Safe Manipulation of Humans in Robot-driven Physical Human-Robot Interaction

TESIS DOCTORAL POR
COMPENDIO DE PUBLICACIONES

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UNIVERSIDAD DE MÁLAGA

Doctorado de Ingeniería Mecatrónica
Departamento de Ingeniería de Sistemas y Automática
Escuela de Ingenierías Industriales
2023

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EDITA: Publicaciones y Divulgación Científica. Universidad de Málaga

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Realizada bajo la tutorización de Jesús Manuel Gómez de Gabriel y dirección de Jesús Manuel Gómez de Gabriel y Juan Manuel Gandarias Palacios.

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Málaga, 7 de Noviembre de 2023

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Abstract

Due to the emergence of collaborative robots, humans and robots have been working in close proximity, and in some tasks, even sharing a common goal. Under these circumstances, physical contact between human and robot has a high probability of occurrence, which has made the field of physical Human-Robot Interaction (pHRI) a hot research topic. Robots could be introduced in home environment to help people in the activities of daily life, assist people with mobility issues, and even help nurses in hospitals. Despite the impact that pHRI applications could have in society, the current state-of-the-art in this field is focused on collaboration, i.e., on how human and robot work together towards the completion of a given task minimizing the physical interaction between both. However, there still a lack of works about pHRI in which robots have a proactive role. This thesis tackles the challenge of studying and implementing robot-driven pHRI tasks. To this end, such a challenge is decomposed into its main components.

First, the mechanical coupling between human and robot becomes crucial in robot-driven pHRI tasks. Hence, a compliant underactuated gripper specifically designed for human limb grasping and human limb manipulation is introduced. The kinetostatic model of the gripper is computed, allowing for the estimation of the grasping forces. The gripper has been built and tested. Compliance and grasping force estimation and control have been successfully evaluated. Results prove that the proposed finger arrangement offers good performance, making our design suitable for pHRI applications.

Secondly, human intention during the interaction is a valuable source of information about the human comfort with the task. Tactile sensing is vital for pHRI, as constant occlusions while grasping make it hard to rely on vision or range sensors alone. Hence, measuring interaction forces in the gripper is crucial to avoid injuries, predict user intention and perform successful collaborative movements. A new method for in-hand estimation of the interaction forces in a compliant gripper is presented. An experimental evaluation of the method and an example application in a control system with active compliance have been included to evaluate performance. Results show that the method offers good performance at measuring the lateral interaction forces and torque around the gripper's Z-axis.

To properly manipulate a human limb, the kinematic model of such limb and the real tracking of limb's joints positions and velocities are needed. In this Thesis a method to estimate the parameters of the kinematic model of a human upper-limb is presented. Such a method relies on the kinesthetic information of a robotic manipulator that moves the human limb, requiring only a simple ascendant motion. Two estimation methods are implemented and compared: i) Hough transform (HT); ii) least squares (LS). The results from six experiments with a dummy arm demonstrate the repeatability and effectiveness of the proposed methodology, which can be used in several rehabilitation robotic applications.

Then, two controllers under the assist-as-needed (AAN) paradigm are developed. The first one serve as a balance assistant to the elderly or people with neurological disorders such as Ataxia or Parkinson's. A mobile collaborative robot with an interaction-assistive whole-body interface is used to help people unable to maintain balance. The postural balance of the human body is estimated through the projection of the body Center of Mass (CoM) to the support polygon (SP) representing the quasi-static Center of Pressure (CoP). Two strategies are developped and evaluated in a laboratory setting on healthy human participants. Quantitative and qualitative results of a 12-subjects experiment are then illustrated and discussed, comparing the performances of the two strategies and the overall system. The second AAN strategy assist the user in the following of a predetermined Cartesian path, providing the minimum required assistance to users. A novel AAN reactive control system where input commands are weighted by their respective local performances is proposed. With the proposed approach, rather than minimizing tracking errors or differences to expected velocities, humans receive more help depending on their needs. The system has been tested on 10 healthy subjects. Tests consisted of completing an on air a planar trajectory displayed on a screen with both arms with the proposed AAN controller, without assistance, and with the most related state-of-the-art AAN controller.

Finally, general conclusions to the field of robot-driven pHRI are extracted. Overall, although some extra considerations should be taken into account, the outcomes of this Thesis lay the foundations for the implementation of a robot-driven pHRI task.

Resumen

Motivación

Inicialmente, los robots se crearon para automatizar tareas simples y repetitivas en la industria. Para garantizar la seguridad de los operarios, el espacio de trabajo estaba dividido: las personas tenían su propia zona de trabajo libre de robots; mientras que los robots trabajaban encerrados en jaulas protectoras libres de humanos. Sin embargo, este enfoque limitaba el número de aplicaciones que los robots podían automatizar. Por lo tanto, la situación de los robot industriales evolucionó adoptando otras formas de trabajar tales como coexistencia, cooperación, y colaboración [1]. Cuando robots y humanos trabajan cerca, hay altas probabilidades de que ocurra interacción física. Por motivos de seguridad, se han desarrollado y estandarizado robots colaborativos (cobots) capaces de trabajar a corta distancia de los seres humanos [2]. Los avances recientes en control han hecho del campo de la interacción física robot-humano (physical Human-Robot Interaction, pHRI) un tema de interés para la comunidad científica [3]. Sin embargo, durante pHRI el contacto físico, a menudo, es limitado. Por motivos de seguridad, normalmente es el operario el encargado de iniciar, mantener, y finalizar la interacción, relegando al robot un papel reactivo.

Sin embargo, considerar el robot como un elemento pasivo durante pHRI limita en gran medida el alcance de la interacción, puesto que el robot, al igual que el humano, posee información valiosa sobre la tarea que no se está aprovechando. Entonces, si los robots ya han probado su utilidad durante pHRI con un comportamiento pasivo, ¿por qué no hacer robots mas participativos durante la interacción física con humanos? Un robot proactivo físicamente podría ser usado en una gran cantidad de situaciones además de en aplicaciones industriales. Es posible imaginar un robot ayudando a una persona dependiente en sus actividades cotidianas [4], o incluso en un hospital ayudando al personal sanitario a atender a pacientes delicados o infecciosos [5]. Los beneficios que aportan los robots proactivos físicamente no se limitan solo al propio hecho de tocar a las personas. Las personas, como seres sociales, necesitan atención y afecto que puede ser proporcionado por medio del contacto físico, tanto por un robot autónomo [6] como por un sistema robótico de telepresencia [7]. Por ejemplo, se ha demostrado que el contacto físico con robots puede ser beneficioso para los niños con autismo [8].

Por los motivos expuestos anteriormente, queda claro que los robots con capacidad para interactuar físicamente con las personas pueden contribuir en gran medida a la sociedad.

Sin embargo, el campo de pHRI es un area de la robótica bastante inexplorado debido a su complejidad. Interactuar activamente con humanos implica que el robot conoce como es el comportamiento dinámico del humano. Sin embargo, los humanos son sistemas altamente no lineales, y como tales, no se puede predecir su comportamiento sin tener en cuenta el contexto. Además, los humanos pueden cambiar su contribución[1] a la tarea de acuerdo a su predisposición a colaborar con el robot. Por tanto, esta tesis abordará los requisitos para la implementación de tareas pHRI con robots proactivos considerando que las personas tienen buena predisposición.

Objetivos

Esta tesis se centra en el desafío de la manipulación segura y autónoma con robots colaborativos para proporcionar asistencia en situaciones en las que el robot inicia la interacción o presenta un comportamiento activo. En concreto, el objetivo principal de esta tesis es el desarrollo de un framework genérico para la integración de tareas pHRI con robots proactivos. Dicho objetivo se puede descomponer en varios objetivos parciales:

- El desarrollo de manos robóticas para el agarre de extremidades humanas. Cuando un robot manipula una extremidad humana, el Efector Final (EF) del robot gana especial importancia. En la literatura se pueden encontrar una amplia variedad de EFs, pero ninguno ha sido diseñado explícitamente par el agarre y la manipulación de extremidades humanas. Esta tesis pretende poner solución a este problema proponiendo un nuevo diseño de mano robótica específicamente diseñada para agarrar extremidades humanas.

- Estimación de los parámetros del modelo cinemático de las extremidades humanas. Antes de comenzar una tarea, el robot debe conocer la cinemática de las extremidades humanas para poder manipularlas de forma segura. El modelado del cuerpo humano es un tema extenso, existen muchos trabajos al respecto pero solo unos pocos pueden calcularse en tiempo real, y en todos ellos se debe conocer de antemano algo de información sobre el humano con el que se va a interactuar. Esta tesis aprovecha la información del movimiento (información kinestésica) de un robot colaborativo durante la manipulación de una extremidad humana para estimar su modelo cinemático.

- El desarrollo de comportamientos para la asistencia a personas bajo el paradigma ”Assist-As-Needed” (AAN). Dicho paradigma abarca aquellos comportamientos en los que un robot ayuda a una persona solo cuando detecta que la persona así lo necesita, respetando la voluntad de la persona siempre que su desempeño sea bueno [9]. Actualmente, este paradigma está orientado a la robótica de rehabilitación, limitando su uso a la clínica del fisioterapeuta. Esta tesis pretende

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[1] Aunque la contribución a la tarea puede considerarse una variable continua, a lo largo de esta tesis, se consideran solo dos niveles de actividad para ambos agentes, robot y humano. Un agente se considera activo si contribuye a la tarea por su propia voluntad; y se considera pasivo si el agente ni contribuye ni se opone al movimiento.

desarrollar comportamientos bajo el paradigma AAN para situaciones cotidianas en las que el robot agarra a la persona.

Antecedentes

La integración de una tarea pHRI se puede separar en dos partes, la física y la cognitiva. La parte física se centra en el humano, el robot, y en cómo se produce la interacción, es decir, en el sistema físico que une robot y humano, el EF. Por otro lado, la parte cognitiva se centra en el comportamiento, es decir, en el controlador del robot, las reglas de comportamiento que se implementan para la tarea, y en la estimación de la intención de la persona. Cada uno de los factores involucrados en las partes física y cognitiva constituye un campo de investigación por sí mismo.

Reglas de comportamiento

Las reglas de comportamiento proporcionan al robot las directivas sobre qué está permitido o qué acciones puede realizar durante la interacción. Dichas reglas pueden cambiar dependiendo del contexto de la tarea. En el campo de la robótica colaborativa, un campo de investigación centrado en la colaboración entre robots y humanos para la consecución de una tarea, se pueden encontrar bastantes trabajos sobre la cooperación robot-humano. En la robótica colaborativa, el robot se considera una herramienta, por lo que los artículos se centran en los beneficios que aporta la presencia del robot para el humano. De esta forma, algunas tareas colaborativas, como la mejora de la ergonomía [10, 11] o la asignación de funciones [12, 13], no requieren de contacto físico entre humanos y robots. Incluso en aquellos casos en los que la interacción física es inevitable, se minimiza el contacto. Que un robot toque a una persona es, generalmente, una situación no deseada, por lo que es el humano el encargado de iniciar y mantener la interacción de forma unilateral [14]. No obstante, en el contexto de esta tesis, se van a tratar situaciones en las que el robot toca intencionadamente al humano, por lo que es de especial interés el desarrollo de reglas de comportamiento para tal situación.

