Abstract

The world of robotics has been growing exponentially over the last decades. Recent advances in control techniques, sensors, and actuators, as well as improvements in the ability to interpret the surrounding environment through the use of Artificial Intelligence (AI) are enhancing the concept of intelligent robots day by day. In a humanity-centered world, advances in robotics are mainly focused on the interaction between humans and robots. Based on this premise, robots should be able to generate interaction strategies for cooperation and coaction with humans, and plan motions that take into account our needs and safety. However, to perform these procedures, robots should be capable of perceiving the world around them. One of the most important senses we humans have to interact with the surrounding environment is the sense of touch. The word haptic refers to everything that is related to the sense of touch. We can define the haptic term as the sensations that encompass tactile and kinesthetic perception. Haptic perception is almost indispensable for physically interacting with the world around us. Therefore, it is critical to design end-effectors for robots with sensors that perceive sensations analogous to haptic perception. It is also necessary to interpret the perceived information to act accordingly. This thesis encompasses the design of grippers with haptic perception capabilities, and the intelligent use of the information perceived.

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Francisco Pastor Martín – Learning-based Haptic Perception in Robotic Grippers: Design and Applications

Learning-based Haptic Perception in Robotic Grippers: Design and Applications

Francisco Pastor Martín

Directores:
Jesús Manuel Gómez de Gabriel
Alfonso José García Cerezo

2023

Tesis doctoral por compendio

Doctorado en Ingeniería Mecatrónica
Departamento de Ingeniería de Sistemas y Automática
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D./Dña FRANCISCO PASTOR MARTÍN
Estudiante del programa de doctorado EN INGENIERÍA MECATRÓNICA de la Universidad de Málaga, autor/a de la tesis, presentada para la obtención del título de doctor por la Universidad de Málaga, titulada: LEARNING-BASED HAPTIC PERCEPTION IN ROBOTIC GRIPPERS: DESIGN AND APPLICATIONS

Realizada bajo la tutorización de ALFONSO JOSÉ GARCÍA CEREZO y dirección de JESÚS GÓMEZ DE GABRIEL Y ALFONSO JOSÉ GARCÍA CEREZO (si tuviera varios directores deberá hacer constar el nombre de todos)

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El Dr. D. Jesús Manuel Gómez de Gabriel y el Dr. D. Alfonso José García Cerezo, directores de la tesis titulada “Learning-based Haptic Perception in Robotic Grippers: Design and Applications" realizada por D. Francisco Pastor Martín, certifican su idoneidad para la obtención del título de Doctor en Ingeniería Mecatrónica.

Málaga, 10 de enero de 2023

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Dr. D. Jesús Manuel Gómez de Gabriel

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Dr. D. Alfonso José García Cerezo

A mis padres.

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Abstract

The world of robotics has been growing exponentially over the last decades. Recent advances in control techniques, sensors, and actuators, as well as improvements in the ability to interpret the surrounding environment through the use of Artificial Intelligence (AI) are enhancing the concept of intelligent robots day by day. In a humanity-centered world, advances in robotics are mainly focused on the interaction between humans and robots. Based on this premise, robots should be able to generate interaction strategies for cooperation and coaction with humans, and plan motions that take into account our needs and safety. However, to perform these procedures, robots should be capable of perceiving the world around them. One of the most important senses we humans have to interact with the surrounding environment is the sense of touch. The word haptic refers to everything that is related to the sense of touch. We can define the haptic term as the sensations that encompass tactile and kinesthetic perception. Haptic perception is almost indispensable for physically interacting with the world around us. Therefore, it is critical to design end-effectors for robots with sensors that perceive sensations analogous to haptic perception. It is also necessary to interpret the perceived information to act accordingly.

This thesis encompasses the design of grippers with haptic perception capabilities, and the intelligent use of the information perceived. The grippers are able to perform tasks where there is direct robot-initiated physical interaction. These tasks are numerous, e.g., grasping human limbs to carry out rehabilitation exercises, performing palpation procedures to grasped bodies, or placing sensors in specific areas. In particular, this dissertation presents three contributions related to the general basis of the thesis. Intelligent grippers are developed and used for diverse purposes: I) Fusing haptic information perceived with grippers; II) Sensing interaction forces while grasping in physical Human-Robot Interaction (pHRI); III) Placing sensorized grippers to victims with a mobile manipulator in Search and Rescue (SAR) scenarios. The present thesis is a compendium of previously published scientific articles, which form the core of the PhD. Four papers published in prestigious indexed scientific journals make up the main body of this study. The contributions addressed in this study are discussed in chapters 2, 3, and 4.

Chapter 2 presents two works about the benefits of fusing haptic sensations in robotics. Humans use these two sources of information together to enhance the recognition or manipulation process. Thus, it is reasonable to assume that an intelligent robot will also make use of all the haptic data at its disposal to conduct similar procedures. This chapter relates the use of deep learning methods for classification and regression using each haptic data separately. Then, an a posteriori analysis of both sources is carried out, fusing the results. Two haptic datasets -one comprising objects and the other consisting of a human forearm- recorded with a gripper were trained. With this methodology, the fusion outputs are more robust and accurate than the approaches with only tactile or kinesthetic information. These pioneering works demonstrate a unique synthesis of this particular type of information, paving the way for future research in the field.

Chapter 3 addresses the problem of the detection of interaction forces produced once a gripper is grasping a human's upper limb. The benefits of a robot manipulating human limbs are manifold and include a broad range of issues relating to assistive or rehabilitation robotics. However, human desires and inconveniences can be difficult to read for robotics systems. The estimation of interaction forces is critical for intelligent grasping, considering an analysis of the modulus and the orientation could help in deciphering human intentions. A new underactuated gripper with proprioceptive capabilities was designed for this purpose. A dataset of kinesthetic information recorded by the gripper was used for training purposes using Machine Learning methods. Then, the trained model is utilized for the estimation of the interaction forces.

Chapter 4 describes an application that consists of a mobile manipulator that performs triage to victims in disaster scenarios. The triage procedure is carried out by reading the biometric sensors included in a gripper. The application of robotics to rescue has gained momentum over the last years, integrating diverse technologies to the associated problems. However, the field of rescue robotics where there is robot-initiated physical contact with the human is still immature. This chapter tackles the victim status recognition problem through the autonomous placement in a forearm of a novel gripper that carries vital sensors. With the help of Artificial Intelligence, a vision sensor detects the pose of the wrist so that the end effector of a robotic manipulator can track, and then attach the sensing gripper.

Finally, chapter 5 gathers the main conclusions of this PhD thesis and sketches out further developments, and chapter 6 includes a summary of the thesis in Spanish.

Special Acknowledgments

The development of this thesis comes to an end. Five years of intense work, valuable learning, and some occasional unpleasant moments that will always remain in my memory for being a very special period in my life. For this reason, I would like to take this opportunity to thank all the people who, in one way or another, have lived this experience with me.

First and foremost, I would like to express my full gratitude to my supervisors, Alfonso García Cerezo and Jesús Gómez de Gabriel. Your invaluable help has been indispensable for the development of this work. Thank you Alfonso for always trusting in me. This thesis would have not been possible without your full support. Jesús, thank you for your valuable comments and guidance, especially at the beginning of this PhD, introducing me to the wonderful world of investigation and in the discovery of my research topic.

There is also a place here for my co-workers. The taller 27, the lab where most of this thesis has been developed, is a fantastic place where many researchers share knowledge and discuss science. These researchers happen to be also good friends. Manuel Castellano, Manuel Toscano, Manuel Sánchez, Juan, Pablo Vera, Pablo Zambrana, Ricardo, and Juan Alberto, working with you has been and actually is amazing. A special thanks to Javier Serón for making my entrance into the University much easier and, above all, for helping me in everything, always with a smile. I also appreciate all the guidance and assistance I received from the Systems Engineering and Automation Department's professors and researchers.

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Thanks to the development of this thesis, I have met incredible researchers. To name just a few, Dani, your research capabilities are extraordinary, I am very proud to have published with you. Jorge, thank you for introducing me to the marvelous world of neural networks. Fran, working with you side by side on some crazy ideas has been a pleasure.

In addition to my supervisors, this PhD has two additional main pillars. Da-hui, what an incredible researcher you are. It was a privilege to sit by your side these last years of the thesis, discussing ideas and inspiring each other. And, of course, Juanma. You got me into this mess. Thankfully, I ended up liking it. I am very lucky to have met you as a researcher, but much more to have you as a friend for life.

Finally, I would like to thank to my family for their unconditional support and absolute trust. Aunt Tere, thank you for always being available to me. Irene, I have learned to trust myself thanks to you.

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Mum and Dad, you inspire me every day. You are the reason I am who I am. Charo, you do not know how much I value your presence in the process of this thesis. You have rejoiced with my achievements even more than I have and suffered with my bad moments as if they were your own. I am very fortunate to have you by my side. The best is yet to come.

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CHAPTER 1

Introduction

1.1 Motivation and Background

Robots are expected to play a key role in the future. Despite the significant impact they have had on society to date, they will undergo a fundamental paradigm shift in the next decades. We still do not know when, but we can safely assume that an immense number of tasks that we humans perform today will someday be handled by robots. It is likely that robots will eventually cohabitate with humans, assisting with daily household tasks or providing companionship similar to pets. Thanks to the improvement in sensor technology and the noteworthy advances in Artificial Intelligence (AI) and Machine Learning (ML), robots will keep growing from simple actuator-based mechanisms to entities capable of thinking and making decisions based on their cognitive functions. These technological advances, and other advances in associated fields, are on an upward trajectory, and robotics will surely benefit from these strides.

Despite meaningful progress has been made, significant work remains to be done in order to achieve this ambitious challenge. Several sub-tasks must be tackled first. This thesis focuses on one of these tasks, which consists of providing robots with the touch sense we humans have and in the ability to interpret perceived information. These capabilities are critical if we expect robot-initiated physical contact with humans. The ability for robots to physically interact with humans is crucial for efficient and effective collaboration in tasks such as manufacturing and healthcare. It also allows for increased productivity, as well as a more intuitive and natural form of communication, ultimately enhancing the user experience. The research topic of physical Human-Robot Interaction (pHRI) is a hot topic nowadays. Classical robots that perform typical automation tasks are known to be dangerous. However, recent advances in mechatronic design have led to the creation of a new generation of robots (co-bots) that are capable of safely and reliably physically interact with humans in a shared workspace. These robots usually have external torque sensors to detect non-desired forces that could lead to possible injuries. However, they still need additional sensing capabilities, similar to the touch sense, to perform more complex grasping-related procedures or more sophisticated collaboration tasks.

