of ROS-MCPyRe. In Chapter 4, the introduction of physical stimulation began with a simple task: participants catching a ball handed over by the robot. This experiment was conducted by a single researcher performing the task, while participants observed videos of this researcher. Although participants did not perform the handover task firsthand, the results indicated that robotic social movements did not have an impact on either the robotic or the human task.

Moving forward in Chapter 5, the physical task progressed, with participants physically present in front of the robot and actively performing the task. In this context, the rehabilitation component was introduced, expanding participants' roles to not only catching the ball handed over by the robotic arm but also placing it in a colored box matching the ball's color.

Within this framework, the optimal social cues for successful HRI and execution by the ROS-MCPyRe system of the physical task aimed at the final rehabilitation scenario were validated, thus fullfilling the aim of OB.7. Finally, in Chapter 7, the physical task reached its culmination with randomized handover points and a semi-casual strategy for releasing the ball, modeled according to rehabilitation protocols. Additionally, the cognitive task was introduced, revealing a significant increase in participants' efforts when performing both alternated tasks. The integration of cognitive and physical load elicited heightened appreciation from patients, signifying the effectiveness of a robotic arm in conducting rehabilitation exercises. Users not only perceived the cognitive stimulation but also perceived the exercise as more challenging, engaging, and interesting when the cognitive load was increased, in contrast to the version without cognitive load. This allowed to meet the target of OB.8.

It is crucial to note that all participants in this experiment were healthy individuals, and subsequent tests with unhealthy subjects are necessary to validate these findings on a more representative sample.

8.1 Future works

This Ph.D. work introduced the ROS-MCPyRe system, highlighting its adaptability, customizability properties, and its effectiveness in incorporating social engagement during HRI. Additionally, it demonstrated the system's capability to seamlessly integrate both physical and cognitive rehabilitation aspects. However, as discussed in previous sections, there are certain aspects that this work couldn't address, opening avenues for future research in this field.

Firstly, achieving closed-loop control is paramount for the evolution of this work. Although ROS-MCPyRe can currently adjust its behavior based on data from the database or direct input from the therapist, it lacks the ability to autonomously fine-tune itself through the perception module. A promising starting point for implementing a perception system and an AI-powered closed-loop control is the work by Zheng *et al.*[106].

To enhance the reader's understanding, it's crucial to specify the nature of the desired adaptations that closed-loop control would bring to the system. For instance, it could enable the system to dynamically adjust the difficulty of exercises or increase both physical and cognitive challenges based on real-time feedback.

These considerations pave the way for the next potential evolution of this thesis. In addition to implementing closed-loop control for auto-tuning based on patient performance, a comprehensive testing campaign involving a different rehabilitation task, ideally encompassing both physical and cognitive stimulation, is recommended. Such a campaign would serve a dual purpose: validating the adaptability of the ROS-MCPyRe system and confirming its efficacy as a valuable tool to support therapists in their work.

A proposed rehabilitation task for this next phase could be related to ADL—specifically, assembling something with the assistance of a robotic arm or doing a cooking related task. This task is particularly beneficial for stimulating dexterity and planning capabilities in patients, as emphasized by Manera *et al.* [107].

Another element of development of this work, resides in the commistion of social and rehabilitation tasks in the same session. In this work, the social interaction of the robotic arm was tested alone and with the physical task, while the cognitive and physical task were only tested with a subset of the social cues (i.e., social movement was omitted). The author of this Ph.D. work forsees the commistion of the two, with an alternation of them. Specifically, the rehabilitation task, such as the handover, should be performed according to therapist will, but between succession of this task there should be a social action, so that the patients are stimulated and engaged in the same session. Such social interaction should not last too much time, but be tuned to improve the engagement and not break the rehabilitation flow. This task is rather complicated and a dedicated testing should be done, with a lot of care for people perception and reaction to this approach.