En general, en un contexto médico o asistivo, varias situaciones requieren de un contacto intencionado y continuo con el paciente. El campo de la robótica de asistencia se centra en gran medida en el desarrollo de reglas de comportamiento para robots sociales [15–17], aunque recientemente la asistencia física está ganando importancia [18, 19]. Por otro lado, en el campo de la robótica de rehabilitación, la interacción física es necesaria en la mayoría de los casos [20]. Sin embargo, se sigue tratando como herramientas a los robots incluso en este campo. Los manipuladores empleados para rehabilitación utilizan EFs pasivos que requieren que la persona se agarre [21] o se fije [22] al robot. Una vez más, es el humano el agente encargado de iniciar y mantener la interacción, mientras que el robot aplica una ligera resistencia al movimiento del humano.

Así, el numero de artículos publicados en los que un robot implementa unas reglas de comportamiento que le permiten tocar intencionadamente al humano es casi nulo, a pesar de que tendría un gran impacto en la sociedad. En un contexto médico, Kowalski [23] usó un robot para ayudar a las enfermeras a reposicionar a los pacientes en la cama. El robot, instalado al lado de la cama, se introduce por debajo del paciente y aplica una fuerza vertical en la espalda del paciente mientras que la enfermera lo reposiciona. Por otro lado, Anquing [24] usó un robot equipado con una sonda ultrasónica para automatizar el proceso de oscultación de pacientes con escoliosis. En dicho proceso, el robot se encargaba de mover la sonda a lo largo de la columna vertebral del paciente manteniendo siempre el contacto sonda-paciente. Además de las consideraciones físicas, el impacto psicológico que la interacción física tiene sobre el humano también es de interés. En [25] los autores estudian la reacción de los humanos ante el contacto físico inesperado con un robot. En la misma linea, Block [26] desarrolló un robot para abrazar. Los autores analizan varias estrategias de abrazo y su impacto en la psicología de las personas.

Manos robóticas para pHRI

Actualmente, existe un amplio catalogo de manos robóticas, desde manos genéricas hasta manos para soluciones específicas [27, 28]. Sin embargo, las manos robóticas para pHRI están orientadas a la colaboración robot-humano [29, 30]. En la bibliografía se pueden encontrar manos robóticas que, aunque no fueron diseñadas para el agarre de humanos, se pueden emplear para tal fin [31, 32]. En este sentido, se puede encontrar una gran cantidad de trabajos en los que se detallan manos robóticas con forma humana para la manipulación diestra de objetos genéricos [33]. Este tipo de EF han sido utilizados para pHRI en aplicaciones como la telepresencia para dar apretones de manos [34]. El apretón de manos es la tarea más explorada, y probablemente la única, en la que un robot agarra una parte del cuerpo humano. Sin embargo, un apretón de manos tiene un objetivo más social que físico, es decir, es una tarea con unos requisitos físicos muy bajos.

Como se comentó anteriormente, un objetivo parcial de esta tesis se centra en el desarrollo de manos robóticas para el agarre de extremidades humanas. Sin embargo, son escasos los trabajos que tratan manos robóticas diseñadas específicamente para el agarre de humanos. Xu [35] diseñó un mano robótica para el agarre de humanos compuesta por dos dedos inspirados en los dedos humanos. En una línea similar pero con un objetivos diferente, Hellman [36] presentó un método para determinar si el robot, al intentar agarrar un objeto, ha atrapado accidentalmente alguna parte del humano. Por otro lado, el grupo de investigación en el que se desarrolla esta tesis ha contribuido al campo del desarrollo de manos robóticas para pHRI. En particular, Gandarias [37] presentó una mano robótica para la recolocación del brazo de una persona tumbada en una superficie horizontal; Ballesteros [38] obtuvo un modelo de machine learning para estimar las fuerzas de interacción que una persona hace sobre una manó robótica; y Pastor [39] usó una mano robótica compuesta por un dedo con un sensor táctil sobre el que ejercen presión dos dedos más para el agarre de antebrazos humanos y determinar en qué sección del antebrazo se produce el agarre. En todos estos trabajos, la mano robótica tiene dedos similares, aunque colocados en diferentes configuraciones. Dichos dedos se diseñaron específicamente para el agarre de extremidades humanas utilizando un mecanismo subactuado, lo que permite que el dedo se adapte a la forma del brazo humano. En capítulos sucesivos, se mejorará el diseño de los dedos tomando como base los usados en los trabajos comentados anteriormente.

Control del robot

La seguridad es importante durante pHRI, por lo que está muy extendido el uso de controladores que se adapten a la interacción con el entorno. Predomina el uso de dos controladores: el control de impedancia, y el control de admitancia. Ambos controladores imponen in comportamiento dinámico al robot, de forma que se comporte como un sistema mecánico pasivo masa-muelle-amortiguador, modelado por tres matrices: la matriz de rigidez, la de amortiguación y la de inercia. La precisión y la estabilidad del sistema depende de los valores que reciban dichas matrices. Las ventajas y desventajas de ambos controladores son bien conocidas. El control de impedancia recibe entradas de movimiento y aplica al robot una referencia de fuerza, es estable y robusto en la interacción con el entorno pero presente baja precisión en el movimiento. Por el contrario, el control de admitancia proporciona al robot una consigna de velocidad tomando como entrada una fuerza, es muy preciso en movimiento pero puede llegar a ser inestable cuando interactúa con entornos rígidos. En la literatura se pueden encontrar multitud de trabajos sobre la teoría y la implementación de ambos controladores [40–43]. Para compensar las desventajas de estos controladores, es usual el uso de controladores de impedancia/admitancia variable [44–47] que se adapten a las necesidades de la interacción. Un enfoque diferente para optimizar el comportamiento de ambos controladores se hace en [48], donde se conmuta a alta frecuencia entre un controlador de impedancia y otro de admitancia para implementar un controlador híbrido con las mejores cualidades de cada uno.

Sin embargo, a pesar de que estos controladores permiten que humanos y robots trabajen cerca, no garantizan la seguridad de la persona. Para mejorar la seguridad, se deberían de imponer sobre el sistema restricciones en forma de posición, fuerza o velocidad. Como los robots son sistemas no lineales, se puede hacer uso de otras formas de control avanzado. El control predictivo por modelos (Model Predictive Control, MPC) es una estrategia de control basada en la optimización de una funcion de coste sujeta a restricciones, por lo que constituye una buena opción para la implementación de tareas pHRI [49]. Merckaert [50] usó una variante del MPC para imponer restricciones sobre el estado y la entrada de un robot colaborativo. En esta dirección, en [51] se propone una estrategia que unifica el problema de la cinemática inversa y el control del robot en un solo problema de optimización. Por otro lado, también se pueden utilizar redes neuronales artificiales (Artificial Neural Networks, ANN) para controlar robots colaborativos. En [52] se usa un método de aprendizaje basado en ANN para estimar la dinámica del robot, y posteriormente controlarlo imponiendo restricciones de movimiento.

Reconocimiento de la intención humana

Como se mencionó anteriormente, las reglas de comportamiento necesitan información sobre el estado del robot y del humano. El estado del robot se puede observar a partir de la información proporcionada por sus sensores internos, pero obtener información acerca del estado del humano es más complejo. La intención del humano no es directamente observable, y normalmente, tiene que ser estimada a partir de las acciones del mismo. Es esencial poner dichas acciones en contexto, porque incluso un comportamiento básico puede tener interpretaciones muy diferentes en distintas situaciones. La intención del humano debería ser estimada en tiempo real, por lo que es preferible el uso de modelos simples. Por tanto, solo las variables que son determinantes de acuerdo con el contexto en el que se encuentra la persona deberían ser consideradas como entrada al modelo. La intención puede ser estimada en términos de objetivos, movimientos (cómo quiere moverse la persona), o emociones (cómo se siente la persona).

Los modelos de reconocimiento de objetivos son capaces de discernir qué meta pretende alcanzar el humano entre un conjunto de posibles objetivos. En la literatura se pueden encontrar multitud de modelos basados en ANN para el reconocimiento de objetivos [53, 54]. En [55] se explora la idea de usar imágenes bidimensionales para reconocer la intención de cruzar o no de ciclistas y peatones. Por otro lado, también está extendido el uso de modelos probabilísticos [56]. Petkovic desarrolló en [57] un modelo para inferir la intención de un operario de almacén a partir de sus movimientos. Dicho modelo era capaz de estimar la probabilidad de que el operario fuera a hacer cada tarea en tiempo real. Si se considera más de una persona al mismo tiempo, la dificultad del modelo crece. En [58] los autores abordan ese reto empleando árboles de decisión, considerando que el entorno es completamente observable.

Los modelos de reconocimiento de movimiento, intentan prever como se va a mover una persona para adaptar en consecuencia el comportamiento del robot [59] o controlar una prótesis [60]. Por tanto, la principal fuente de información para estos modelos son los sensores de electromiografía de superficie (surface electromyography, sEMG) [61, 62], seguidos de los sensores de electroencefalografía (EEG) [63, 64] y los sensores de fuerza[65]. Aunque los modelos de reconocimiento de movimiento se suelen basar en el uso de deep learning y ANNs, también existen trabajos que fusionan los datos obtenidos por sensores sEMG y EEG [66]. Con respecto al reconocimiento de emociones, hay trabajos enfocados en estimar las emociones humanas a partir de la voz [67], imágenes de expresiones faciales [68], y combinaciones de ambas [69].

Contribuciones

Esta tesis contribuye al campo de la interacción física robot-humano y la robótica de asistencia:

- El diseño e implementación de manos robóticas para el agarre y manipulación segura de extremidades humanas se desarrolla en el capítulo 2. El diseño de los dedos permite calcular las fuerzas de agarre e interacción a partir de información kinestésica del dedo, tal como se muestra en el capítulo 3.

- El desarrollo de un método para la estimación de parámetros del modelo cinemático del brazo humano a partir de información kinestésica que proporcionan los sensores de un robot mientras lo manipula, como se muestra en el capítulo 4.
- El desarrollo de reglas de comportamiento bajo el paradigma AAN; en concreto, una estrategia de asistencia al equilibrio con un manipulador móvil, y un esquema de control compartido reactivo para la asistencia en tareas de manipulación se presentan en los capítulos 5 y 6 respectivamente.

El contenido de los capítulos y la estructura de la tesis se describen con mas detalle en las siguientes secciones. A medida que el lector profundiza en este documento, se dará cuenta de la progresión en el comportamiento de robot y humano. La idea de esta tesis es avanzar hacia situaciones realistas partiendo de unas suposiciones iniciales.

Publicaciones

A continuación se muestra un listado de las publicaciones que avalan esta tesis y la contribución del autor a cada una de acuerdo con la taxonomía CRediT.