The integration of haptic perception capabilities in a robot allows for the imitation of the human sense of touch. The haptic term can be divided into two subsystems: tactile and kinesthetic sensations. Tactile data is the information we perceive through our skin, such as pressure, vibrations, slippage, pain, or temperature. On the other hand, kinesthetic data refers to the capacity to know the positions and movements of the skeletal joints. Mainly thanks to the touch sense, human hands can manipulate tools precisely and they have the power to grab objects of many forms and sizes. It is a well-known fact that with practice, one can move a pen by rolling or sliding, manage things with stick-like shapes acrobatically, and execute operations requiring precise control of small devices or tools. However, humans use our hands for more than only grasping and manipulating objects. Exploration, touch, and the perception of physical characteristics, such as roughness, warmth, and weight, are other fundamental tasks that we can typically accomplish with the help of our hands.

Robotic grippers were developed with the intention of performing equivalent tasks with the dexterity and adaptability that a human hand has. Even being still far from operating with these capabilities, however, recent progress is providing them with haptic perception skills. State of the art tactile sensors can measure many properties, such as pressure, thermal conductivity, shear forces, and surface temperature with high accuracy using a variety of transduction mechanisms. The kinesthetic information is also obtainable by measuring the relative position between two links, the torque and the angular velocity of a joint.

Hence, this type of information could be utilized in conjunction with Machine Learning approaches to develop new functionalities. Machine Learning is one of the most important research topics in robotics nowadays, considering it allows robots to perform tasks that require a level of flexibility and adaptability that is difficult to achieve with traditional approaches. Machine learning algorithms are based on imitating the way humans learn from experience via computational methods. We can train a learning algorithm with data to obtain a model that is able to classify or estimate new outputs. Haptic data presents a very convenient structure for these type of approaches: I) Tactile data resembles to images; therefore, similar techniques to those used with visual data can be employed. II) Haptic data can present a temporal structure if it has been obtained dynamically; thus, methods that present good results with time data could be applied. As aforementioned, haptic information is provided by two sources. Fusion techniques combine outputs from several sensors to produce a robust and thorough description of an environment or process of interest. The integration of these techniques with haptic data could lead to outperforming results of the one source of information-only approaches.

Although robotic grippers that mimic the skills of a human hand have several advantages, some tasks require other capabilities. It may be more appropriate to equip grippers with alternative utilities for specific activities. Several grippers only need good grasping capabilities and the ability to hold heavy weights since they will operate in automation and mechanization procedures; thus, hardly any sensor feedback is needed. Other applications focus on including medical sensors to grippers to develop triage procedures and monitor the patient. These devices could be used in Search and Rescue (SAR) scenarios where, usually, rescue resources are limited; thus, the help of robots could be valuable. The integration of grippers with biomedical sensors with pHRI approaches is a big challenge that promises significant advances in SAR applications.

1.2 Objectives

The scope of research on grippers is vast and cannot be fully explored within the confines of a single thesis. However, some specific tasks can be addressed. This thesis presents several concepts, from the design of grippers with haptic sensing capabilities and the analysis of the data perceived from the grasps, to the process of robot-initiated interaction with a human using grippers. The main aims of this thesis are outlined below.

1. **Enhancement of robotic haptic perception capabilities.** Humans can actually discriminate between different items and manipulate them using their tactile and kinesthetic sensations together. Robotic grippers have used haptic information separately to develop recognition and manipulation tasks. However, the fusion of both outcomes to improve the results has yet to be considered. This thesis focuses on developing methods that merge haptic information perceived with grippers.

2. **Development of methods to recognize human intentions while being grasped with a gripper.** Human purposes can sometimes be unpredictable for robots, especially if they are being grasped. Therefore, robots must have the capability to feel these discomforts and act accordingly, showing empathy with the subject being held. This thesis focuses on, with the help of Machine Learning methods, being able to estimate forces in a novel-designed gripper that is grasping a human limb.

3. **Development of applications based on pHRI for Search and Rescue scenarios.** Scarce works in the literature have considered a robot initiating contact with casualties in disaster scenarios due to the numerous challenges to be overcome. This thesis aims to develop an autonomous robotic system that is able to physically interact with a victim to monitor its status using a novel detachable gripper and vision sensors.

1.3 Contributions

The three main sections in which this thesis' contributions are divided are presented in chapters 2, 3, and 4. A compilation of the grippers developed as a result of this thesis is shown in Figure 1.1.

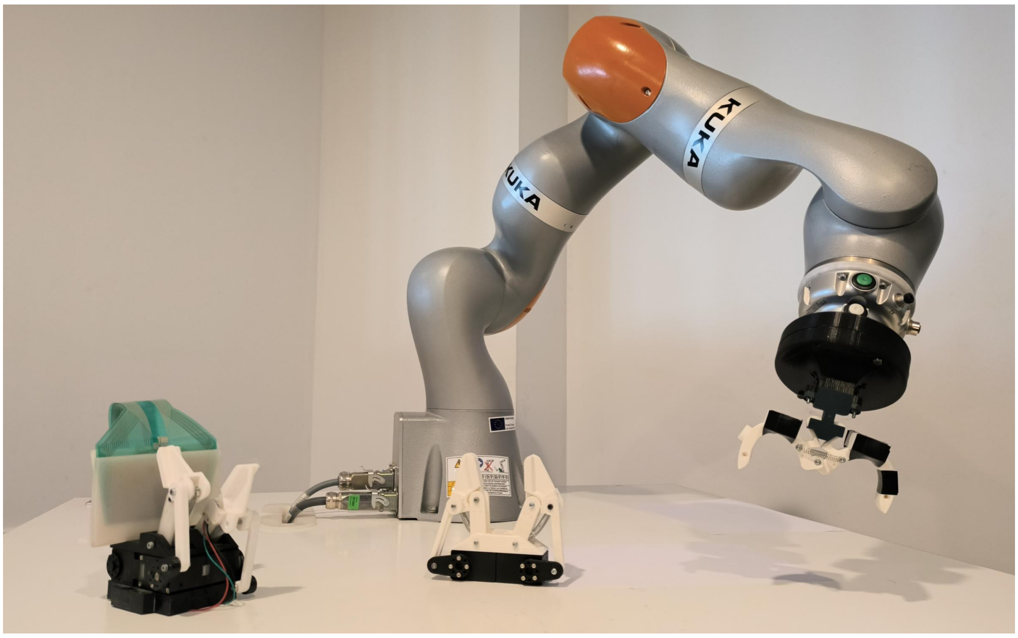


Figure 1.1: *The grippers utilized in this thesis are presented together with the KUKA manipulator.*

- **Fusing haptic information perceived with grippers:**

  The benefits of combining multiple sources of haptic information are presented in this contribution. In concrete, tactile and kinesthetic data are trained with AI methods based on Long short memory (LSTM) neural networks for classification and regression purposes. This thesis contributes to this research topic with two works. Besides, two haptic datasets recorded with a gripper are included. In section 2.3, the first contribution relates an object recognition method that uses haptic information separately and then fuses outputs with a Bayesian and neural inference approach. The second contribution is included in section **??** and presents an estimation of the forearm grasping section location. The experiments of both contributions proved that, as expected, the fusion of the data obtains better and more robust results than the training of the data separately. It is also worth mentioning that the article resulting from the contribution in section 2.3 has been relevant to the scientific community, generating nineteen citations until the publication of this thesis from authors outside the University of Málaga. Besides, the two datasets have been published in the GitHub platform, with the section 2.3 dataset having more than eight hundred visits and three forks.

- **Sensing interaction forces while grasping in pHRI:**

  This thesis tackles the problem of recognizing human intentions while being grasped with a robotic system. Section 3.3 presents a gripper that, with only kinesthetic perception capabilities and the development of Machine Learning approaches, is able to recognize the forces exerted between the human and the gripper. The results of the experiments proved that the estimation method is capable of deciphering the interaction forces' magnitude and direction reliably. This contribution ignited the development of a new gripper with improved grasping capabilities, which has been presented in [7], and a new method to estimate the grasping forces in this new gripper [8].

- **Human robot interaction in search and rescue scenarios:**

  An application involving physical interaction between a victim and a robot in SAR scenarios is presented as a contribution of this thesis. Section 4.3 relates a method to autonomously sensorized victims with a novel gripper and its mechanism based on two stable states. The gripper is placed using a vision sensor and a robotic manipulator. The vision sensor is able to detect the wrist pose by using a hand landmark neural network based method and the Horn algorithm. The robotic manipulator is able to, using a Model Predictive Control (MPC), replan the trajectory based on the detected pose and then place the gripper into the victim's forearm. Two experiments were carried out satisfactorily. The first in a lab with controlled boundary conditions, and the second as a part of a large scale disaster exercise in the International Conference on Security, Emergencies and Catastrophes (Jornadas Internacionales de Seguridad, Emergencias y Catástrofes) held in Málaga in 2021.

1.4 Methodological Frame and Tools

The development of intelligent grippers is the methodological frame of this thesis. This dissertation includes a wide variety of grippers. However, all of them are based on the same methodology: underactuated mechanisms. This type of mechanism is widespread in robotics grippers due to its numerous advantages over traditional mechanisms. Besides, a Machine Learning methodology has been considered for processing the information perceived by the sensory system. The application of Machine Learning algorithms to robotics is a prominent topic in the field, as evidenced by the numerous publications with related keywords presented at the 2022 International Conference on Intelligent Robots and Systems (IROS) [9], a prestigious conference in the field of robotics.