The next phase of this work entails seamlessly integrating social and rehabilitation tasks within a single session. While the robotic arm's social interaction was assessed both independently and alongside physical tasks, cognitive and physical tasks were evaluated using only a subset of social cues. The author envisions a harmonious combination of these elements, alternating sequences of rehabilitation tasks with brief social 'interludes.' This aims to engage and stimulate patients without disrupting the rehabilitation flow. Although intricate, dedicated testing is imperative to gauge people's perceptions and reactions accurately.

To achieve the purpose of strongly intertwined social and rehabilitation sessions, the future idea is to leverage Large Language Models (LLMs) to allow the use of natural interfaces (i.e., speech) to establish strong social interaction between humans and robots. LLMs such as GPT-4 have the potential to revolutionize social robotics, especially in personalized rehabilitation. LLMs can enhance the interaction capabilities of social robots by enabling more natural and adaptive communication with patients. Initially, LLMs will be integrated at the user level, allowing the core system to function while processing user inputs through the LLM. In a subsequent phase, LLMs will interact with users and generate context-specific information for the robotic system to read, thereby dynamically improving and adapting therapy sessions. To measure patient engagement, the system will utilize advanced techniques such as eye-tracking, body posture analysis, and facial expression recognition. Qualitative feedback will be gathered through open-ended questions and structured questionnaires. Ethical and privacy considerations are paramount in this integration, requiring robust data security measures and informed patient consent to comply with stringent regulatory standards. Healthcare professionals play a crucial role, needing to understand the importance and functionality of LLM models, be trained in their use, and be aware of associated risks. Their presence ensures they can intervene if the system does not perform as expected, maintaining patient safety and therapy effectiveness. For large-scale deployment, the system must be scalable and adaptable to various healthcare settings, addressing challenges like variability in patient needs and healthcare infrastructure differences. Future advancements may include integrating more sophisticated sensors, expanding rehabilitation exercises, and applying the technology to broader healthcare applications. Integrating LLMs into the ROS-MCPyRe system could significantly improve patient engagement and the overall effectiveness of the rehabilitation process, supported by a robust evaluation framework, ethical considerations, and interdisciplinary collaboration, holding great potential for advancing the field and improving patient outcomes.

Augmented Reality (AR) is another technology that holds significant potential for enhancing personalized rehabilitation. By overlaying digital information onto the physical environment, AR can provide patients with real-time guidance and feedback during exercises, making rehabilitation sessions more engaging and effective. Integrating AR into the ROS-MCPyRe system could involve using AR glasses or displays to show patients the correct movements, track their progress, and provide instant corrections. Patients could choose thematic elements, such as a Pokémon-style interface for children, to make sessions more enjoyable and tailored to their preferences. Additionally, incorporating AR can introduce virtual reality challenges on top of the real exercises created by the robotic arm, increasing variability and engagement as patients experience different exercises each time.

However, the technological integration of robotic systems with VR/AR is complex and should be approached with caution, as improper use could introduce more stress than benefits. To mitigate this, thorough testing and validation in clinical settings are essential. The long-term goal of integrating AR into the ROS-MCPyRe system is to shift rehabilitation towards highly personalized, effective, and engaging therapies. This approach promises to enhance patient adherence to rehabilitation protocols and accelerate recovery, ultimately leading to better patient outcomes and higher satisfaction with the rehabilitation process.

Additionally, there is a need to validate ROS-MCPyRe's adaptability to various robots and tasks. Future works should explore its adaptability to different robotic arms and potentially extend its use beyond arms. For instance, the integration of a rover-like platform could be explored for walking rehabilitation paradigms, with dedicated LEDs serving various rehabilitation actions. While the ROS-MCPyRe system anticipates accommodating these diverse robotic behaviors, rigorous testing is required to confirm its effective adaptability and the validity of incorporating such rehabilitation scenarios into standard therapy.