Artículos en revistas

- J. Ruiz-Ruiz, J. M. Gandarias, F. Pastor and J. M. Gómez-De-Gabriel, ”Upper-Limb Kinematic Parameter Estimation and Localization Using a Compliant Robotic Manipulator”, IEEE Access, vol. 9, pp. 48313-48324, 2021, doi: 10.1109/ACCESS.2021.3067108, [70]. Contribución del autor: conceptualization, data curation, formal analysis, methodology, resources, software, visualization, writing – original draft, and writing – review & editing.
- F. J. Ruiz-Ruiz, J. Ventura, C. Urdiales, J. M. Gómez-de-Gabriel, ”Compliant gripper with force estimation for physical human–robot interaction”, Mechanism and Machine Theory, Volume 178, 2022, 105062, doi:10.1016/j.mechmachtheory.2022.105062, [71]. Contribución del autor: data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing – original draft, and writing – review & editing.
- F. J. Ruiz-Ruiz, C. Urdiales, and J. M. Gómez-de-Gabriel, “Estimation of the Interaction Forces in a Compliant pHRI Gripper”, Machines, vol. 10, no. 12, p. 1128, Nov. 2022, doi: 10.3390/machines10121128, [72]. Contribución del autor: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing - original draft, and writing - review & editing.

Actas en congresos

- F. J. Ruiz-Ruiz, A. Giammarino, M. Lorenzini, J. M. Gandarias, J. H. Gómez-De-Gabriel and A. Ajoudani, ”Improving Standing Balance Performance through the Assistance of a Mobile Collaborative Robot,” 2022 International Conference on Robotics and Automation (ICRA), 2022, pp. 10017-10023, doi: 10.1109/ICRA46639.2022.9812284, [73]. Contribución del autor: conceptualization, investigation, methodology, resources, software, validation, visualization, writing - original draft, and writing - review & editing.

Otras Contribuciones

- F. J. Ruiz-Ruiz, C. Urdiales, M. Fernández-Carmona and J. M. Gómez-de-Gabriel, “A Reactive performance-based Shared Control Framework for Assistive Robotic Manipulators”, Under Review. Contribución del autor: conceptualization, data curation, investigation, methodology, resources, software, validation, visualization, writing – original draft, and writing – review & editing.

Actividades de investigación relacionadas

Esta tesis comenzó en noviembre del 2019 dentro del grupo de investigación de Robótica y Mecatrónica del departamento de Ingeniería de Sistemas y Automática de la Universidad de Málaga. Desde entonces, el autor ha trabajado para contribuir al estado del arte del campo de pHRI con los trabajos que avalan esta tesis, mientras llevaba a cabo actividades complementarias. El autor ha colaborado en la consecución de los siguientes proyectos:

- Proyecto singular de transferencia UMA-CEIATECH-23 (RAFI).
- Proyecto de investigación UMA20-FEDERJA-052 (HANDCARE).
- Proyecto del Plan Nacional PID2021-127221OB-100.
- Proyecto de transferencia de la Junta de Andalucía AT21-00051.

Otras publicaciones

Artículos en revistas

- F. Pastor, F. J. Ruiz-Ruiz, J. M. Gómez-de-Gabriel and A. J. García-Cerezo, ”Autonomous Wristband Placement in a Moving Hand for Victims in Search and Rescue Scenarios With a Mobile Manipulator,” in IEEE Robotics and Automation Letters, vol. 7, no. 4, pp. 11871-11878, Oct. 2022, doi: 10.1109/LRA.2022.3208349, [49].

Otras actividades

Durante el desarrollo de esta tesis, el autor ha participado en otras actividades de investigación, que han contribuido de forma indirecta al desarrollo de la tesis, al mismo tiempo que a su desarrollo profesional. Así pues, el autor ha tenido la oportunidad de participar en el European Robotic Forum 2020, en la zona de exposición de la mano de la empresa KUKA roboter GmbH. El autor también ha asistido a workshops organizados durante congresos internacionales prestigiosos en el campo de la robótica, como el IEEE International Conference on Robotics and Automation (ICRA) 2020, y Humanoids 2020. Además, el autor ha defendido un trabajo en el ICRA 2022 en Filadelfia, EEUU. Por otro lado, el autor también ha asistido a webinars de interacción robot-humano y sensores inteligentes organizados por la Universidad de Málaga y el IEEE.

El autor ha hecho una estancia de tres meses en el Human-Robot Interfaces and Interaction (HRI^2) lab en el Istituto Italiano di Tecnologia (IIT), tras la que se publicó un trabajo en el congreso internacional ICRA 2022. El autor también ha servido de revisor para revistas de alto impacto (Biomimetics, Mechanism and Machine Theory, e IEEE Robotics and Automation Letters entre otras) y para congresos internacionales (como ICRA e IROS).

Estructura de la tesis

Como se mencionó con anterioridad, esta tesis contribuye al inexplorado campo de pHRI y la manipulación de humanos. Esta tesis se presenta como un compendio de artículos, que le dan forma al cuerpo del documento, distribuidos en 5 capítulos. Esta tesis se estructura como sigue:

- En el capítulo 2 se presenta una mano robótica para el agarre de extremidades humanas y se obtiene el modelo cineto-estático analítico del dedo para estimar las fuerzas de interacción y agarre. La mano se compone de cuatro dedos subactuados con dos falanges cada uno y un eslabón elástico en la cadena cinemática del dedo, lo que le permite medir las fuerzas aplicadas en el agarre. Este capítulo se centra en la garra y sus características, por lo que no participan ni humanos ni robots. Por tanto, como no se desarrolla ninguna tarea, tanto el humano como el robot pueden ser considerados pasivos.
- El capítulo 3 presenta un método para estimar las fuerzas de interacción que un humano aplica mientras permanece agarrado con una mano robótica. Esto se consigue analizando la distribución de fuerzas de los dedos. En este capítulo, el humano permanece activo, mientras que el robot es pasivo.
- El capítulo 4 presenta un método para la estimación de los parámetros del modelo cinemático del brazo humano a través de la manipulación del mismo. Bajo la suposición de que la persona se encuentra inconsciente, el robot lo agarra por el antebrazo e intenta seguir un camino definido con anterioridad bajo un control

de impedancia. La desviación del camino de referencia sirve como entrada para estimar los parámetros del modelo. En este capítulo el robot es activo y el humano pasivo.

- En el capítulo 5 se presenta un método para la asistencia al equilibrio con un manipulador móvil bajo el paradigma AAN. El estado de equilibrio del humano se estima gracias a la información proporcionada por un sistema de captura de movimiento, que monitoriza el centro de masas de la persona y su polígono de soporte. En este capítulo el humano es activo y el robot es reactivo.
- El capítulo 6 presenta un esquema de control compartido para manipulación de humanos bajo el paradigma AAN. Para el funcionamiento de dicho controlador se considera que ambos agentes contribuyen a la tarea simultáneamente. Los comandos proporcionados por el robot y el humano se combinan de acuerdo con factores de eficiencia para obtener el comando compartido, que es el que se ejecuta finalmente. En este capítulo, tanto el humano como el robot son activos.
- Finalmente, en el capítulo 7 se presentan las conclusiones y las posibles líneas de trabajo futuras.

Conclusiones

Esta tesis ha resaltado los desafíos pendientes en el campo de la interacción física robot-humano. En particular, se ha evidenciado la necesidad de trabajos relativos a la interacción intencionada con humanos. Este trabajo ha presentado una serie de contribuciones en este campo, en el formato de una tesis por compendio de artículos, publicados en revistas y congresos científicos internacionales. Dichas contribuciones se pueden resumir de la siguiente manera:

- El EF del robot es un elemento crucial cuando se interactúa físicamente con el entorno, y gana mayor importancia cuando se interactúa con humanos. La arquitectura del EF define la forma en que el robot interactúa con el entorno. En el caso de tareas pHRI con robots proactivos, el EF debería cumplir una serie de requisitos para asegurar la seguridad de la persona. El capítulo 2 ha enfatizado la necesidad de diseñar una garra para el agarre y manipulación de extremidades humanas. Se ha presentado el diseño de una mano robótica de cuatro dedos subactuados. La presencia de muelles en la cadena cinemática de los dedos permiten la medida de las fuerzas de agarre, mientras que la estructura subactuada permite que los dedos se adapten a la forma de la extremidad agarrada. Tomando esto como base, en el capítulo 3, se analiza el gradiente de fuerzas cartesianas aplicadas por los dedos para extraer información de las fuerzas de interacción que el humano aplica a la mano robótica que lo mantiene sujeto.
- En el capítulo 4, se ha presentado una maniobra para la estimación de los parámetros del modelo cinemático del brazo humano, a partir de la información kinestésica que proporciona un robot mientras manipula el brazo humano. La estimación de

un modelo de las extremidades humanas que se pueda calcular en tiempo real es esencial para el campo de pHRI. Se ha demostrado que el uso de sensores específicos, como los sistemas de movimiento, no es necesario. En su lugar, se puede aproximar el modelo adoptando una estrategia diferente. El método también tiene sus limitaciones. Para el funcionamiento del método, se restringió el movimiento del brazo humano a un plano, de forma que se pudiera considerar un modelo cinemático simplificado. Para diseñar una estrategia de manipulación adecuada, se consideró que el humano estaba tumbado sobre su espalda. Esta suposición puede considerarse como un criterio de implementación más que como una limitación; si se considerara una posición diferente para la persona habría que recalcular la estrategia de manipulación. Además, el humano se considera completamente pasivo, por lo que el movimiento del humano solo se debe a las acciones del robot.

- En el capítulo 5 se presentaron dos estrategias para la asistencia al equilibrio con un manipulador móvil. Para monitorizar el estado de equilibrio del humano se hace uso de un sistema de capturas de movimiento, mientras que el humano se mantiene agarrado al EF del robot. Cuando el sistema detecta una pérdida de equilibrio, el robot aplica una fuerza sobre el humano para evitar la caída. Durante este procedimiento, el humano estaba activo, podía mover el brazo sin restricciones, mientras que el robot reaccionaba al comportamiento del humano ayudándolo cuando era necesario y, en caso contrario, no impidiendo su movimiento. Sin embargo, la dificultad que entraña detectar la pérdida de equilibrio de una persona desplazándose limita la aplicación del sistema al caso en el que la persona permanece de pie. Ademas, solo se considera la pérdida de equilibrio en el plano sagital.

- Finalmente, en el capítulo 6 presentó un control compartido reactivo para la asistencia a humanos en tareas de manipulación bajo el paradigma AAN. Dicho controlador requiere de la existencia de un acoplamiento físico entre humano y robot, que se hizo a través de la mano robótica desarrollada en capítulos anteriores. Esta estrategia de control combina la intención del humano (extraída de las fuerzas de interacción) con el comando propuesto por el robot para seguir el camino (obtenido del algoritmo de seguimiento de caminos implementado en el robot) en base a la eficiencia local de cada comando. La eficiencia local se obtiene de acuerdo con dos factores de eficiencia: el factor de suavidad (penaliza cambios de dirección bruscos), y el factor de directividad (favorece aquellos comandos que contribuyen a seguir el camino). Como resultado, durante la aplicación de esta estrategia de control, tanto el robot como el humano contribuyen a la tarea simultáneamente. Sin embargo, el controlador está limitado a traslación cartesiana, la orientación no se considera en esta estrategia.