1.4.1 Underactuated Grippers

The concept of underactuation in fingers is slightly different from the general concept of underactuation in standard robotic systems. We usually define an underactuated robot as a system with more degrees of freedom than actuators. However, an underactuated robotic finger usually employs elastic elements in its underactuated joints. Therefore, it is more reasonable to define these joints as passive-driven and not as unactuated. A finger's underactuated mechanism, which is usually a four bar linkage, is composed of gears, tendons, pulleys, etc. These elements distribute the applied actuation torque to the phalanx joints, exerting pressure on each phalanx surface. As previously mentioned, underactuated fingers have more degrees of freedom than actuators, therefore passive elements such as springs and mechanical limits are often used to constrain the structure and ensure that grasping procedures occur as planned. These passive elements also allow the fingers to adapt to the grasped body. An example of an underactuated four bar mechanism with two phalanxes is shown in Figure 1.2. A closing sequence is presented, with a

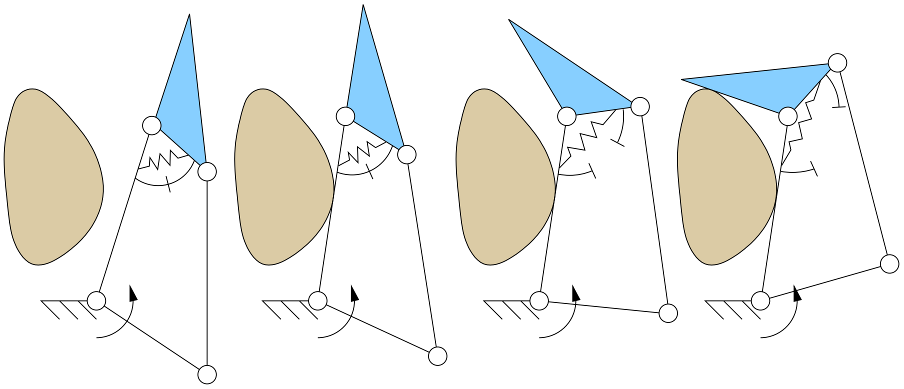
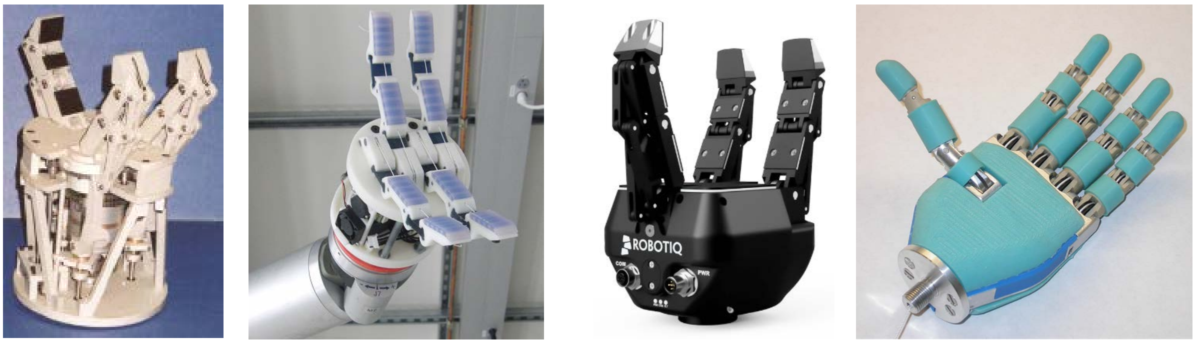


Figure 1.2: *Grasping procedure of a two phalanx finger. The mechanism consists of a four bar with a spring. The finger adapts to the shape of the object whenever the closing sequence advance. (Source: [1]).*



a) b) c) d)

Figure 1.3: *Examples of underactuated grippers of different types and configurations. a) SARAH [2], b) Yale OpenHand [3], c) Robotiq [4], d) anthropomorphic prosthetic hand [5] .*

torque applied in the fixed joint. Note that the spring maintains the phalanxes parallel until the grasped object touches one phalanx, and then the other phalanx rotates and adapts to the shape of the object.

Thanks to underactuation, fingers can self-adapt to an item without the aid of expensive and sophisticated control architectures. Using their capacity to modify their shape, underactuated grippers serve as an intermediate approach between simple grippers and complex robotic hands for manipulation with multiple degrees of freedom and intricate designs. A collection of underactuated grippers developed by different prestigious authors and companies is shown in Figure 1.3.

1.4.2 Machine Learning

Machine Learning is a subcategory of the field of AI. It encompasses the algorithms or techniques that use computational resources to find recurrent patterns in a set of data without being explicitly programmed. Once the patterns are recognized, Machine Learning methods are capable of performing predictive analytics and estimate the outputs of non trained data. Machine Learning was first introduced in 1959 by Arthur Samuel; however, it has gained momentum over the last years due to the increasing computational capacities and the increment of massive datasets (Big Data). Deep learning is a Machine Learning subcategory based on artificial neural networks and has been widely used in the development of this thesis. Machine Learning algorithms can be categorized into three main types, depending on the learning techniques:

- **Supervised learning**: These algorithms train a dataset that has been previously labeled with their desired outputs. The objective is to learn the general rules that map an input to an output based on example input-output pairs. The two most common supervised learning cases are: I) Classification, where outputs are divided into classes, and the algorithm must learn which input patterns correspond to each class ($f:\mathscr{X}\rightarrow\{1,2,...,k\}$, with $\mathscr{X}$ representing the input and k the number of classifications). II) Regression, where the outputs are continuous rather than discrete ($f:\mathscr{X}\rightarrow\mathbb{R}$).
- **Unsupervised learning**: This type of Machine Learning algorithm also draws inferences from datasets, but, in this case, data is unlabeled. Therefore, these algorithms find hidden patterns on their own. There are two types of unsupervised learning approaches: I) Clustering, where the data is divided into groups depending on their similarities or their differences, and II) Association, where the algorithm finds relationships between some of the variables in the dataset.
- **Reinforcement learning**: This type of learning enables an agent to learn from its environment by trial and error, and is based on rewarding actions that are beneficial, and punishing the ones that are undesired. This type of algorithm usually uses a cost function to evaluate the performance based on the choices made, and is provided as feedback to the agent.

Machine Learning algorithms have been widely used in the literature for multiple purposes, i.e., image classification approaches [10], medical diagnosis [11], online fraud detection [12], self-driving cars [13], or chemoinformatics [14]. The compendium of publications presented in this thesis use supervised Machine Learning methods. In concrete, three works apply regression approaches (section **??**, section 3.3, and section 4.3), and one uses classification approaches (section 2.3).

1.4.2.1 Deep Learning

Deep Learning is a Machine Learning technique substantiated by the functioning of the human neurological system. Deep neural network methods are based on multiple layers formed by a group of artificial neurons. Each layer is specialized in identifying some specific characteristics, similar to the way a human brain operates. There exists a wide variety of deep learning architectures, and this thesis focuses on two of them:

- **Convolutional Neural Networks (CNNs/ConvNets)**: Convolutional Neural Networks are very similar to ordinary Neural networks. The main difference is that CNNs are prepared to have visual

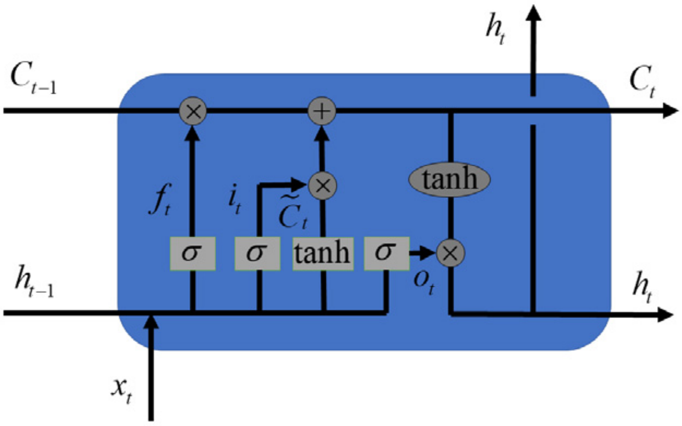


Figure 1.4: *Graphical illustration of a long short-term memory neural network (Source: [6]).*

data as input. Three main types of layers are used to build CNNs architectures: Convolutional layers, Pooling layers, and Fully connected layers. The convolutional layer main objective is to extract characteristics from the images and compress their initial size. This process is realized thanks to consecutive filters that move across the receptive fields of the image. Pooling layers, also named as downsampling, reduce the number of inputs' parameters. The fully connected layer performs the classification procedure based on the previously extracted features.

- **Long-Short Term Memory Neural networks (LSTMs)**: Long-short term memory networks are an advanced version of Recurrent Neural Networks (RNNs). A scheme of the structure of a LSTM network is shown in Figure 1.4. RNNs are capable of remembering previous information and use it to process the current input. However, they are not able to remember Long-term dependencies due to gradient exploding or vanishing. This issue is solved with LSTM networks, which structure established 'gates' in its basic unit, called as 'cell'. These gates prevent RNNs issues and ensure the capture of both long and short memory term along the time steps. Therefore, LSTMs are very well suited for time series data. This thesis presents in chapter 2 haptic information of a squeeze and release procedure recorded among time. Thus, conventional LSTMs [15] are used for the kinesthetic data. In case of tactile data, a different approach is considered. Convolutional LSTM Networks(ConvLSTMs) [16] are a variant of LSTMs in which both input and recurrent transformations are convolutional. Hence this type of network is chosen considering is suitable to analyze spatio-temporal structures as tactile data.

1.5 Main Publications Supporting the Thesis

The core of this thesis is composed of a compendium of articles that constitute the main contribution of this work. The present thesis encompasses the following publications, accompanied by a concise explanation of the author's specific contributions to each article.

- J. Ballesteros, F. Pastor, J. M. Gómez-de-Gabriel, J. M. Gandarias, A. J. García-Cerezo and C. Urdiales “Proprioceptive Estimation of Forces Using Underactuated Fingers for Robot-Initiated pHRI", Sensors, vol 20(10), pp. 2863, 2020 (Q2, T1) [17] DOI: 10.3390/s20102863

  Listed below are the author’s contributions: Conceptualization of the idea, Forward kinematics study, validation of the research and methodology, software and electronics concerning the kinesthetic data, visualization of the results, and writing of the different versions of the manuscript.