As emphasized in the previous section, a critical evolution of this work involves including a relevant sample of unhealthy individuals in the experimental setting. Comparing standard rehabilitation sessions with robot-aided sessions for both healthy and unhealthy groups would be crucial. The outcomes of such studies could definitively establish the validity of this work or unveil challenges that future researchers must address to ensure effective robot-aided rehabilitation.

Chapter 9

Conclusion

This Ph.D. work unveiled results in the domain of robotic rehabilitation, and based its fundamental structure on the development of the ROS-MCPyRe system, and its adaptability and cusomizability properties. The results underlined the possiblity to include in the same rehabilitation session features of social engagement, as well as physical and cognitive stimulation. During this work, multiple experiments have been defined, in order to verify the hypoteses, slowly increasing the layering of the system, until its completion. Therefore, his work defined a possible paradigm for the definition and implementation of a software system to pursue rehabilitation tasks, and to overcome modern limitations in this environment. The inclusion of participants with different backgrounds enhanced the social capabilities of a robotic arm and underlined the limitations of this approach, leaving room for further improvements and next versions of this system. Various participants also allowed the testing of the rehabilitation strategy and the robotic capablities on multiple subjects, thus allowing to verify the efficacy and portability of the overall system.

The results in the field of system development and engineering enphasized the validity of the modular approach and allowed single testing of the different modules. In this way the ROS-MCPyRe system has been verified and its potential tested in the different experiments of this work. The achievements obtained in the field of social engagement pose solid bases for further evolution of this approach, ensuring that social movements based on Laban theory are a valid solution for social robotics and that their implementation on a robotic arm is possible. In this work it was also possible to verify what kind of movements are the best, so to give a base of development to next researcher that will work on this topics. Also other social cues where verified and it was proved that for a robotic arm, it is beneficial to include in its social features also non verbal sounds and facial expression. Finally, the integration of cognitive and physical rehabilitation exercises within the same HRI was examined. The promising results demonstrate the effectiveness of this approach in inducing heightened cognitive load among participants. The optimized increase in task difficulty not only enhanced social engagement but also aligned with the gamification paradigm, as emphasized in current studies.

In conclusion, this work proved the possibility of creating a robotic system, that leverages the manipulation capabilities of a robotic arm to perform cognitive and physical stimulation; moreover, the study on social features allowes to conclude that also a robotic arm is capabe of triggering a social interaction in the participants for the benefit of the final social interaction.

Appendix A

Ph.D. Activities

A.1 Papers published

This section collects all the papers published and in preparation, produced as an output of this Ph.D. work. They are divided in groups, depending on the type of publication.

A.1.1 ISI Journal

- *"Robotic technologies for HRI in rehabilitation and assistance: a systematic review."*, **Carlo La Viola**, Chiara Brogi, Francesco Di Iorio, Laura Fiorini, Nicola Secciani, Francesco Buonamici, Luca Puggelli, Filippo Cavallo, Alessandro Ridolfi, Lapo Governi and Benedetto Allotta. IEEE Transactions on Neural Systems & Rehabilitation Engineering, 2023 (IN REVISION)

- *"Design and evaluation of personalized services to foster active aging: the experience of technology pre-validation in the Italian pilots."*, Letizia Lorusso, Miran Mosmondor, Andrej Grguric, Lara Toccafondi, Grazia D'Onofrio, Sergio Russo, Jure Lampe, Tarmo Pihl, Nicolas Mayer, Gianna Vignani, Isabelle Lesterpt, Lucie Vaamonde, Francesco Giuliani, Manuele Bonaccorsi, **Carlo La Viola**, Erika Rovini, Filippo Cavallo and Laura Fiorini, 2022 Sensors, MDPI.