En general, los resultados de este trabajo sientan las bases para la implementación de tareas pHRI con robots proactivos. Se muestra una cierta progresión que puede ser observada a dos niveles: en la interconexión entre contribuciones; y en la naturaleza de la interacción robot-humano. Con respecto a las contribuciones, este documento sigue un orden claro: primero se presenta una garra específicamente diseñada para agarra humanos y sus capacidades sensoriales; posteriormente se obtiene un modelo cinemático del brazo humano; se construye una aplicación básica bajo el paradigma AAM sin acoplamiento fijo entre robot y humano; y por último se presenta un esquema de control compartido bajo el paradigma AAN en el que robot y humano trabajan de manera conjunta y mientras el robot agarra al humano. Esta última contribución, presentada en el capítulo 6, constituye una aplicación pHRI con robot proactivo plenamente funcional, que representa la integración de todas las lecciones aprendidas durante el desarrollo de esta tesis. Con respecto a la naturaleza de la interacción, se puede observar como el nivel de interacción evoluciona conforme avanza la tesis. Se presenta un robot completamente activo manipulando a un humano completamente pasivo en el capítulo 4. Después, se presenta a un humano activo asistido por un robot reactivo en el capítulo 5. Para finalizar, en el capítulo 6, humano y robot son completamente activos durante la interacción. La seguridad requiere una mención especial. En el estado del arte, la seguridad se trata de manera preventiva, es decir, el robot reacciona para minimizar las consecuencias de una posible colisión. En esta tesis, la seguridad se ha incluido en el controlador del robot, y ha sido incentivada por el autor a todos los voluntarios durante los experimentos.

Aunque esta tesis cubre las bases para la implementación de una tarea pHRI con robot proactivo, debería tenerse en cuenta algunas consideraciones adicionales. Debido a la complejidad de modelar el cuerpo humano y su comportamiento, se han hecho algunas simplificaciones. En todas las contribuciones se ha considerado que el humano tiene buena predisposición a la tarea, es decir, el comportamiento del humano se ha simplificado a un humano cooperativo que ejecuta la tarea sin forzar el sistema. En el mundo real, esta consideración no se cumple siempre. Por la personalidad, miedo, o incluso curiosidad, las personas pueden comportarse de forma inesperada. Esto se vuelve crítico en tareas en las que la interacción física es necesaria. En general, esta tesis hace énfasis la parte física, relegando la parte social y psicológica a un segundo plano (debido a que están fuera del alcance de esta tesis). Sin embargo, se pueden extraer algunas conclusiones en este sentido a partir de los voluntarios que participaron en los experimentos. A pesar de la apariencia del robot y de la incertidumbre sobre cómo se iba a comportar, los voluntarios mostraron emoción al trabajar cerca del robot y curiosidad sobre su funcionamiento. Ademas, tras los experimentos, los voluntarios reflejaron su disposición para participar en futuros experimentos de colaboración con el robot. Esto constituye una señal clara de que los humanos están cómodos ante la idea de recibir ayuda de un robot, incluso si eso requiere ser tocado o agarrado.

Acknowledgements

Durante el tiempo que ha durado mi doctorado he tenido la suerte de poder trabajar jugando con robots y de poder viajar a varios lugares. Todos aquellos que ya han pasado por este proceso sabrán que, en general, es bastante duro, es una experiencia de constantes altibajos. En un instante las cosas van viento en popa y tienes ganas de seguir trabajando, y al instante siguiente se tuercen, quedándote sin hilos de donde tirar durante algún tiempo. Si bien es cierto que hay veces que se puede remontar, hay otras en las que tienes que hacer borrón y cuenta nueva, empezando desde el principio con todo lo que ello implica psicológicamente. Hay bastante gente que ha acompañado a lo largo de todos esos picos emocionales (en los que estaba loco contento o completamente abatido, sin punto intermedio), por lo que hay bastante gente que debería figurar en esta sección. Eso de abrirme al mundo nunca se me ha dado bien, asi que voy a intentar ordenar un poco lo que tengo en la cabeza y expresarlo de forma coherente.

En primer lugar, quiero darle las gracias a los directores de mi tesis. Sin su ayuda y orientación en el cómo abordar determinados problemas esta tesis posiblemente no hubiera terminado nunca. Además, no solo me han servido como orientadores en lo que al aspecto técnico y de investigación se refiere, sino que también me han ayudado en los momentos en los que no estaba precisamente contento. Me habeis aportado multitud de herramientas para desenvolverme en el mundo laboral con soltura. Jesús, Juanma, por esto y todas las cosas se me quedan en el tintero, muchas gracias.

Por otro lado, quiero darle las gracias a mi familia, los pilares de mi estabilidad emocional. Son ellos los que me han soportado en todos esos picos emocionales que he sufrido a lo largo de todo este tiempo. Además, aunque ellos no me lo hayan dicho, tengo constancia de que en mis peores momentos ellos han sufrido conmigo. Sin vosotros probablemente habría abandonado el doctorado hace tiempo, estais ahí cada vez que lo necesito, me distraeis en mis peores momentos y sobretodo sois capaces de aguantarme, por todo eso y mucho más, muchas gracias.

En último lugar, pero no por ello menos importante, quiero darle las gracias a todos esos compañeros con los que he tenido la suerte de trabajar a lo largo de estos años. Hemos pasado buenos momentos tanto en el trabajo como fuera de él. Me habeis ayudado a resolver ciertos problemas y me habeis demostrado que acompañado soy mucho más eficiente. A mis compañeros de la nave-taller y del lab. 2005 (lo siento, sois muchos como para nombraros a todos), por todos esos momentos inolvidables que hemos compartido, muchas gracias.

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CHAPTER 1

Introduction

1.1 Motivation

Initially, robots were conceived to automate simple and repetitive tasks in industry. To ensure safety, the workspace was separated: humans had their working zone free from robots; whereas robots worked enclosed in protective cages away from humans. However, this approach limited the number of applications that robots could automate. Thus, robots' situation in industry evolved to other working paradigms[1] such as coexistence, cooperation, and collaboration [1]. When humans and robots work nearby, physical interaction has a high probability of occurring. For safety reasons, collaborative robots (cobots) to work safely alongside humans have been developed and standardized [2]. Recent advances in control and planning have made the field of physical Human-Robot Interaction (pHRI) a hot research topic nowadays [3]. Nevertheless, during pHRI, physical contact is limited. For safety reasons, the human is the only agent allowed to initiate, maintain, and finish physical interaction, relieving the robot to a reactive role.

However, considering the robot as a passive element in pHRI limits the achievable significance of the interaction itself since the robot, like the human, possesses valuable knowledge about the task that is not fully exploited. Thus, if robots have already proven their usefulness during pHRI with a passive behavior, why not make robots more participative during physical interaction with humans? A physically proactive robots could be used in a wide set of situations besides industrial applications. Think of robots assisting elderly or disabled people in the daily life activities at their homes [4], or even at the hospital, assisting healthcare workers in attending to infectious or fragile patients [5]. In this scenarios, it would be useful to have proactive robots capable of grasping and manipulating human limbs. Nevertheless, the benefits of physically proactive robots are not limited to just the ability of performing these tasks. Humans, as social beings, need attention and affection, which can be lent in the form of physical contact either given by an autonomous robot [6] or a telepresence robotic system [7]. E.g., it has been proven that physical contact with a robot is beneficial for children with autism [8].

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[1] In industry, three principal paradigms of work are defined: coexistence, cooperation, and collaboration. Under the coexistence paradigm, humans and robots work in a delimited zones with different goals. Under cooperation, human and robot share a common workspace, but different goal. Under collaboration, human and robot works simultaneously in a common workspace towards a common goal.

The norm ISO 13482:2014 [74] underscores the necessity of safe and reliable technologies in the domain of personal care robotics. This standard provides guidelines on hazard identification, risk assessment, and human-robot interaction, that should be used in the design of robotic assistants to improve humans' quality of life. Such robotic assistants can benefit specially to elderly and dependent people, helping them to have fulfilling and independent lives. Nevertheless, pHRI is a rather unexplored field of robotics due to its inherent complexity. To proactively interact with humans means that robots know how humans behave dynamically. However, humans are highly nonlinear systems, and as such, their behavior cannot be predicted without a context. In addition, humans can change their level of activity[2] during a certain task due to their predisposition to collaborate with the robot. Thus, in subsequent chapters, this work will address the requirements for the implementation of robot-driven pHRI focusing on assistive and rehabilitation scenarios considering humans with good predisposition.

1.2 Objectives

This Thesis focuses on the challenge of safe and autonomous human manipulation with compliant robots to provide assistance in situations where the robot either initiates the interaction or present an active behavior. More specifically, the main objective of the Thesis is the development of a generic framework for the integration of assistive/rehabilitation robot-driven pHRI tasks. Such an objective can be decomposed into some sub-objectives:

- The development of robotic hands for human limbs grasping. During a pHRI task, robot and human have to be physically attached. It is common the use of a comfortable End-Effector (EE) that the human grasp to collaborate with the robot. However, in some situations (e.g. during rehabilitation) the opposite interaction is required, relieving to the robot the responsibility of grasping human parts (e.g. human limbs). When a robot manipulates human limbs, the features of the EE employed become specially relevant. A wide variety of EEs for robots can be found in the literature, but none have been explicitly designed for human grasping and manipulation. This Thesis intend to fill this gap by proposing a new inherently compliant robotic gripper for safe human limb grasping and capable of measuring grasping and interaction forces.
- Kinematic parameter identification of human limbs. During assistive/rehabilitation task, the robot must know the kinematics of the limb to manipulate it safely. Modeling of the human body is a vast research topic. Lots of works have been made, but only a few can be computed online and previous information about the human to interact with has to be known a priori. This Thesis exploit the kinesthetic information provided by a compliant robot that manipulates a human

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[2] Although the level of activity can be considered as a continuous variable, along this work, two levels of activity will be considered for both agents, humans and robots. An agent is considered active if it contributes to the task by their own will; whereas it is considered passive if the agent neither contribute to motion nor oppose to it.

limb to estimate its kinematic model. More specifically, two methods are used to estimate human arm links, and their performance is compared. To ensure safety and to simplify the complexity of the problem, the movement is restricted to the sagittal plane of the human.

- The development of two compliant robot behaviors for human assistance under the Assist-As-Needed (AAN) paradigm. The AAN paradigm encompass those behavior policies in which a robot provides help to a human only when the robot detects that the human needs assistance, respecting humans' will as long as they perform well [9]. However, the existing AAN approaches are oriented to rehabilitation, limiting their use to the therapist's examination room. This Thesis aims at developing robot behaviors under the AAN paradigm for more general situations. Hence, a first assistive behavior for human balance assistance is proposed, in which the human has to grasp the robot EE. On the contrary, in the second assistive behavior, the robot grasp the human forearm and help the human user to follow a predefined Cartesian path.