- F. Pastor, J. García-González, J. M. Gandarias, D. Medina, P. Closas, A. J. García-Cerezo, J. M. Gómez-de-Gabriel, “Bayesian and Neural Inference on LSTM-based Object Recognition from Tactile and Kinesthetic Information", IEEE Robotics and Automation Letters, pp. 231–238, 2020 (Q2, T1) [18] DOI: 10.1109/LRA.2020.3038377

  Listed below are the author’s contributions: Conceptualization of the idea, dataset creation, training and test of the different neural networks, validation of the research and methodology, software and electronics concerning the haptic data, visualization of the results, and writing of the different versions of the manuscript.

- F. Pastor, F. J. Ruiz-Ruiz, J. M. Gómez-de-Gabriel, A. J. García-Cerezo, “Autonomous Wristband Placement in a Moving Hand for Victims in Search and Rescue Scenarios With a Mobile Manipulator", IEEE Robotics and Automation Letters, pp. 11871–11878, 2022 [19] DOI: 10.1109/LRA.2022.3208349

  Listed below are the author’s contributions: Conceptualization of the idea, implementation of the MPC scheme and the 6D pose estimation algorithm, calibration concerning the vision sensor, design and kinematics analysis of the wristband, definition of the whole method, experimental validation, visualization of the results, and writing of the different versions of the manuscript.

- F. Pastor, D. Lin-Yang, J. M. Gómez-de-Gabriel, A. J. García-Cerezo, “Dataset with Tactile and Kinesthetic Information from a Human Forearm and its Application to Deep Learning",Sensors, vol 22(22), pp. 8752, 2022 [20] DOI: 10.3390/s22228752

  Listed below are the author’s contributions: Conceptualization of the idea, design of the dataset collection procedure and the dataset acquisition device, dataset creation, training and test of the different neural networks, validation of the research and methodology, software and electronics concerning the haptic data, visualization of the results, and writing of the different versions of the manuscript.

1.6 Research Activities

This thesis was initiated in November 2017 as part of the author’s work as a member of the Robotics and Mechatronics Group [1], at the Department of Systems Engineering and Automation of the University of

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[1] `https://www.uma.es/robotics-and-mechatronics`

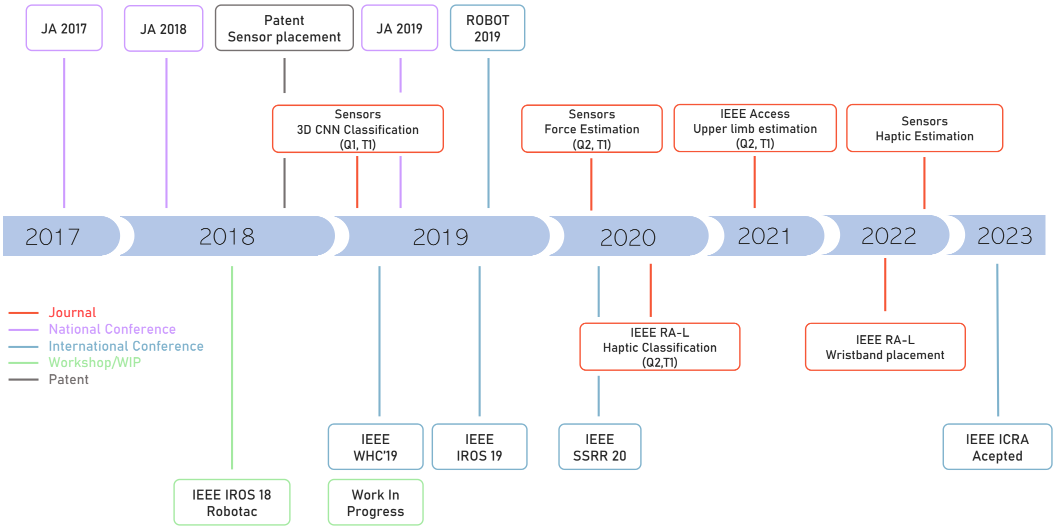

Figure 1.5: *Timeline of the main research contributions of this thesis.*

Málaga. Even though the publications that support the thesis are crucial, a thesis is much more than that. Other research activities, such as collaborating with co-workers in other publications, organizing events to promote the thesis results, or participating in prestigious international conferences to share knowledge were developed, and are also a noteworthy part of this thesis. A summary of the more remarkable activities has been included, with the addition of a timeline, shown in Figure 1.5, representing the research contributions realized for this PhD.

1.6.1 Additional Publications

The following publications are not included in the compendium of articles, but are within the scope of the PhD and related to the research topic of this thesis, thus they are also considered as a contribution. Each publication is accompanied by a brief description of each work.

1.6.1.1 Journal articles

- F. J. Ruiz-Ruiz, J.M. Gandarias, F. Pastor, J.M. Gómez-de- Gabriel "Upper-limb kinematic parameter estimation and localization using a compliant robotic manipulator" IEEE Access, 9, 48313-48324, 2021. (Q2, T1). [21]

  This work addresses an upper limb manipulation challenge: To estimate an arm's human kinematics parameters and pose using a robotic manipulator with no external sensors. The method uses only proprioceptive information provided by the manipulator with a cartesian impedance-based controller. A compliant trajectory is commanded and, due to the human arm kinodynamics, the trajectory adapts to the human constraints. Once the end effector pose is recorded, two estimation methods are implemented: The Hough transform and the least squares. These methods consider the human arm moves on a plane; thus, its model can be simplified as a two degrees of freedom kinematic chain. Besides, a sensorized, resizable dummy arm was designed for the experimental validation of the estimation methods. Experiments considering six different arm's lengths have been performed, with the results validating both of the proposed methods.

- F. Pastor, J.M. Gandarias, A.J. García-Cerezo, J.M. Gómez-de-Gabriel, "Using 3D convolutional neural networks for tactile object recognition with robotic palpation", Sensors, vol. 19(24), 5356, 2019. (Q1, T1). [22]

  This paper presents a novel gripper designed to perform a human palpation procedure. The gripper has three fingers, two underactuated parallel fingers that perform the entire grasping procedure and one larger static finger located in front of the other two. The parallel fingers perform the active palpation thanks to two independent actuators that increase and decrease the torque applied, similarly to how a human would perform a grasping procedure. The static finger contains a tactile sensor that records the tactile data as a tensor $[28 \times 50 \times 51]$ whenever the squeeze and release procedure is being performed. A tactile dataset of 24 objects that present different internal characteristics (e.g., internal inclusions, rigid or deformable objects) is trained with 3D convolutional neural networks for classification purposes. Results showed a better performance with the 3D convolutional neural networks than with the conventional 2D convolutional neural networks.

1.6.1.2 Conference articles

- F. Pastor, F. J. Ruiz-Ruiz, J. M. Gómez-de-Gabriel, A. J. García-Cerezo, "Autonomous Wristband Placement in a Moving Hand for Victims in SAR Scenarios With a Mobile Manipulator", IEEE International Conference on Robotics and Automation (ICRA), 2023, accepted

  The article, entitled "Autonomous Wristband Placement in a Moving Hand for Victims in Search and Rescue Scenarios With a Mobile Manipulator," has been proposed for publication at the International Conference on Robotics and Automation (ICRA) in accordance with the guidelines set forth by the IEEE Robotics and Automation Letters editorial board. It is currently accepted, and will be presented between 29 May – 2 June 2023.

- A. Mandow, J. Serón, F. Pastor, A.J. García-Cerezo, "Experimental Validation of a Robotic Stretcher for Casualty Evacuation in a Man-Made Disaster Exercise", IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), 2020 [23]

  This work relates a cooperative search and rescue exercise where a military team uses a ground robot (Rambler Robot) for casualty evacuation in a typical military scenario, where natural vegetation, rough terrain, and multiple altitudes scenarios are commonly presented. Regarding the casualty extraction, a stretcher was adapted, using a roll-in mechanism to be able to perform a quick attachment to the ground robot. The system was validated in a realistic one-shot exercise, considering the validation was performed with rescue team members with no experience using the device.

- J.M. Gandarias, F. Pastor, A.J. Muñoz-Ramírez, A.J. García-Cerezo, J.M. Gómez-de- Gabriel, “Underactuated Gripper with Forearm Roll Estimation for Human Limbs Manipulation in Rescue Robotics", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019. [24]

  In this congress paper, we presented a method to perform stable grasping of a human forearm lying on the ground, thanks to the design of a novel gripper and its grasping strategy. Besides, once the human wrist is grasped, the roll angle of the forearm is estimated with Machine Learning methods using the data provided by the gripper as input. With this information, safe and stable grasping manipulation can be performed, being one of the first works that tackle a robot actively manipulating a human.

- F. Pastor, J.M. Gandarias, A.J. García-Cerezo, J.M. Gómez-de-Gabriel, “Grasping Angle Estimation of Human Forearm with Underactuated Grippers Using Proprioceptive Feedback", ROBOT 2019: Fourth Iberian Robotics Conference, Springer, 2019. [25]

  This article presents a method to estimate the angle of grasping of a human forearm with respect to a resting position when grasped with an underactuated gripper. Regression methods, such as the Gaussian Process Regression (GPR), the Regression tree (RT), and the Bagging Regression Tree (BRT), were trained with the proprioceptive information provided by the gripper. Several experiments were conducted to train the regression methods, using data to train and test from known subjects, and data from known subjects to train and unknown subjects to test. Results showed the good performance of the method, providing sufficient accuracy in all of the experiments.

- J.M. Gandarias, F. Pastor, A.J. García-Cerezo, J.M. Gómez-de-Gabriel, “Active Tactile Recognition of Deformable Objects with 3D Convolutional Neural Networks", IEEE World Haptics Conference (WHC), 2019. [26]

  This conference paper presents a novel 3D convolutional neural network called TactNet3D used to classify a set of objects with the active data recorded from a tactile sensor. The data obtained by the sensor is a 3D tactile tensor that contains sequences of tactile images recorded over time with different incremental forces applied, forming a matrix of $[28 \times 50 \times 10]$. In concrete, a classification with an accuracy of 96.39 % of 9 deformable objects is presented, considering each object presents different stiffness and internal characteristics.