- *"Dancing With Parkinson's Disease: The SI-ROBOTICS Study Protocol."*, Bevilacqua, R., Benadduci, M., Bonfigli, A. R., Riccardi, G. R., Melone, G., La Forgia, A., Macchiarulo, N., Rossetti, L., Marzorati, M., Rizzo, G., Di Bitonto, P., Potenza, A., Fiorini, L., Cortellessa Loizzo, F. G., **La Viola, C.**, Cavallo, F., Leone, A., Rescio, G., Caroppo, A., Manni, A., Maranesi, E. (2021). Frontiers in public health, 9, 780098. https://doi.org/10.3389/fpubh.2021.780098.

- *"Enhancing the Analysis of Robotic Arm Micro-movements for Rehabilitative Purposes through Laban Theory."*, **Carlo La Viola**, Laura Fiorini, Gianmaria Mancioppi, Leopoldina Fortunati, Filippo Cavallo, 2022, Robotic and Automation Letter (SUBMITTED).
- *"How do you like me? Effect of personality traits in the perception of a robotic arm endowed with various social cues."*, **Carlo La Viola**, Laura Fiorini, Gianmaria Mancioppi, Filippo Cavallo, 2023, International Journal of Social Robotics (IN PREPARATION)
- *"Teleoperation and Human-Robot Interaction in Public Spaces: Insights from a Field Study at the Avatar Festival."*, **Carlo La Viola**, Laura Fiorini, Gianmaria Mancioppi, Shogo Nishimura, Arne Hitzmann, Yukiko Horikawa, Filippo Cavallo and Takahiro Miyashita. Robotic and Automation Magazine (IN PREPARATION)

A.1.2 International Conference

- *"Humans and Robotic Arm: Laban Movement Theory to create Emotional Connection."*, **C. La Viola**, L. Fiorini, G. Mancioppi, J. Kim and F. Cavallo, 2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2022, pp. 566-571, doi: 10.1109/RO-MAN53752.2022.9900708.
- *"Design and development of a social assistive robot for music and game activities: a case study in a residential facility for disabled people."*, A. Sorrentino, L. Fiorini, **C. La Viola** and F. Cavallo, 2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), 2022, pp. 2860-2863, doi: 10.1109/EMBC48229.2022.9871513.

A.1.3 Italian Conference

- *"Influence of Personality Traits in the Perception of Movement by a Robotic Arm"*, **C. La Viola**, L. Fiorini, G. Mancioppi, J. Kim and F. Cavallo, (2023) 8th National Congress of BioEngineering, (GNB), June 21-23, Padova, Italy.

A.1.4 Workshop

- *"Dancing with a robot: an inner view on technology for rehabilitation and support to therapists in the stimulation of Parkinson's disease patients"*, F.G. Cornacchia Loizzo, **C. La Viola**, L. Fiorini, R. Bevilacqua, M. Benadduci, L. Rossi,

E. Maranesi, G. R. Riccardi, G. Pelliccioni, G. Melone, A. La Forgia, N. Macchiarulo, L. Rossetti, A. Potenza, A. Leone, G. Rescio, A. Caroppo, A. Manni, A. Cesta, G. Cortellessa, F. Fracasso, A. Orlandini, A. Umbrico, R. De Benedictis, Y. Gentili, A. Puglisi, G. Pioggia, M. Tritto, A. Merla, C. Porfirione, N. Casiddu, F. Burlando, A. Vacanti and F. Cavallo, 2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2022, APHRODITE Workshop

- *"Investigating the role of different social cues in the human perception of a social robotic arm."*, **C. La Viola**, L. Fiorini, G. Mancioppi, and F. Cavallo, 2022 14th Springer International Conference on Social Robotics (ICSR), 2022, ALTRUIST Workshop
- *"Please ASTRO, can you follow me? Design of a social assistive robot for monitoring gait parameters."*, Alessandra Sorrentino, Niccolò Vezzi, **Carlo La Viola**, Erika Rovini, Filippo Cavallo and Laura Fiorini, 2022 14th Springer International Conference on Social Robotics (ICSR), 2022, ALTRUIST Workshop.