1.3 Background

In this section, a deep analysis of pHRI for assistive and rehabilitation robotics is presented. Next, the factors involved in the physical interaction are itemized and analyzed. Then, the current state of the art of each factor is studied.

The integration of a pHRI task can be separated on a physical and a behavioral part, as shown in Figure 1.1. The physical part focuses on the human and the robot, and on how both agents engage during the interaction, i.e., the physical system that attach the human to the robot, the robot EE. On the other hand, the behavioral part concentrates on how both agents behave, namely, the robot controller, the robot behavior policy implemented for the task, and the estimation of human intention. Each one of the features involved in the physical and behavioral part constitutes a research field by itself.

1.3.1 Behavior policy

Behavior policy provides the robot with directives on what is allowed, or what actions are expected from it during the interaction. The behavior policy of a robot changes depending on the context of the task. In the field of collaborative robotics, a particular blend of pHRI in which humans and robots works together for the completion of a task, many works centered in cooperation for industrial tasks can be found in the literature. In collaborative robotics, the robot is considered as a tool, so the works are directed at the benefits of the robot presence for a human worker. This way, some collaborative tasks, such as human ergonomics assessment [10, 11] or role allocation during collaboration [12, 13], do not involve physical contact between human and robot. Even in those cases in which physical interaction is required by the task, contact level is low or limited. A robot

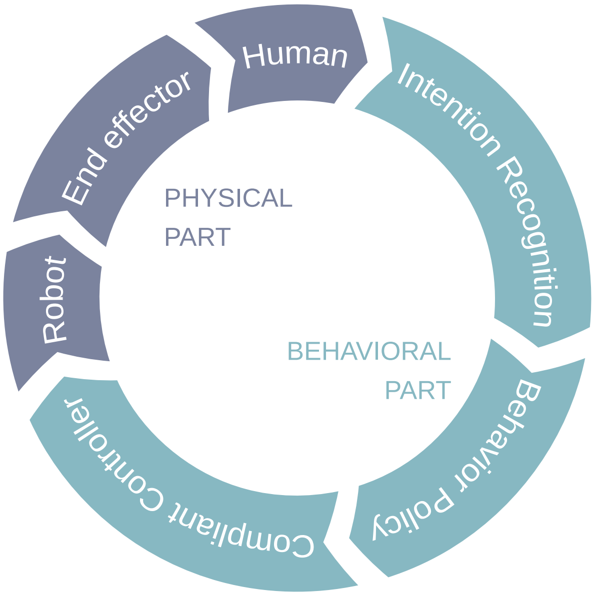

FIGURE 1.1: Scheme of a robot-driven pHRI task. A robot governed by a compliant controller manipulates/touches a human with a special EE following a predefined behavior policy that checks the state of human and robot.

actively touching a human is generally an unwanted rather than a desired situation, relieving to the human the task of initiate and maintain the interaction unilaterally [14]. Notwithstanding, as mentioned in section 1.2, in the context of this work, situations in which robots intentionally touch humans are expected, so the development of behavior policies for such situations are of special interest.

Overall, in a medical or assistive context, many situations require the therapist to establish an intentional and continuous physical contact with the patient, and so it would be in the robot-therapist or robot-patient case. The field of assistive robotics focuses to a great extent in the development of behavior policies for socially assistive robots [15–17], although recently physical assistance is an emerging interest among researchers [18, 19]. On the other hand, in the field of rehabilitation robotics, physical interaction is necessary in the most of the cases [20]. However, even in this field, robots are still seen as tools. Rehabilitation manipulators rely on passive EEs which require the human to grasp the EE [21], or to be fixedly attached [22] to the robot. So once again, the human is the agent responsible for initiate and maintain interaction, whereas the robot opposes lightly to the motion of the human.

Still, the number of published articles in which a robot implements a behavior policy for intentionally touching a human is almost nonexistent, even though this would have huge impact on society. In a medical context, Kowalski *et al.* [23] used a robot to assist nurses during the repositioning of patients at the care bed. The robot, placed on the side of the bed, introduced itself under the patient and applied a lifting force on the patient's back when the nurse tried to reposition the patient. Anqing *et al.* [24] used a robot equipped with an ultrasonic probe to automate the scoliosis assessment of a patient. During such a procedure, the robot applied a force at the human back while moving the probe along the spine. In addition to physical considerations, the human psychological impact during

Table 1.1: State of the art of active pHRI. Only the works that involved direct human-robot contact have been considered in the elaboration of this table. The objective of the work, a description about the interaction considered, and the level of activity of each agent are listed.

Author	**Objective**	**pHRI**	**Level of Activity**	**Tested with humans**
L. Zhang [21]	Develop a rehabilitation robot for human upper limbs and an impedance-based controller under the AAN paradigm.	The human grasps the robot handle and performs the rehabilitation exercise assisted by the robot.	Robot Reactive, Human Active	Yes
F. J. Ruiz-Ruiz [70]	Develop a method to estimate human upper-limb kinematic model with a compliant robotic manipulator.	The robot grasp the human forearm and moves the human arm following a predefined path.	Human Passive, Robot Active	Yes
A. Duan [24]	Develop an automated ultrasound-probe with an assistive robot for scoliosis assessment	The robot touches the human's back with the ultrasonic probe, and move it along human's spine.	Robot Active, Human Passive	Yes
Y. Hu [25]	Study human state and reaction with active pHRI robots, more specifically, when an unexpected physical contact is produced.	Volunteers played a game assisted by the robot. The robot could touch volunteers without previous notification to indicate something to the volunteer.	Robot Active, Human Reactive	Yes
F. J. Ruiz-Ruiz [73]	Develop strategies to help humans with balance issues with a robotic assistant.	The human grasp the robot. If the human is in balance, the robot does not hamper human motions; otherwise, robot helps human to regain balance.	Robot Reactive, Human Active	Yes
C. Kowalski [23]	Develop an assistive strategy for helping nurses relocate patients at the care bed.	The robot moves between the patient and the bed and pushes the patient in the back.	Robot Active, Human Passive	No

the interaction is also of great interest. Hence, in [25] the authors study the reaction of humans when unexpected physical interaction with a robot occurs. For this purpose, the information provided by several sensors and an interview after the experiments is used to measure the physiological state of the volunteers. On the same topic, Block *et al.* [26] developed a hugging robot. The authors test some forms of hugging and their impact in the human psychology.

1.3.2 Grippers for pHRI

Currently, there exist a vast catalog of robotic grippers, from general grasping devices to solution-specific grippers [27, 28]. Nevertheless, grippers for physical human interaction are oriented mainly to human-robot collaboration tasks [29, 30]. In the literature, there also exists grippers that were not designed for human interaction, but they can be used with that purpose in mind [31, 32]. In this direction, lots of works detailing human-like robotic hands for dexterous manipulation can be found in the bibliography [33]. This kind of robotic EE which has been designed for dexterous manipulation, could be used for pHRI. Its use has been applied to create hand-shaking robots [34]. Hand-shake is the most, and probably the only, explored task in which a robot grabs a human part. Nevertheless, hand-shaking has not a physical but a social background, i.e., it is a task with low physical requirements (the robotic hand only grasp the human hand).

As already mentioned in section 1.2, one sub-objective of this Thesis focuses on the development of robotic hands for human limb manipulation. However, to the best of the author's knowledge, grippers specifically designed for active human grasping are scarce. Xu *et al.* [35] designed a robotic hand for human limb grasping made of two opposed fingers bio-inspired by the human fingers. On a similar line but with a different objective, Hellman *et al.* [36] presented a method to determine if in the grasping process a robot was trapped the human operator during the development of a collaborative task. By means of this method, a robot equipped with a general purpose gripper was able to identify if a human part was accidentally grabbed and stop the grasping to release the operator. Previous work of the research group in which this Thesis has been conducted has contributed to this topic. In particular, Gandarias *et. al* employed a specific pHRI gripper to relocate the arm of a human lying on a flat surface [37]; Ballesteros *et. al* in [38] derived a machine learning model to estimate the interaction forces that a grabbed human applied at the gripper; and Pastor *et. al* used a gripper composed by two aligned fingers opposed to a fixed finger with a tactile sensor to recognize the bones and muscles of the human forearm in [39], which allowed for the determination of the grabbed forearm section. In all these works, the grippers were composed by the same fingers, but arranged in different configurations. The fingers were designed for human limb grasping, hence an underactuated structure with two phalanxes was used so the finger could adapt itself to the form of the human limb. In subsequent chapters, the structure of the finger used by these works will used as a baseline to improve its design.

TABLE 1.2: State of the art of compliant grippers.

Author	**Purpose**	**No. Fingers**	**No. DOFs**	**Usable for human grasping**
J. Spiliotopoulos [32]	Dexterous manipulation	3	8	Yes
J. M. Gandarias [37]	Human limb grasping	2	2	Yes
C. Ulagaoozhian [29]	General manipulation	2	1	No
O. Shorthose [31]	Dexterous manipulation	5	15	Yes
D. Xu [35]	Human limb grasping	2	1	Yes
F. J. Ruiz-Ruiz [75]	Human limb grasping	4	4	Yes

1.3.3 Compliant Robot Control

Safety has to be ensured during pHRI, so the use of control schemes that yield a compliant robot behavior are widely extended. In the literature, there can be found two predominant controllers: impedance control, and admittance control. Both controllers impose a desired dynamic behavior to the robot, so it behave as a passive mass-spring-damper mechanical system modeled by three matrices: the virtual inertia, virtual damping, and virtual stiffness matrix. The final accuracy, compliance, and stability of the system depend on the values given to these matrices. The advantages/disadvantages of both forms of control are well-known. In impedance control the controller receives motion inputs and yields force outputs, it is stable and robust when interacting with the environment but present poor accuracy in free-motion space. In contrast, in admittance control, the controllers yields motion outputs from force inputs, it is more precise in motion, but it can become unstable with stiff contacts. In the literature, lots of works about theory and implementation of both controllers can be found [40–43]. To compensate the drawbacks and enhance its performance, researchers often use variable impedance/admittance controllers [44–47] to adapt to the stiffness of the environment. A different approach to optimize the performance of the controller consist of commuting with high frequency between impedance and admittance [48], implementing a sort of hybrid impedance-admittance control that takes the best of both approaches at the expense of a much more complex implementation.