- T. Sánchez-Montoya, J.M. Gandarias, F. Pastor, A.J. Muñoz-Ramírez, A.J. García-Cerezo, J.M. Gómez-de-Gabriel,“Diseño de una pinza subactuada híbrida soft-rigid con sensores hápticos para interacción física robot-humano", XL Jornadas de Automática, 2019. [27]

  This work presents the design of a novel gripper with hybrid characteristics, containing both rigid and soft links. The rigid links are two parallel underactuated fingers that record proprioceptive information thanks to the actuators' feedback and the potentiometers installed in the joints. The soft link is another underactuated finger, but includes a tactile sensor; therefore, the gripper is capable of obtaining tactile information in addition to the proprioceptive data. Two possible configurations of the soft link are used to grasp a human arm, and a discussion of the results is included.

- F.J. Ruíz-Ruíz, J.M. Gandarias, A.J. Muñoz-Ramírez, A.J. García-Cerezo, F. Pastor, J.M. Gómez-de-Gabriel, "Monitorización de víctimas con manipuladores aéreos en operaciones de búsqueda y rescate", XXXIX Jornadas de Automática, 2018. [28]

  This work presents a device to monitor human vital signs and the procedures to locate them with an unnamed aerial vehicle that includes a delta manipulator. This device has been designed to operate in search and rescue scenarios, where performing the triage of a victim is critical to implement an optimal rescue strategy. The victims' vital signs are recorded and sent to the rescues via the internet of things. An exercise was performed to prove the device's viability, with the results being satisfactory.

- F. Pastor, J.M. Gandarias, J.M. Gómez-de-Gabriel, "Cinemática y prototipado de un manipulador paralelo con centro de rotación remoto para robótica quirúrgica", XXXVIII Jornadas de Automática, 2017. [29]

  This work presents the design and kinematics of a two degrees of freedom parallel robot to perform laparoscopic procedures. The robot structure consists of a five bar mechanism, but their axes are not parallel to each other. Instead, each axis intersects at a common point, called the remote center motion, on which the end effector of the robot pivots. The design and kinematics are validated with the construction of a real prototype, which is also subjected to several experiments that are carried out satisfactorily.

1.6.2 Patents

A patent has been developed as a result of this thesis:

- J.M. Gómez-de-Gabriel, A.J. MuñozRamírez, J.M. Gandarias, F. Pastor, J. Ballesteros, A.J. García-Cerezo. "Dispositivo, sistema y método de fijación controlable mediante un brazo mecánico"

1.6.3 Other activities

During the development of this thesis, the author had the opportunity to collaborate with KUKA on the design of a demonstration for the European Robotic Congress (ERF) 2020, and also played a role in organizing the event held in Málaga. The author also had the chance to publish in two Work in Progress (WIP) papers in IROS 2018 and IEEE World Haptic Conference (WHC) 2019, and to act as a reviewer for prestigious journals and conferences: IEEE Transactions on Instrumentation & Measurement, IEEE Robotics and Automation Letters, IEEE Sensors Journal, IEEE Access and the

Iberian Robotic conference, where the author has also been a member of the program committee. Two students were supervised in order to obtain their bachelor's thesis. Besides, it is also worth mentioning that the author served as an assistant lecturer in the department of System Engineering and Automation from the Bs degree of Engineering in Industrial Technologies (Grado en Ingeniería en Tecnologías Industriales), and the Bs degree in Electronics, Robots and Mechatronics (Grado en Ingeniería Electrónica, Robótica y Mecatrónica). In concrete, teaching tasks of Automatic Control (Regulación Automática) were performed for two consecutive years, from 2020 to 2022. Besides, the author of this thesis participated in two Spain National projects: FIRST-ROB (DPI-2015-65186-R) and TRUST-ROB (RTI2018-093421-B-100). The main objectives of both projects are described below.

FIRST-ROB: The main objective of this project was to develop a multi-robot system that could support rescue teams and reduce the risk of possible injuries, as well as to improve their efficiency. The multi-robot system consisted of an unmanned ground vehicle (UGV) and an unmanned aerial vehicle (UAV), both operating autonomously. These robots included multiple types of sensors to perceive the environment and, in concrete, the ground robot included a robotic manipulator. Human and dog rescue resources included monitoring systems. This project took place between 2015 and 2019 under the supervision of Prof. Alfonso José García Cerezo and Prof. Anthony Mandow Andaluz.

TRUST-ROB: This project aimed to build critical fault-tolerance and resilience capabilities required to achieve a heterogeneous team of mobile robotic manipulators, with both UAVs and UGVs, cooperating in challenging disaster scenarios. In order to achieve this, the project addressed the key technical issues that robots face in these types of situations, such as communication breakdowns, GNSS denial, perception limitations brought on by smoke or poor lighting, difficult mobility conditions caused by surface characteristics, and ineffective task decomposition and assignment. This project took place between 2019 and 2022 under the supervision of Prof. Alfonso José García Cerezo and Prof. Anthony Mandow Andaluz.

1.7 Thesis Organization

This thesis is organized into six chapters. Each chapter (excluding the introduction, the conclusions and the Spanish summary) consists of a background of the researched topic, including the state of the art of the chapter and a contribution section to summarize the problems that needed to be solved.

Chapter 1 presents the research topic, describes the main contributions of this thesis, details the research activities realized during the thesis's period, and also includes the methodological frame and a timeline to emphasize the works developed.

Chapter 2 emphasizes the benefits of fusing haptic information. Concretely, a tactile and kinesthetic dataset is recorded with a gripper, and the obtained information is trained via deep learning methods. Two different approaches are considered, an object recognition problem (section 2.3) and a grasping location estimation problem (section **??**).

Chapter 3 focuses on the problem of sensing interaction forces between a gripper and a grasped wrist. This chapter tackles this issue with a kinesthetic approach and Machine Learning methods.

Chapter 4 addresses the necessity of pHRI solutions in SAR scenarios. In this sense, an application to autonomously locate a gripper with sensing capabilities into a victim's forearm is included.

Chapter 5 discusses the conclusions drawn from the work realized in this thesis, including their limitations and prospective works.

Chapter 6 includes a summary in Spanish of the contents of this thesis.

CHAPTER 2

Fusing Haptic Information Perceived with Grippers

2.1 Background and Context

The sense of touch is almost indispensable for humans. It uses the cutaneous inputs sensed from mechanoreceptors and thermoreceptors that are incorporated within the skin, as well as kinesthetic inputs from mechanoreceptors located in muscles, tendons, and joints [30]. Active touch is defined as the situation where sensations arise through the sensor's movement rather than through the movement of the stimulus [31]. Haptics is a perceptual system that usually involves active exploration and is mediated by the tactile and kinesthetic afferent subsystems [32]. Humans sense of touch is perceived by our biological haptic system. The ability of haptic systems to perceive surface characteristics and object material type is particularly effective. Haptic data can sometimes be the only source of information, considering low light environments. There are also situations in which the sense of sight is compromised, e.g., when there are occlusions or closed spaces such as a bag or a box where we can reach inside to grab something but cannot see what is inside [33]. Besides, even if other senses are available, the sense of touch can, in specific situations, give the most reliable information, considering it provides direct physical contact. Properties such as friction and compliance can be obtained, while other senses provide very limited or indirect information. With the sense of touch, humans are capable of performing complex haptic related tasks, such as manipulation, object recognition, and exploration [34]. Lederman et al. defined eight specific movements to explore certain object features [30]. These actions are termed as exploratory procedures (EPs) and are very varied movements, such as applying pressure to the object to determine its hardness or performing contour tracking to determine its shape.

Human haptic exploration is efficient, quick to adjust to changing circumstances, and robust to noise [31]. Furthermore, human hand control employs biological mechanisms to produce an astounding level of functional adaptability under a wide range of environmental situations. Robotic systems should acquire these abilities to be able to establish physical contact with the environment and perform basic daily tasks, avoiding potential human injuries [35]. Thus, robots need to acquire haptic perception capabilities and develop algorithms to interpret perceived information and act accordingly.

Multiple solutions have been proposed to implement artificial tactile perception. Existing tactile sensors can be categorized depending on their sensing technology, e.g., piezoresistive systems [36] that sense variations of electrical resistance when the material is deformed; optical sensors [37] which are based on the reflections between mediums with different refractive indices; or piezoelectric systems [38] that, whenever an external pressure deforms a crystalline material, the sensor can detect the electrical charge generation produced. Tactile sensors have already proven their effectiveness in robotic systems [39]. The most extensively used option among tactile sensors is the one based on independent sensor units (tactels) that, when combined, form a tactile array [40]. There are several commercially available options for these type of sensors, such as the BioTac sensor, developed by SynTouch [41], the Tekscan mapping sensors solutions [42], the TactArray-pressure mapping sensors pads [43], or the Takktile sensors from Righthand Labs [44]. Multiple works have used tactile arrays similarly to images, since both have the same data structure, with the tactel of a tactile array being analogous to a pixel in an image. As a result, the output of this type of sensor is often referred to as a tactile image. Machine learning methods that have provided excellent results with conventional images have also been applied to tactile images in numerous works. Convolutional neural networks (CNNs) have been utilized with tactile images as an input to classify objects [45–47], to predict the slip of grasped objects [48], or for shape recognition [49].

Haptic perception is also composed of the kinesthetic information sensed with the joints. In robotic grippers, the kinesthetic data is perceived as the phalanxes' relative position and velocity [50]. The joints are moved by actuation systems. The most commonly used in this case are rotary motors [51]. On the other hand, encoders are used to measure the angular position of the joints. These are digital sensors that allow the relative or absolute position of a joint to be measured. The most commonly used are optical encoders. The minimum resolution of an encoder for a haptic system is determined by the ratio between the angular distance of one encoder tick and the end point displacement in Cartesian space. Velocity measurement is necessary for many haptic applications and is typically obtained through numerical differentiation of position data from the encoder. It is necessary to choose a noise-free velocity estimation algorithm that reduces phase lag at the frequencies of interest [52]. Machine Learning methods have also been considered using proprioceptive data for object recognition [53], intrinsic and extrinsic forces estimation [54], or prediction of the 3D configuration of a soft robot [55].

Moreover, haptic data is often utilized with the aid of other sensing systems, such as vision sensors. In [56], the 6D pose of several objects is estimated using both tactile and vision data. A localization and detection of surfaces cracks algorithm has been developed with visual-tactile information in [57]. Besides, in [58], a method to detect slippage using haptic and visual information is presented. Although visual information only approaches may seem to be the most straightforward methodology, it is also of great interest to present alternative methods to complement or even substitute visual information under contingency conditions where visual information is not available, such as poor lighting or sensor failure.