A.2 External activities

Throughout my Ph.D. journey, I not only expanded my research capabilities but also enhanced my professional maturity by actively participating in diverse projects alongside researchers from various countries. Below is a brief list of projects, providing insights into these enriching experiences.

- Si-Robotics (Italy): Development of a sensing system to evaluate movement performances of people affected by Parkinson's disease; development and deployment of a humanoid robot as a therapist aid during the rehabilitation session.
- Pharaon (Europe): Creation of a technological ecosystem to monitor and support healthy aging, involving various actors and various location.
- Age-It (Europe): Promote healthy aging through the implementation of robot-aided rehabilitation and stimulation therapies.
- INTRIDE (Europe): Participation in seminars and workshops aimed at developing skills related to "Design for Sustainability".

- METRICS (Europe): Participation in robotics competitions, testing the robotic capabilities of vision and assistance to people.

A.3 Achievement of CFU

In this paragraph a table summary of the various courses and activities that granted the acquisition of 40 CFU, nedded for the fullfillment of the Ph.D. course.

Table A.1: CFU acquired during the Ph.D. for the internal courses

Date	**Speaker**	**Title**	**CFU**
06/12/2021	Prof. Scott Sampson	Task Automation in Professional Services - developing a theoretical framework	1
07/12/2021	Prof. Scott Sampson	Reengineering Professional Services - can we change the world?	1
24/02/2022	Alessandro Ridolfi	Trends and challenges in underwater robotics	1
18/05/2022	Prof. Peyman Givi	Turbulent Combustion Computation in the Age of Big Data and Quantum Information	1
24/05/2022	Prof. Beheshte Momeni	Case exercise: Managing industrial service business in good and bad times	1
29/09/2022	Laura Fiorini	APHRODITE workshop	2
16/12/2022	Prof. Oliver Korn	Designing an Emotion-Sensitive Companion Robot for the Elderly	1
16/12/2022	Prof. Kristiina Jokinen	Conversational AI meets Social Robots: Towards Virtual Coaches for Wellbeing and Smart Aging	1
16/12/2022	Prof. Alessandro Di Nuovo	Social Applications of Multimodal Cognitive Robots	1
8/2/2023	Laura Fiorini	Socially Assistive robotics and allied technology for healthy living and active ageing	2
23/2/2023	Andrés Meana Fernandez	Hygroscopic Cycle Technology – heat release from power cycles in hot and dry environments	1
6/3/2023	Nicola Secciani	Wearable Robotics: Trends and Challenges	1
24-25/10/2023	Leonardo Leoni	Bayesian Modeling and Machine learning for reliability analysis and condition-based maintenance	3
27/10/2023	Alessandra Cantini	Sustainability in supply chain management	2
22/11/2023	Pietro Valdastri	#BioroboticsSeries SOFT ROBOTICS FOR EARLY DETECTION AND TREATMENT OF CANCER	1
		Totale CFU:	20

Table A.2: CFU acquired during the Ph.D. for the external courses

Date	**Speaker**	**Title**	**CFU**
03/2022 - 06/2022	DIDA (Unifi) DIEF (Unifi) ELISAVA (Barcelona School of design and engineering) WSB University (Polonia) University of Art and Design UAD (Cluj-Napoca, Romania)	INTRIDE PROJECT	15
		Totale CFU:	15

Table A.3: CFU acquired during the Ph.D. for the soft skills

Date	**Speaker**	**Title**	**CFU**
29 e 30/06/2021	DIDA, IUSSAF	Exploring the Future, Le mappe della Ricerca	3
03/2022 - 06/2022	DIDA (Unifi) DIEF (Unifi) ELISAVA (Barcelona School of design and engineering) WSB University (Polonia) University of Art and Design UAD (Cluj-Napoca, Romania)	INTRIDE PROJECT (Sof skills module)	5
		Totale CFU:	8

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