However, despite the fact that compliant robots allow humans to work in close distance with robots, they do not ensure safety by themselves. To further improve safety, some constraints should be imposed over the system in terms of force, velocity, and even position. As robots are highly nonlinear systems, other advanced control approaches can be applied. Model Predictive Control (MPC) is a control strategy based on the numerical optimization of a cost function subject to constraints, so it offers a good option for implementing a pHRI task as proven by Pastor *et al.* in [49]. Merckaert *et al.* [50] used a slight variation of the MPC, a trajectory-based Explicit Reference Governor controller, to impose both state and input constraints over a collaborative robot. In the same line, a strategy that unifies the inverse kinematics and the robot control problems into an optimization problem with motion constraints is proposed in [51]. On the other hand, Artificial Neural Networks (ANN) can also be used to control collaborative robots. In [52] a learning method based on radial basis function ANN is proposed to estimate the unknown dynamics of a robot, and further combined with an adaptive ANN admittance controller to impose movement constraints in the task space.

1.3.4 Human Intention Recognition

As mentioned above, the policy behavior need information about human and robot status. Robot status is observed via the sensors embedded in the robot structure, but determining the human status is more complex. Human intention is not directly observable, and usually needs to be estimated from human actions. It is also essential to put those actions in context, because even basic behaviors can be interpreted different in each situation. Intentions should be estimated in real time, so a simplistic model is preferred. Hence, only the variables that are determinant according to the context should be used as input to the model. Intention can be estimated in terms of goal, motion (determining how the human is going to move a part of their body), or emotion (how the human feels).

Goal recognition models are capable of discern among a wide set of activities and return the one the human is about to perform. CNN models for human goal recognition are abundant in the literature [53, 54]. In [55] the authors explore the idea of using 2D pose estimation from monocular images to recognize the crossing or non-crossing intention of pedestrians and cyclists. On the other hand, probabilistic models can also be found in the literature [56]. Petkovic *et al.* developed a hidden Markov model to infer the intention of a warehouse worker from their motion [57]. Such a model was capable of estimating the probabilities of the worker desiring each goal in real time. When more than a human is considered, the difficulty of deriving a model for intention recognition increases. In [58] the authors tackle such a challenge. The authors simplify the problem by considering a fully observable environment. Then, a model based on behavior trees is obtained.

Motion recognition models, try to determine how a human is going to move, thus adapting the behavior of a collaborative robot [59] or controlling a robotic prosthesis [60]. This way, surface electromyography (sEMG) sensors [61, 62] are the main source of information for this models, followed by electroencephalography (EEG) sensors [63, 64], and force sensors [65]. Although motion recognition models are usually based on deep learning and CNN, there also exists works that rely on a fusion of the data obtained from both sEMG and EEG sensors [66]. Regarding emotion recognition, it can be obtained from CNNs that receive as input human voice [67], images of facial expressions [68], or a combination of both [69].

1.3.5 Safety in pHRI

Whenever a robot moves in the vicinity of a human, safety has to be ensured. As discussed in [76], there exist several works about hazard analysis and risk assessment, but the vast majority of the works in this respect are related to industrial tasks. Nevertheless, the authors also provide some strategies for risk assessment of assistive tasks. In this regard, in [74], the risk assessment and the safety requirements for personal care robotics are extensively addressed. In the context of pHRI, conducting a risk assessment and implementing safety mechanisms may not be enough in most of the cases. In order to ensure human safety, the human has to feel safe. Otherwise, humans can startle by unexpected robot movements, leading to human involuntary motions that can be potentially dangerous [77]. Hence, the perceived safety of an autonomous system need to be addressed [78], and some metrics in this regard should be implemented [79].

Regarding robot safety mechanisms, it is common the implementation via software of control schemes capable of dealing with unexpected events. Model-based observers can be used to detect a possible collision and act to reduce the impact [80, 81]. Energy-based controllers check the energy absorbed and provided by the robot during the interaction to ensure passivity [82, 83]. If an obstacle is detected on time, the robot motion can be re-planned to avoid a possible collision [84]. Alternatively, safety mechanisms can be implemented in the robot hardware in the form of compliant robot mechanisms. In [85] the authors compared the performance of robots with compliant links and robots with compliant joints under an impact. This study proved that compliant links were capable of reducing drastically the impact force over compliant joints. Moreover, a parametric study for the design of robot links geometry and actuation to reduce the impact force was presented in [86]. Another way of implementing safety measures in the hardware is to use sensors that allow the robot to notify the presence or absence of a human in it surroundings. Artificial skins based on capacitive and/or inductive sensor [87] can be used to detect human presence and stop/deviate the robot accordingly.

Along this Thesis, safety has been considered by using compliant control schemes, e.g., impedance controllers. Moreover, during the experiments with human subjects, both the subject and the researcher had a safety button to stop the motion of the robot in case of necessity. To increase subjects' safety, robot motion was restricted in velocity, position, and force.

1.4 Contributions

This Thesis contributes to the fields of pHRI and assistive robotics:

- The design and implementation of a safe robotic gripper to grasp and manipulate humans is introduced in chapter 2. Its inherently compliant design allows to determine grasping and interaction forces based on the kinesthetic information of the fingers, as shown in chapter 3.

- The development of an agnostic online procedure to estimate the kinematic parameters of the human upper-limb by the exploitation of the kinesthetic information obtained by a robot under compliant control scheme is presented in chapter 4.
- The development of robot behaviors under the AAN paradigm; namely, a reactive balance assistance strategy with a mobile robotic system, and a performance-based shared control policy for manipulation tasks are presented in chapters 5 and 6 respectively.

The content of the ensuing chapters and the Thesis outline are further described in section 1.6. As the reader delves into this document, they will notice the progression in the behavior of both agents, human and robot, as shown in Figure 1.2. The idea behind this Thesis is to flow into realistic situations from some initial assumptions. Hence, at first a motionless human agent (e.g. unconscious or asleep human) and a proactive robot agent are considered, whereas at the end both agents become completely active.

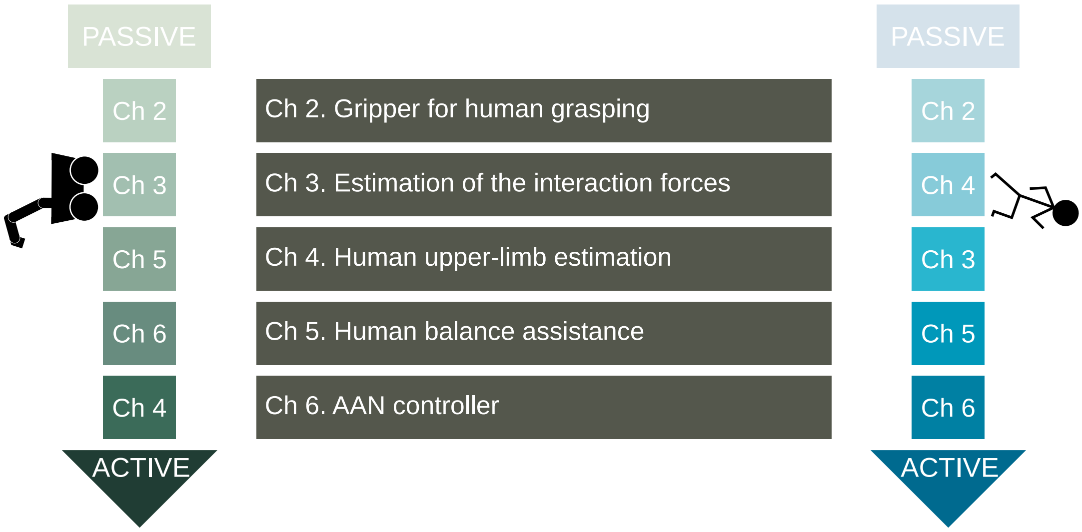

FIGURE 1.2: Evolution on the behavior of human and robot along this Thesis. The simplifications on robot and human behaviors become more realistic as the Thesis advances. In the final chapter, both human and robot contribute actively to a common task.

1.4.1 Publications

The publications that support the present Thesis and the contribution of the author to each one according to the CRediT Taxonomy[3] are listed below.

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[3] https://credit.niso.org/contributor-roles-defined/

Journal Articles

- F. J. Ruiz-Ruiz, J. M. Gandarias, F. Pastor and J. M. Gómez-De-Gabriel, ”Upper-Limb Kinematic Parameter Estimation and Localization Using a Compliant Robotic Manipulator”, IEEE Access, vol. 9, pp. 48313-48324, 2021, doi: 10.1109/ACCESS.2021.3067108, [70].

  Author’s contribution: conceptualization, data curation, formal analysis, methodology, resources, software, visualization, writing – original draft, and writing – review & editing.

- F. J. Ruiz-Ruiz, J. Ventura, C. Urdiales, J. M. Gómez-de-Gabriel, ”Compliant gripper with force estimation for physical human–robot interaction”, Mechanism and Machine Theory, Volume 178, 2022, 105062, doi:10.1016/j.mechmachtheory.2022.105062, [71].

  Author’s contribution: data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing – original draft, and writing – review & editing.

- F. J. Ruiz-Ruiz, C. Urdiales, and J. M. Gómez-de-Gabriel, “Estimation of the Interaction Forces in a Compliant pHRI Gripper”, Machines, vol. 10, no. 12, p. 1128, Nov. 2022, doi: 10.3390/machines10121128, [72].

  Author’s contribution: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing - original draft, and writing - review & editing.

Conference Proceedings

- F. J. Ruiz-Ruiz, A. Giammarino, M. Lorenzini, J. M. Gandarias, J. H. Gómez-De-Gabriel and A. Ajoudani, ”Improving Standing Balance Performance through the Assistance of a Mobile Collaborative Robot,” 2022 International Conference on Robotics and Automation (ICRA), 2022, pp. 10017-10023, doi: 10.1109/ICRA46639.2022.9812284, [73].

  Author’s contribution: conceptualization, investigation, methodology, resources, software, validation, visualization, writing - original draft, and writing - review & editing.

Other Contributions

- F. J. Ruiz-Ruiz, C. Urdiales, M. Fernández-Carmona and J. M. Gómez-de-Gabriel, “A Reactive performance-based Shared Control Framework for Assistive Robotic Manipulators”, Under Review

  Author’s contribution: conceptualization, data curation, investigation, methodology, resources, software, validation, visualization, writing – original draft, and writing – review & editing.

1.5 Related Research Activities

This Thesis began in November 2019 within the framework of the Robotics and Mechatronics Group at the Department of Systems Engineering and Automation of the University of Málaga. Since then, the author has worked to contribute to the state of the art of pHRI with the works that support this Thesis, while carrying out complimentary activities.

The author has collaborated in the completion the following projects focused on the integration of pHRI tasks:

- Technology transfer project UMA-CEIATECH-23 (RAFI) granted by the University of Málaga.
- Project UMA20-FEDERJA-052 (HANDCARE) granted by the University of Málaga.
- Project PID2021-127221OB-100 granted by the Spanish Ministerio de Ciencia e Innovación.
- Technology transfer project AT21-00051 granted by the Junta de Andalucía.

1.5.1 Other Publications

Journal articles

- F. Pastor, F. J. Ruiz-Ruiz, J. M. Gómez-de-Gabriel and A. J. García-Cerezo, "Autonomous Wristband Placement in a Moving Hand for Victims in Search and Rescue Scenarios With a Mobile Manipulator," in IEEE Robotics and Automation Letters, vol. 7, no. 4, pp. 11871-11878, Oct. 2022, doi: 10.1109/LRA.2022.3208349, [49].