2.2 Contributions

This chapter addresses the benefits of fusing the tactile and kinesthetic data obtained from a gripper for recognition and estimation purposes. In concrete, two contributions are presented:

- The gripper is utilized to perform EPs, specifically a squeeze and release procedure, to recognize the shape, internal characteristics, and softness of grasped bodies. A dataset of both tactile and kinesthetic data is obtained from 36 objects. Then, two LSTM neural networks are trained for classification purposes. The object recognition problem is enhanced with two different fusion approaches. Both strategies use as input the probabilistic distribution provided by the tactile and kinesthetic LSTMs. A bayesian fusion strategy using a maximum a posteriori (MAP) estimation approach and a data-driven fusion approach, where a fully connected layer is used to improve the results, are considered.
- The gripper is used in this case to record a haptic dataset of a full forearm. This dataset is obtained employing a specific support that, with the help of its design, allows the gripper to record evenly spread measurements of the forearm's sections. Besides, the dataset is trained to estimate the forearm grasping location. For this purpose, in the first place, both haptic sources are trained with LSTM neural networks, and the estimation is obtained as an output. Then, both tactile and kinesthetic data are fused with a data-driven approach using consecutive dense layers to enhance estimation results.

2.3 Fusing Haptic Information for Object Recognition

Published as:
Francisco Pastor, Jorge García-González, Juan M. Gandarias, Daniel Medina, Pau Closas, Alfonso J. García-Cerezo, Jesús M. Gómez-de-Gabriel, "Bayesian and Neural Inference on LSTM-based Object Recognition from Tactile and Kinesthetic Information", IEEE Robotics and Automation Letters, vol. 6, no 1, pp. 231–238, 2020 DOI: 10.1109/LRA.2020.3038377

Abstract

Recent advances in the field of intelligent robotic manipulation pursue providing robotic hands with touch sensitivity. Haptic perception encompasses the sensing modalities encountered in the sense of touch (e.g., tactile and kinesthetic sensations). This letter focuses on multimodal object recognition and proposes analytical and data-driven methodologies to fuse tactile- and kinesthetic-based classification results. The procedure is as follows: a three-finger actuated gripper with an integrated high-resolution tactile sensor performs squeeze-and-release Exploratory Procedures (EPs). The tactile images and kinesthetic information acquired using angular sensors on the finger joints constitute the time-series datasets of interest. Each temporal dataset is fed to a Long Short-term Memory (LSTM) Neural Network, which is trained to classify in-hand objects. The LSTMs provide an estimation of the posterior probability of each object given the corresponding measurements, which after fusion allows to estimate the object through Bayesian and Neural inference approaches. An experiment with 36-classes is carried out to evaluate and compare the performance of the fused, tactile, and kinesthetic perception systems. The results show that the Bayesian-based classifiers improves capabilities for object recognition and outperforms the Neural-based approach.

2.4 Neural Networks Hyperparameters Tuning

In this chapter, several neural networks were trained. In the course of both studies, selecting appropriate hyperparameters played a crucial role in achieving optimal performance of the presented neural networks. Hyperparameters are settings that are not learned by the network during training but are instead specified by the user beforehand. These include the number of neurons and layers in the network, learning rate, and filter size, among others. To select the initial hyperparameters, prior knowledge of the architecture and operation of the neural networks was used. An appropriate number of neurons and layers was selected based on the experience training other neural networks. Additionally, standard learning rates and filter sizes were considered, considering the input data's size and complexity.

However, it is worth noting that the selection of hyperparameters is not an exact science, and it is often a challenging task that requires trial and error. Therefore, once the initial values of the hyperparameters were set, the optimization process was carried out through experimentation. This involved testing different combinations of hyperparameters to identify the best configuration.

In summary, while prior knowledge provided guidance in the selection of initial hyperparameters, the optimization process ultimately relied on empirical methods to achieve an optimal performance.

CHAPTER 3

Sensing Interaction Forces While Grasping in pHRI

3.1 Background and Context

The field of robotics interacting with humans has been widely studied. Some Human Robot Interaction (HRI) researches have focused on social robotics [59, 60], which goal is to achieve positive outcomes from interaction in diverse topics, such as education, communication, or entertainment. Robots have proved to be beneficial for the therapeutic treatment of children with Autistic Spectrum Disorder (ASD). In [61], a robot teaches gestural recognition to children with ASD, and in [62], a humanoid robot acts as a social mediator, eliciting specific behaviors in children with ASD. Other researchers focused their HRI studies on healthcare applications. Bauer et al. presented a mobile robot for monitoring the health conditions of elderly patients and residents. The robot can also indicate unusual conditions, detect fallen patients and send warning signals [63]. Another example is Lio [64], a mobile robot platform for personal care assistant tasks, helping staff and patients on an everyday basis.

However, the intentional physical contact between participants has not been tackled by any of the aforementioned works. The field of physical Human-Robot Interaction (pHRI) investigates what occurs when people and robots establish direct contact while operating together in the same place. Software issues, operator mistakes, or mechanical breakdowns can all compromise safety. Ensuring the safe design and control of robots is therefore a critical prerequisite for successful physical human-robot interaction [65]. Some existing researches present robotic systems that have direct physical contact with people for rehabilitation, such as exoskeletons [66] or prostheses [67]. Other works present pHRI with the human initiating the contact. In [68], a social robot receives hugs to encourage self-disclosure. Besides, in [69], the authors focused on one specific social interaction, the handshake, and analyzed the pressure exerted by the participants to discriminate their mood. On the other hand, some works are developed with a third person supervising the whole process, such as surgical assistance robots [70, 71] that allow doctors to perform surgical operations with greater accuracy.

Not many works have focused on the robot initiating physical contact with the human, considering it is a very complex task. The main difficulties are the high sensorial capabilities required in the robot, the risk of non-intentionally injuring the human, and the adaptation to a hypothetical non collaboration of the subjects [72]. Some studies have been conducted on humans to analyze their comfort during this type of interaction [73, 74]. In order to have safe interaction whenever the robot initiates contact, measuring the forces between the human and the robot is critical. Admittance control methods, typically used for mobile manipulators in pHRI applications [75, 76], need force feedback. Force/Torque sensors are a potential solution for measuring interaction forces, but they are often cost-prohibitive, making them financially inaccessible for many researchers and organizations. As an alternative, several estimation methods have been designed based on the robot sensing capabilities, e.g., the Disturbance Observer (DOB) algorithm [77, 78], or on the error of a position control method [79]. Other estimation techniques are based on the Time-Delay Estimation (TDE) scheme, which can provide a precise estimation of non-linear robot dynamics, including external forces [80].

Sensing forces with grippers is a challenging task. Many works have focused their research on the development of advanced grippers. They can be classified in different ways, e.g., by the number of fingers and their configuration, according to the intended application, or based on their type of actuation [81]. Considering in this case the classification according to the application, grippers have been utilized for a wide range of possibilities. The earliest grippers were developed for industrial solutions. They present high load capabilities, as well as external sensors to decrease assembly uncertainty [82]. On the other hand, a wide variety of grippers have been presented for medical applications, such as in [83], where a soft-based robotic gripper was designed as a tool for minimally invasive surgery, considering the benefits of its soft design in order to provide safe interactions. Other works have focused their efforts on assistive robotics, designing grippers for individuals with disabilities for activities of daily living [84].

Some researchers have used Machine Learning methods with the data provided by the gripper's sensors as input to obtain information about the grasped body or the state of the grasping procedure. In [85], a gripper is equipped with an electromagnet to improve Machine Learning autonomous clothing methods. On the other hand, in [86], an underwater robot equipped with a robotic gripper uses its torque sensor and kinesthetic information to feed a hidden Markov model and predict three contact states. Grippers with tactile sensing have also proved to be valid for Machine Learning classification approaches. In [87], a robotic system is able to distinguish objects using the information provided by two piezoresistive tactile sensors using Decision Tree and Bayesian approaches.

3.2 Contributions

This chapter presents the design of a novel underactuated gripper which is used to estimate human interaction forces and motions whenever they are grasped. This information is relevant in pHRI applications to understand human intentions and react accordingly. The gripper is designed to apply constant torque to grasp the wrist of the subject, adapting to its shape thanks to its underactuated mechanism. The estimation is performed using Machine Learning methods, in concrete, the Support Vector Regression (SVR) and the Random Forest Regression (RFR) methods. Considering the increased design complexity involved in the addition of force sensors and that they are expensive, only proprioceptive information is utilized as an input. This work also ignited a novel study in the sensorless estimation of forces whenever a human arm is grasped with a novel designed gripper presented in two papers [7, 8].

3.3 Kinesthetic Estimation of Interaction Forces

Published as:

Joaquin Ballesteros, Francisco Pastor, Jesús M. Gómez-de-Gabriel, Juan M. Gandarias, Alfonso J. García-Cerezo and Cristina Urdiales “Proprioceptive Estimation of Forces Using Underactuated Fingers for Robot-Initiated pHRI", Sensors, vol 20(10), pp. 2863, 2020 DOI: 10.3390/s20102863

Abstract

In Physical Human-Robot Interaction (pHRI), forces exerted by humans need to be estimated to accommodate robot commands to human constraints, preferences, and needs. This paper presents a method for the estimation of the interaction forces between a human and a robot using a gripper with proprioceptive sensing. Specifically, we measure forces exerted by a human limb grabbed by an underactuated gripper in a frontal plane using uniquely the gripper’s own sensors. This is achieved via a regression method, trained with experimental data from the values of the phalanxes angles and actuator signals. The proposed method is intended for adaptive shared control in limb manipulation. Although adding force sensors provides better performance, the results obtained are accurate enough for this application. This approach requires no additional hardware: it relies uniquely on the gripper motor feedback -current, position and torque- and joint angles. Also, it is computationally cheap, so processing times are low enough to allow continuous human-adapted pHRI for shared control.

CHAPTER 4

Human Robot Interaction in Search and Rescue Scenarios

4.1 Background and Context

In disaster scenarios like tsunamis, earthquakes, hurricanes, volcanic eruptions, or terrorist attacks, Search and Rescue (SAR) activities are crucial. The main goal of SAR is to find trapped people in dangerous locations or injured and retrieve to stabilize them medically. Rescuers have roughly 48 hours to locate stranded victims; after that time, their chances of finding survivors decrease dramatically [88]. In SAR scenarios, the use of robotics has been widely proven to be beneficial. Their resistance to extreme heat conditions [89] and to toxic environments [90], as well as their ability to enter into spaces that are inaccessible to larger rescue team members [91], makes them an extremely useful accessory. The safety and effectiveness of rescue teams is also a critical issue where robots can help with their presence. Approximately 48% of the rescuers who perished in the 1985 earthquake in Mexico City died while seeking survivors in enclosed spaces that flooded [92]. Nevertheless, it is important to note that robots are replaceable, and only economic loss occurs if they get lost or damaged. Besides, rescuing a victim under challenging conditions, such as being enclosed in a void, needs an average of ten hours with around ten formed rescue members [93], and having enough experts in a SAR scenario is very unusual. Thus, robots replacing some team members could potentially allow for the simultaneous rescue of a larger number of victims.

However, despite all the advantages that rescue robots provide, fully autonomous solutions are not yet possible with the current technology, considering they still need to cooperate with rescue team members. These robots usually are also designed to interact with victims; therefore, HRI is critical in an effective rescue system. As aforementioned, one of the main goals in a SAR scenario is to find the victims in the rubble or debris as efficiently and safely as possible [94]. Unmanned Aerial Vehicles (UAVs) have been used for this purpose considering their advantages, such as their low cost, good maneuverability, reduced rescue operators' resources, and rapid deployment [95]. Rescue teams can almost instantly start looking for victims in areas where humans cannot easily access thanks to UAVs [96]. Several works have used Machine Learning approaches to find victims [97–100]. Convolutional Neural Networks (CNNs) have been used to detect victims in Mediterranean landscapes [97] or to identify a human with thermal images [100]. Other works present methods to track multiple victims [99]. Mobile phone detection methods have also been proven to be effective in locating victims [101, 102].

Ground robots are also commonly used in SAR scenarios. The main challenge of these robots is that they must overcome obstacles in the environment, typically unstructured and unknown in advance, in order to reach their target position [103]. Regarding these necessities, several tracked and wheeled robots have been designed [104–108] considering these key metrics that rescue robots must accomplish: survivability, mobility, sensing, communicability, and operability [109]. SAR robots usually present several sensors to perceive the maximum amount of information. Some works [104, 107, 108] focus on performing Simultaneous Localization and Mapping (SLAM) in unknown environments, whereas some other works specialize in providing the maximum mechanical capabilities to the robot [104, 106]. Some applications have been designed to use rescue robots to interact with victims. In [110], robots equipped with two-way video and audio communication for interacting with trapped victims were presented, and in [111], a robotic hand was designed to perform a novel fuzzy triage system to sense key vital signs in victims.

Nevertheless, despite the recent advances in rescue robotics, not many works focus on the pHRI with the victims. In [112], a semi humanoid robot equipped with high power motor systems performs casualties extractions, thanks to its dual arm upper body design. Besides, in [105], a ground robot is equipped with a stretcher bed conveyor. With this configuration, the robot platform approaches to the victim and carries him/her to a safe zone.

4.2 Contributions

This chapter presents a contribution to pHRI in SAR scenarios. An autonomous method is introduced to place a sensorized gripper with a robotic manipulator into a forearm. A tracking algorithm of the moving hand is presented, with a Model Predictive Controller (MPC) replanning the manipulator end effector trajectory each time the hand pose changes in a certain threshold. The gripper has a novel design to detach from the robotic manipulator end effector once the victim is ready and certain forces are applied, and is sensorized, being able to perform an online triage of the sensed victim. The whole system's performance is evaluated in two experiments, one conducted in the lab to prove the feasibility of the method, and the second realized in outdoor conditions to prove its viability in a SAR scenario.

4.3 Autonomous Gripper Placement for Victims in SAR Scenarios

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Abstract

In this letter, we present an autonomous method for the placement of a sensorized wristband to victims in a Search-And-Rescue (SAR) scenario. For this purpose, an all-terrain mobile robot includes a mobile manipulator, which End-Effector (EE) is equipped with a detachable sensorized wristband. The wristband consists of two links with a shared shaft and a spring. This configuration allows the wristband to maintain fixed to the EE while moving and get placed around the victim's forearm once the contact is produced. The method has two differentiated phases: i) The visual moving hand tracking phase, where a 3D vision system detects the victim's hand pose. At the same time, the robotic manipulator tracks it with a Model Predictive Controller (MPC). ii) The haptic force-controlled phase, where the wristband gets placed around the victim's forearm controlling the forces exerted. The wristband design is also discussed, considering the magnitude of the force needed for the attachment and the torque the wristband exerts to the forearm. Two experiments are carried out, one in the laboratory to evaluate the performance of the method and the second one in a SAR scenario, with the robotic manipulator integrated with the all-terrain mobile robot. Results show a 97.4% success in the wristband placement procedure and a good performance of the whole system in a large scale disaster exercise.

CHAPTER 5

Conclusions

This thesis has explored and made contributions to the wide topic of robotic grippers. The research provided here has been published at prestigious international conferences and in scientific journals. As a common denominator, applications involving grippers have been developed. Besides, the works presented rely on perceiving some type of haptic information, and use Machine Learning methods as a tool to learn from the obtained data. This thesis can be summarized as three principal contributions: I) The benefits of fusing the haptic data obtained with a gripper to enhance the information perceived and improve the quality of recognition and estimation tasks. II) Sensing interaction forces between a gripper and a human whenever a forearm is grasped using kinesthetic information only. III) The autonomous location of a sensorized gripper into a victim's forearm with the help of vision sensors and a novel mechanism included in the aforementioned gripper. After the previous general description, the main findings of this work are listed below:

- Chapter 2 presented two papers that use haptic information recorded with a gripper. Both works have used tactile and kinesthetic data to train neural networks, in concrete LSTM networks. The two sources were trained separately, and then, the outputs of those neural networks were fused to enhance the performance of the one source of information only approach. In the first work, a dataset of 36 objects was recorded, and an object recognition problem was considered. The output of both tactile and kinesthetic neural networks is a posterior distribution. Two approaches were considered to fuse the aforementioned outputs to obtain a final probability distribution: a

Bayesian inference method, which used a MAP estimation, and a neural inference, which included a dense layer. The second work presented a dataset with haptic information of an entire human forearm. Each haptic data recorded had labeled its grasping location. The tactile and kinesthetic information was trained, but this time as an estimation problem that provided the grasped forearm location. Similarly as in the previous work, both outputs were used, but this time the outputs are a normalized scalar, and the method used is a neural inference with various concatenated dense layers. The results of both papers proved the benefits of fusing information, more precisely, haptic information.

- In chapter 3, a work was presented concerning the force sensing capabilities of a gripper. This paper provided an estimation of forces between a human and a gripper grasping a wrist with kinesthetic information only. Understanding the intentions of a human grasped by a robotic gripper is critical to act accordingly and maintain a safe interaction with the subject, interrupting the task if necessary. The presented gripper has two underactuated fingers that adapt to the shape of the forearm. With the kinesthetic information recorded from various experiments, Machine Learning methods have been trained to learn the relationship between these kinesthetic inputs and the interaction forces. Various methods have been considered, with a varied dataset that included information from five subjects. These methods were tested with known and unknown subjects to prove their effectiveness with satisfactory results.

- Chapter 4 presented an application for autonomous gripper placement for victims in SAR scenarios. Human rescuers are usually very limited in number and often in high demand whenever a disaster strikes. Therefore, robots that help with rescue procedures are highly valued. This paper presented an autonomous method to place a sensorized wristband in a forearm with the help of a robotic manipulator and a vision sensor. The wristband was sensorized to perform triage procedures on the sensed victims, allowing the prioritization of evacuation based on the victim's likelihood of survival, thus improving the organization of rescue teams. The aforementioned gripper presented a novel design based on springs to detach from the robotic end effector to the victim's forearm whenever certain forces are applied. The magnitude of that force was parameterized and can be defined by setting certain values, such as the springs' length or elastic constant. Besides, a novel method to estimate the pose of a hand was presented. The method uses a deep learning approach to detect hand landmarks. With the depth information provided by the camera, the method estimates the 3D position of specific landmarks. Then, with the help of the Horn algorithm, the 6D hand pose is calculated. Experiments in a lab and in real SAR scenarios were conducted with favorable results.

5.1 Discussion

This thesis has proved the benefits of fusing two sources of information, concretely tactile and kinesthetic data. An estimation of interaction forces with a human using only kinesthetic information has also been presented. Finally, a method to locate a sensorized gripper in victims of disaster scenarios was included. Considering the contributions of this thesis, more complex applications that unify the presented methodologies could be developed. Thus, a robotic gripper could be designed that, due to the tactile sensors it includes and the kinesthetic information of its phalanges, can recognize both the interaction forces between a human and the gripper, as well as the section of the forearm that is being grasped. This device could be used to perform medical procedures such as injecting medicines, and be able to cancel the process if the human presents any kind of resistance or discomfort. It would also make sense to integrate this solution into an application for rescue scenarios where, once a victim is sensed with the detachable gripper, it would detect if any of the aforementioned medical procedures are urgently needed and perform it. The estimation of the forearm grasped section could also be improved by fusing the information sensed by the 3D vision sensor.

5.2 Future works

Robotic grippers are still far from having the controllability, adaptability and sensorial capabilities of a human hand. Despite the field of grippers applied to pHRI is well advanced, there are still much room for improvement. This thesis has shown a glimpse of some of these improvements, yet there are still many issues to be faced. Hereafter, some of these possible research lines based on the output of this thesis are presented:

- **Enhancement of robotics grippers haptic capabilities:** Design of a new underactuated gripper with haptic perception. The gripper presented in chapter 2, with both tactile and kinesthetic capabilities, has some drawbacks that could be overcome. The tactile sensor is placed only on its fixed finger. The new version should also include tactile sensors in the underactuated fingers and in the rest of the grasping surface. Besides, having a fixed finger limits the grasping capabilities of the whole gripper when grasping certain bodies. It might be useful to design a mechanism so that the distance between the underactuated fingers and the tactile finger would be variable. It would also be beneficial to provide some flexibility to the fixed finger surface to enhance its grasping capabilities.