1.5.2 Other Activities

During the development of this Thesis, the author has also participated in other research activities, which indirectly contributed to the Thesis while also contributing to his professional development. The author has had the opportunity to participate in the European Robotic Forum 2020 at the exposition zone, hand in hand with the company KUKA roboter GmbH. He has also assisted to workshops organized during prestigious international conferences in the field of robotics, such as the IEEE International Conference on Robotics and Automation (ICRA) 2020, and Humanoids 2020. Moreover, the author presented a work at ICRA 2022 in Philadelphia, USA. Apart from that, the author has also assisted to webinars on human-robot interaction and intelligent sensors organized by the University of Málaga and the IEEE.

Besides, the author has made a research stay of three months at Human-Robot Interfaces and Interaction lab (HRI^2) at the Istituto Italiano di Tecnologia (IIT), which resulted in an article published at the ICRA 2022. The author has also served as reviewer for high impact journals (such as Biomimetics, Mechanism and Machine Theory, and IEEE Robotics and Automation Letters) and international conferences (such as ICRA and IROS).

1.6 Thesis Outline

As aforementioned, this Thesis contributes to the field of robot-driven pHRI and human manipulation. This Thesis is displayed as a compendium of articles that shapes the body of this document, distributed along 5 chapters defining the general framework of this Thesis according to Figure 1.2. Under this format, each article should be regarded as an independent contribution supporting the central research topic of this thesis. Consequently, each article is presented as a chapter, so a similar structure has been adopted among chapters: first an introduction to the the chapter's topic is made, followed by methodology, experiments, and concluding with specific insights. Hence, this Thesis is organized as follows:

- Chapter 2 presents a compliant robotic gripper for human grasping and its kinetostatic model for grasping and interaction force estimation. The gripper is composed of four underactuated fingers with two phalanxes each and an elastic link in the actuation kinematic chain to measure the forces applied by the finger. This chapter describe the gripper and its capabilities, so neither human nor robot participate in any task. Thus, as any agent have a level of activity, it can be considered that both agents are passive.

- Chapter 3 presents a method to estimate the interaction forces that a human may apply while being grasped with a compliant gripper. This is achieved by analyzing the distribution of forces at the fingers. In this chapter, the human is active and the robot is passive.

- Chapter 4 presents a method to estimate the parameters of a human arm kinematic model through direct human limb manipulation. Under the assumption of an unconscious or collaborative human, the robot grasps the human forearm and follows a predefined path under impedance control mode. The deviation from such a path serve as input to estimate the kinematic parameters of the human limb. In this chapter the robot has an active role whereas the human remains completely passive.

- Chapter 5 presents an AAN method to provide balance assistance with a supernumerary robotic body. The human balance status is determined thanks to the information provided by a motion capture system, which records the human center of mass and support polygon. In this chapter the human is completely active whereas the robot is reactive.

- Chapter 6 presents a AAN shared velocity-based controller for human manipulation. Such a control scheme assumes that both agents (robot and human) contribute to a common task simultaneously. Then both commands are combined to obtain the shared command which is executed. The combination of robot and human commands is made according to performance factors. In this chapter both human and robot are completely active.

- Finally, Chapter 7 discusses the conclusions extracted from this Thesis and describes future research lines.

Chapter 2

Compliant Gripper for Human Manipulation

The material presented in this chapter has been published as:
F. J. Ruiz-Ruiz, J. Ventura, C. Urdiales, J. M. Gómez-de-Gabriel, "Compliant gripper with force estimation for physical human–robot interaction", Mechanism and Machine Theory, Volume 178, 2022, 105062, doi:10.1016/j.mechmachtheory.2022.105062.

Abstract: *Despite the major interest in the field of Human-Robot Interaction (HRI) in recent years, not much work has been presented on physical HRI (pHRI), especially for robot-initiated contact. Although pHRI is a key skill in areas like assistive or rescue robots, advances are limited by hard constraints in safety and compliance that require specific hardware features and force estimation capabilities. This chapter presents a new compliant gripper with four underactuated fingers and force-sensing capabilities designed to manipulate a human forearm. Fingers are based on the rigid-link approach, where one of the links has been replaced by a compression spring. High-resolution angular sensors at the passive joints allow computing the spring compression and the actuator torque. Then grasping forces are estimated through the kinetostatic model of the fingers. The gripper has been built and tested. Compliance and grasping force estimation and control have been successfully evaluated. Results prove that the proposed finger arrangement offers good performance, making our design suitable for pHRI applications.*

CHAPTER 3

Estimation of the Interaction Forces in a Compliant Gripper

The material presented in this chapter has been published as:
F. J. Ruiz-Ruiz, C. Urdiales, and J. M. Gómez-de-Gabriel, "Estimation of the Interaction Forces in a Compliant pHRI Gripper", Machines, vol. 10, no. 12, p. 1128, Nov. 2022, doi: 10.3390/machines10121128.

Abstract: *Physical human–robot interaction (pHRI) is an essential skill for robots expected to work with humans, such as assistive or rescue robots. However, due to hard safety and compliance constraints, pHRI is still underdeveloped in practice. Tactile sensing is vital for pHRI, as constant occlusions while grasping make it hard to rely on vision or range sensors alone. More specifically, measuring interaction forces in the gripper is crucial to avoid injuries, predict user intention and perform successful collaborative movements. This chapter exploits the inherent compliance of a gripper with four underactuated fingers which was previously designed by the authors and designed to manipulate human limbs. A new analytical model is proposed to calculate the external interaction forces by combining all finger forces, which are estimated by using the gripper proprioceptive sensor readings uniquely. An experimental evaluation of the method and an example application in a control system with active compliance have been included to evaluate performance. The results prove that the proposed finger arrangement offers good performance at measuring the lateral interaction forces and torque around the gripper's Z-axis, providing a convenient and efficient way of implementing adaptive and compliant grasping for pHRI applications.*

CHAPTER 4

Human Upper-Limb Kinematic Parameter Estimation and Localization

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The material presented in this chapter has been published as:
F. J. Ruiz-Ruiz, J. M. Gandarias, F. Pastor and J. M. Gómez-De-Gabriel, "Upper-Limb Kinematic Parameter Estimation and Localization Using a Compliant Robotic Manipulator", in IEEE Access, vol. 9, pp. 48313-48324, 2021, doi: 10.1109/ACCESS.2021.3067108.

Abstract: *Assistive and rehabilitation robotics have gained momentum over the past decade and are expected to progress significantly in the coming years. Although relevant and promising research advances have contributed to these fields, challenges regarding intentional physical contact with humans remain. Despite being a fundamental component of assistive and rehabilitation tasks, there is an evident lack of work related to robotic manipulators that intentionally manipulate human body parts. Moreover, existing solutions involving end-effector robots are not based on accurate knowledge of human limb dimensions and their current configuration. This knowledge, which is essential for safe human–limb manipulation, depends on the grasping location and human kinematic parameters. This paper addresses the upper-limb manipulation challenge and proposes a pose estimation method using a compliant robotic manipulator. To the best of our knowledge, this is the first attempt to address this challenge. A kinesthetic-based approach enables estimation of the kinematic parameters of the human arm without integrating external sensors. The estimation method relies only on proprioceptive data obtained from a collaborative robot with a Cartesian impedance-based controller to follow a compliant trajectory that depends on human arm kinodynamics. The human arm model is a 2-degree of freedom (DoF) kinematic chain. Thus, prior knowledge of the arm's behavior and an estimation method enables estimation of the kinematic parameters. Two estimation methods are implemented and compared: i) Hough transform (HT); ii) least squares (LS). Furthermore, a resizable, sensorized dummy arm is designed for experimental validation of the proposed approach. Outcomes from six experiments*

with different arm lengths demonstrate the repeatability and effectiveness of the proposed methodology, which can be used in several rehabilitation robotic applications.

Chapter 5

Standing Balance Assistance with a Mobile Collaborative Robot

The material presented in this chapter has been published as:
F. J. Ruiz-Ruiz, A. Giammarino, M. Lorenzini, J. M. Gandarias, J. H. Gómez-De-Gabriel and A. Ajoudani, "Improving Standing Balance Performance through the Assistance of a Mobile Collaborative Robot," 2022 International Conference on Robotics and Automation (ICRA), 2022, pp. 10017-10023, doi: 10.1109/ICRA46639.2022.9812284.

Abstract: *This chapter presents the design and development of a robotic system to give physical assistance to the elderly or people with neurological disorders such as Ataxia or Parkinson's. In particular, we propose using a mobile collaborative robot with an interaction-assistive whole-body interface to help people unable to maintain balance. The robotic system consists of an Omni-directional mobile base, a high-payload robotic arm, and an admittance-type interface acting as a support handle while measuring human-sourced interaction forces. The postural balance of the human body is estimated through the projection of the body Center of Mass (CoM) to the support polygon (SP) representing the quasi-static Center of Pressure (CoP). In response to the interaction forces and the tracking of the human posture, the robot can create assistive forces to restore balance in case of its loss. Otherwise, during normal stance or walking, it will follow the user with minimum/no opposing forces through the generation of coupled arm and base movements. As the balance-restoring strategy, we propose two strategies and evaluate them in a laboratory setting on healthy human participants. Quantitative and qualitative results of a 12-subjects experiment are then illustrated and discussed, comparing the performances of the two strategies and the overall system.*

CHAPTER **6**

Reactive Performance-based Shared Control Framework for Assistive Robotic Manipulators

The material presented in this chapter is currently under review as:
F. J. Ruiz-Ruiz, C. Urdiales, M. Fernández-Carmona and J. M. Gómez-de-Gabriel, "A Reactive Performance-based Shared Control Framework for Assistive Robotic Manipulators", preprint doi:10.48550/arXiv.2311.03232

Abstract: *In Physical Human–Robot Interaction (pHRI) grippers, humans and robots may contribute simultaneously to actions, so it is necessary to determine how to combine their commands. Control may be swapped from one to the other within certain limits, or input commands may be combined according to some criteria. The Assist-As-Needed (AAN) paradigm focuses on this second approach, as the controller is expected to provide the minimum required assistance to users. Some AAN systems rely on predicting human intention to adjust actions. However, if prediction is too hard, reactive AAN systems may weigh input commands into an emergent one. This chapter proposes a novel AAN reactive control system for a robot gripper where input commands are weighted by their respective local efficiencies. Thus, rather than minimizing tracking errors or differences to expected velocities, humans receive more help depending on their needs. The system has been tested using a gripper attached to a sensitive robot arm, which provides evaluation parameters. After the robot gripped a person's upper limb, tests consisted of completing an on air a planar trajectory displayed on a screen with both arms with and without assistance. The proposed control has been compared to results without assistance and to impedance control for benchmarking. ANOVA proves that global performance improved and tracking errors decreased for ten volunteers in shared mode. Besides, unlike impedance control, the proposed one does not significantly affect exerted forces, command variation or disagreement, measured as the angular difference between human and output command. Results support that the proposed control scheme fits the AAN paradigm, although future work will require further tests for more complex environments and tasks.*

CHAPTER 7

Conclusions and Future Work

7.1 Conclusions

This Thesis has highlighted the open challenges in the field of pHRI. In particular, it has been evidenced that there is a lacking of works in the context of robot-driven pHRI due to the complexity inherent to this topic. This work has presented a series of contributions to this field in the format of a Thesis by a compendium of publications previously published in international scientific journals and conferences. Such contributions can be summarized as follows:

- The EE of the robot is crucial when interacting physically with the environment, and it gains even more importance when dealing with humans. The architecture of the EE defines how the robot can interact with the world. In the case of robot-driven pHRI tasks, the EE should meet special requirements of safety and compliance. Chapter 2 emphasized the need for a gripper designed for human limb manipulation. The design of a inherently compliant four-fingered underactuated gripper was presented. The presence of springs in the actuation mechanism of the fingers allowed for the measurement of the grasping forces, while the underactuated structure permitted the adaption of the fingers to the shape of the grasped limb. Thereafter, in chapter 3, the gradient of Cartesian forces applied by the fingers were analyzed to extract information about the interaction forces that the human applied to the gripper while being grasped. Although the sensing capabilities of the gripper were limited by the structure of the fingers.

- Then, a maneuver to estimate the human upper-limb kinematic parameters with a compliant robot by manipulating the limb was presented in chapter 4. The derivation of real-time computed human limbs models is essential to the field of pHRI. It has been proven that the use of specific sensors, such as motion capture systems, are unnecessary. Instead, by adopting a clever approach, an approximate model that fulfills the needs of the task to be implemented was derived. This work also presents some limitation. For the functioning of the method, the motion of the human limb was restricted to a plane, so the limb's kinematics could be simplified. To design an appropriate manipulation strategy, it was also assumed that the human subject was lying on their back. Such an assumption was an implementation criteria rather than a limitation; a new manipulation strategy should be designed for different human poses. Besides, the human was considered entirely passive, i.e., the movement of the human limb was due only to the robot manipulation strategy.

- Next, two assistive strategies for human balance assistance with a collaborative robot were presented in chapter 5. A motion capture system monitored the balance status of the human while the human grasped the EE of a mobile manipulator. When the system detected a loss of balance, the robot applied a force over the human to prevent falling. During this procedure, the human was active, they could move their arms without restrictions, whereas the robot reacted to the human inputs by helping when needed or not hindering human motion on the contrary case. However, the difficulty of detecting balance loss during walking limited the system to the standing case. Besides, only the loss of balance in the sagittal plane was considered.
- Finally, chapter 6 presented a reactive velocity-based shared control approach for human upper-limb assistance in the following of a predefined path. This approach required the physical coupling of human and robot, which was achieved by grasping the human forearm with the compliant gripper described in chapter 2. This control strategy combined human intention, which was extracted from the interaction forces applied at the gripper, with the preferred robot action, which was obtained from the path following mechanism of the robot, according to the local performance of each command. Local performance was obtained in accordance with two performance factors: smoothness (penalize abrupt changes in the direction of the movement); and directness (favors commands that contribute to follow the path). As a result, during the application of this control strategy, both human and robot were entirely active during the interaction and both contributed to the task simultaneously. However, orientations are not considered in the control strategy, so it only works for Cartesian translations.

As commented in Chapter 1, the contributions presented in this thesis find application in real world scenarios such as rehabilitation and assistive robotics. The contributions presented in Chapters 5 and 6 are the ones that clearly find a specific application. More specifically, the Chapter 5 presents an AAN controller for balance assistance. As mentioned in section **??**, such a controller is developed for people suffering from neurological diseases that affect balance (e.g., cerebellar ataxia or Parkinsons'). Due to the neurodegenerative nature of these diseases, rehabilitation can not increase patients' quality of life. Hence, this contribution should be understood from the perspective of an assistive robotic platform that helps humans in their daily life. On the other hand, the contribution presented in chapter 6 can be easily extrapolated to rehabilitation tasks. During rehabilitation therapy, it is common the use of repetitive motions to regain the lost mobility of a limb. In this situation, the controller described in 6 can be of utility, as the human only receive help if they need it, so the user will receive less assistance as joint mobility improves. Moreover, this contribution not only provides a tool for rehabilitation, but also a means to quantitatively identify the improvement of the user thanks to the metrics that the robot can provide. In other direction, the contribution presented in Chapter 4 can be used in conjunction with the contributions presented in Chapters 2 and 3. For example, this combination can be used to assist nurses in the relocation of unconscious patients in the care bed at hospitals. The estimation method can be employed to monitor limbs' pose grasped by the compliant gripper.

In general, the outcomes of this work lay the foundations for the implementation of a robot-driven pHRI task. It shows a progression that can be observed in two levels: in the interconnection among contributions; and in the nature of the human-robot interaction. In terms of contributions, this document follows a clear order: a compliant gripper for human grasping has been designed and built; then a human model is obtained; next a basic AAN control without fixed physical coupling between human and robot has been proposed; and finally, a reactive AAN control where the human is grasped by the robot is presented. This last contribution, presented in chapter 6, constitutes a fully operational robot-driven pHRI task that represents an integration of all the lessons learned during the development of this Thesis. Regarding the nature of the interaction, it can be observed how the interaction evolves along the Thesis. It began with an entirely active robot manipulating a passive human lying on their back in chapter 4. Then, an active human was assisted by a reactive robot in chapter 5. Lastly, in chapter 6, both human and robot became entirely active during. Safety requires a special mention. In the current state of the art in the field of pHRI, safety is a hot topic. However, safety is usually addressed in a preventive way, the robot reacts to diminish the consequences of a possible collision with the environment/humans. In this Thesis, safety was included in the controller of the robot, and was also encouraged by the author to all the volunteers during the experiments. On the other hand, several mentions have been made to the exploitation of the sensory information, namely, in relation to kinesthetic information. As has been pointed out in chapters 3 and 4, the measures supplied by the sensors can also provide information relative to variables different from the measured ones.

Along this thesis, robot-driven phri tasks have been presented and studied. In each chapter, a different topic has been addressed, identifying one open challenge in the field of pHRI. Overall, the requirements for the implementation of a robot-driven pHRI task can be summarized as follows:

1. Human safety is the first factor that must be considered for robot-driven pHRI tasks. Safety has to be ensured at different levels during the whole task. Humans are unpredictable and unreliable, and as such, humans can perform unexpected actions that were not considered in the designing of the task and/or the robot's controller. Preventive safety measures can be implemented according to the norm ISO 13482:2014 [74], that specify how to perform risk assessment and the safety requirements for personal care robotics. However, not only preventive safety measures must be contemplated in the designing of the task and controller, but also reactive safety measures to unexpected events need to be developed.

2. The physical coupling between human and robot is one of the pillars of pHRI with proactive robots. The use of shape-adaptive mechanisms during human limb

grasping is an interesting feature to enhance human comfort. Moreover, the addition of in-hand sensing capabilities allow the robot for considering human related variables, such as human intent. The addition of passive safety mechanism to allow the human release from the robot in case of necessity is a must.

3. The capability of detecting and monitoring the human body in real time has to be implemented during robot-driven pHRI tasks. Humans are unpredictable, so the use of precomputed models to estimate human behavior should be avoided when possible.

4. The use of reactive controllers that render compliant robot behaviors are encouraged. This can minimize the harm produced to a human during an unexpected event, while providing a human-aware robot behavior.

From the requirements described above, it can be observed the importance of considering the human in the design process of all elements: the task, the physical interface, and the controller. When designing a task suitable for robot-driven pHRI, ergonomics are key to ensure a good user experience. In applications in the field of rehabilitation and assistive robotics, the range of motion of the human limbs involved during the task have to be considered to avoid uncomfortable human poses during the interaction. Humans shapes and dimensions should also be considered for the design of the human-robot physical attachment, to generate user-friendly geometries that can be used for extended periods of time without fatigue. Overall, a proper human-centered design can improve vastly the user experience.

Although this Thesis covers the basis for a successful implementation of a robot-driven pHRI task, some extra considerations should be taken into account. However, due to the complexity of modeling the human body and its behavior, some simplifications have been made along this document. In all the contributions of this Thesis, one primary assumption has been made: humans has been considered to have a good predisposition, i.e., the human behavior has been simplified to a cooperative human that performs the task as it is intended without trying to force the system. In the real world, this consideration is not always true. Due to their personality, fear, or even curiosity, humans can behave unexpectedly. This becomes critical in tasks where the physical interaction is required. Overall, this Thesis has emphasized the physical part of the tasks relieving the social and psychological dimensions of the interaction to a second plane, since they are beyond the scope of this work. Nevertheless, some conclusions in that regard can be extracted from the human volunteers recruited for the experiments of the assistive tasks. Despite the robot appearance and the uncertainty of how it would behave intimidated the volunteers before the experiments, during the tests all volunteers were excited to work in close proximity with a robot and were also curious about its functioning. Moreover, after the experimental procedure, the subjects reflected their willingness to participate in future experiments with the robot. This is a clear sign that human are enthusiastic about the idea of being helped by a robot, even if it requires being touched or grabbed.

7.2 Future work

Despite the advances of this Thesis and the recent findings in the field of study discussed in this work, there are still significant challenges to overcome in order to fully introduce robots in people daily life. One of the most important short-term objectives should include deeper physical, social and psychological considerations during the interaction. E.g., it could be useful for the robot to understand what is the human's opinion about the interaction and use it to adapt its behavior, yielding a more enjoyable interaction for the human. Regarding physical considerations, this Thesis presents some limitations in the sense that only the human upper-limb has been considered, although the methods presented here could be extrapolated to other human limbs or even animals. However, in order to safely manipulate any human limb, the robot should know how the human body moves as accurately as possible. This imply the derivation of a full dynamic model of the human, considering all joints and its respective ranges of motion. To implement such a model in the robot controller, the model should be computed in real time from sensors observations. To this end, a high variety of sensors could be contemplated. As mentioned in previous chapters, wearable sensors have been widely used to measure human-related variables. However, such sensors present some inconveniences and limitations that should be considered in order to improve user comfort and safety. Thus, it would be interesting to develop human modeling approaches sensorizing the environment (with force plates, RGB-D cameras, etc.) rather than directly attach sensors to the human body.

Another future line of research must focus on the implementation of other behaviors, making robots able to assist humans in more tasks. Advancing in this direction could result in a library of behaviors and a policy for behavior selection based on context awareness. Thus, a multipurpose robotic assistant could be implemented. The addition of social behavior could also be implemented to create human-friendly robots, which may bring robots closer to humans. However, to accomplish such an objective, the concept of safety should be revisited. As mentioned above, the current definition of safety for pHRI focuses on collaboration, so physical contact is avoided to the extent possible. Notwithstanding, in robot-driven applications, intended physical contact is necessary. In this case, safety becomes more complex in the sense that it needs to contemplate factors related to the human status and comfort.

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