- **Design of techniques to perform new exploration procedures:** Implementation of new EPs procedures to the gripper with both haptic perception capabilities, presented in chapter 2. The effectiveness of the squeeze and release process in deciphering the internal characteristics and shape of grasped bodies has been demonstrated. Further improvement in the performance of deep learning approaches for recognition and estimation tasks could be achieved by incorporating additional exploratory procedures, such as lateral movement to recognize textures.

- **Additional phalanxes to improve kinesthetic information:** Design of new underactuated fingers to include more phalanxes, increasing the complexity of the gripper design. However, this design change would provide enhanced information about the shape of the grasped object due to improved adaptation of the fingers. This increased complexity would result in richer kinesthetic information, improving the comfort felt by grasped users. The grasped surface would be more significant, and the applied forces would be better distributed.

- **Influence of wrist pose on the interaction forces estimation:** Although in the work presented in section 3.3 it was assumed that the wrist pose is stable, this may not always be the case. Conducting a study on how variation in forearm pose affects the estimation of interaction forces could be interesting. An in-depth study of the best pose for the estimation of specific requirements (best estimation in the X-axis, in the Y-axis, best estimation of the magnitude or the direction) could also be valuable.
- **Integration of soft robotics:** Implementation of soft robotics based techniques to the grippers presented in this thesis. It is notable that all of the grippers in this study were designed to have direct physical contact with human limbs. As such, it is suggested that incorporating soft fingers into the design of these grippers would improve the comfort experienced by the subjects. Besides, the design of soft grippers with haptic capabilities is a novel research topic; thus, providing contributions would benefit the scientific community.
- **New applications regarding pHRI in SAR scenarios:** Even though some contributions about this topic have been included in this thesis, this field is still very immature. The help of robotics whenever a disaster strikes would be more efficient and produce a more significant impact if they could safely interact with victims, similarly as a human rescuer would do. Overall, the incorporation of robotics solutions in disaster response is a promising avenue for future research that will help saving a larger number of victims.

CHAPTER 6

Resumen

Introducción

Antecedentes y motivación

Se espera que los robots jueguen un papel fundamental en la sociedad del futuro. A pesar del impacto tan significativo que han tenido hasta la fecha, van a generar un cambio de paradigma en las próximas décadas. No sabemos todavía cuándo, pero podemos asumir que los robots se encargarán de una inmensa cantidad de tareas que hoy en día realizamos los humanos. Lo más seguro es que acaben incluso viviendo con nosotros, ayudándonos con las tareas diarias de casa o proporcionándonos compañía como si de mascotas se tratasen. Gracias a las mejoras en la tecnología de sensores y a los grandes avances producidos en la inteligencia artificial (Artificial Intelligence) y en el aprendizaje automático (Machine Learning), los robots seguirán creciendo desde meros mecanismos actuados hasta entidades capaces de pensar y tomar decisiones basadas en sus funciones cognitivas. Estos avances tecnológicos, y otros avances en campos asociados seguirán su trayectoria ascendente, y la robótica se beneficiará de ello con toda seguridad.

A pesar de los avances significativos que se han conseguido, queda mucho trabajo todavía por hacer para alcanzar este tremendo desafío. Hay muchas subtareas pendientes por abarcar. Esta tesis se enfoca en una de esas tareas, que consisten en proveer a los robots con el sentido del tacto que tenemos los humanos y la habilidad de interpretar esa información percibida. Poseer estas habilidades es fundamental si pretendemos que los robots interactúen iniciando el contacto con los humanos. Que los robots sean capaces de interactuar de forma física con los humanos es crucial para una colaboración eficiente en tareas como el cuidado de enfermos o de fabricación. También permite mejorar la productividad, así como una comunicación con el robot más natural e intuitiva, mejorando la experiencia del usuario.

El campo de la robótica que estudia sus interacciones físicas con el humano (physical Human Robot-Interaction (pHRI)) es un tema candente en la actualidad. Los robots clásicos que fueron diseñados para realizar procesos de automatización pueden ser peligrosos. Sin embargo, avances recientes en diseño mecatrónico han conducido a una nueva generación de robots, llamados cobots, que son capaces, de forma segura y fiable, de compartir espacio y realizar tareas en las que haya interacción física. Este tipo de robots normalmente incluyen sensores de par externo en sus articulaciones para detectar fuerzas no deseadas que puedan acarrear accidentes. Sin embargo, hacen falta más capacidades sensoriales, parecidas al sentido del tacto, si se quieren realizar tareas más complejas de agarre o procedimientos más sofisticados dónde haya colaboración.

La integración de capacidades de percepción háptica en un robot permite imitar el sentido del tacto humano. El término háptico se puede dividir en dos: sensaciones táctiles y kinestésicas. La percepción táctil es la información que sentimos a través de la piel, como la presión, vibración, temperatura, deslizamiento o dolor. Por otro lado, la información kinestésica hace referencia a la capacidad de conocer las posiciones y los movimientos de las articulaciones. Fundamentalmente gracias al sentido del tacto, con las manos podemos manipular herramientas de forma precisa y coger objetos de diferentes formas y tamaños. Es bien sabido que, con práctica, se pueden usar las manos para mover un lápiz de forma acrobática, o realizar operaciones que requieren el manejo preciso de dispositivos pequeños. Sin embargo, los humanos usamos las manos para más que coger y manipular objetos. Explorar, tocar, percibir ciertas características físicas como la dureza, temperatura o el peso, son otras de las tareas que podemos realizar.

Las pinzas robotizadas han sido desarrolladas con la intención de que realicen tareas equivalentes con la destreza y adaptabilidad que tiene una mano humana. Aún estando lejos de funcionar con estas capacidades, sin embargo, los últimos avances están dotándolas de percepción háptica. Los sensores táctiles más avanzados pueden medir muchas propiedades, como la presión, la conductividad térmica, las fuerzas de cizallamiento y la temperatura de la superficie con precisión utilizando diversos mecanismos de transducción. Se puede obtener también información kinestésica midiendo la posición relativa entre dos eslabones, el par y la velocidad angular de una articulación.

Es coherente por lo tanto pensar en utilizar este tipo de información junto con enfoques de aprendizaje automático para el desarrollo de nuevas funcionalidades. El aprendizaje automático es uno de los temas de investigación más importantes de la robótica actual, ya que permite a los robots realizar tareas que requieren un nivel de flexibilidad y adaptabilidad que es difícil de obtener con enfoques tradicionales. Los algoritmos de aprendizaje automático se basan en imitar el modo en que los humanos aprenden de la experiencia mediante métodos computacionales. Se puede entrenar un algoritmo de aprendizaje con datos para obtener un modelo que sea capaz de clasificar o estimar resultados de información distinta a la usada en el entrenamiento. Los datos hápticos presentan una estructura muy conveniente para este tipo de enfoques: I) Los datos táctiles se parecen a las imágenes; por lo tanto, se pueden emplear técnicas similares a las utilizadas con datos visuales. II) Los datos hápticos pueden presentar una estructura temporal si se han obtenido de forma dinámica; en consecuencia, podrían aplicarse métodos que presentan buenos resultados con datos temporales. Como ya se ha mencionado, la información háptica procede de dos fuentes. Las técnicas de fusión combinan las lecturas de varios sensores para producir una descripción robusta y completa de un entorno o proceso de interés. La integración de estas técnicas con datos hápticos podría llevar a superar los resultados de los enfoques basados únicamente en una fuente de información.

Aunque las pinzas robotizadas que imitan las capacidades de una mano humana tienen numerosas ventajas, puede ser más apropiado equiparlas con otras utilidades para ciertas tareas. Algunas pinzas solo necesitan buena capacidad de agarre y poder sostener gran cantidad de peso, ya que funcionarán en procedimientos de automatización y mecanización; por tanto, apenas necesitan retroalimentación de sensores. Otras aplicaciones se centran en incluir sensores que midan constantes vitales a las pinzas para realizar el triaje y monitorizar al paciente. Estos dispositivos podrían utilizarse en escenarios de búsqueda y rescate, donde, por lo general, los recursos para servicios de rescate son limitados; por tanto, la ayuda de los robots podría ser valiosa. La integración de pinzas con sensores biomédicos con el campo de la interacción física entre el robot y el humano es un gran reto que promete avances significativos en las aplicaciones de búsqueda y rescate.

Fusión de datos hápticos

El sentido del tacto es casi indispensable para el ser humano. Utiliza datos cutáneos obtenidos mediante mecanorreceptores y termorreceptores, así como información kinestésica percibida desde mecanorreceptores situados en músculos, tendones y articulaciones [30]. El tacto activo se define como la situación en la que las sensaciones surgen a través del movimiento del sensor y no a través del movimiento del estímulo [31]. El término háptico hace referencia a un sistema perceptivo que normalmente implica exploración activa y está mediado por dos subsistemas aferentes, el táctil y el kinestésico [32]. El sentido del tacto de los humanos se percibe mediante nuestro sistema háptico biológico. La habilidad del sistema háptico para percibir las características de las superficies y los tipos de materiales de los objetos es especialmente eficaz. Los datos hápticos pueden ser a veces la única fuente de información, teniendo en cuenta que hay entornos con poca iluminación. También hay en situaciones en las que el sentido de la vista se ve comprometido, como cuando hay oclusiones o espacios cerrados como una bolsa o una caja en los que podamos introducir la mano para coger algo pero no veamos qué hay en el interior [33]. Además, aunque se disponga de otros sentidos, el sentido del tacto puede, en situaciones específicas, dar la información más fiable, teniendo en cuenta que proporciona contacto físico directo. Se pueden percibir propiedades como la dureza, mientras que otros sentidos proporcionan información muy limitada o indirecta. Gracias al sentido del tacto, el ser humano es capaz de realizar tareas hápticas complejas, como la manipulación y el reconocimiento de objetos y la exploración [34]. Lederman et al. definieron ocho movimientos específicos para explorar determinadas características de los objetos [30]. A estas acciones se las denomina procedimientos exploratorios (Exploratory Procedures (EPs)) y son movimientos muy variados, como aplicar presión al objeto para determinar su dureza o realizar un seguimiento del contorno para determinar su forma.

La exploración háptica humana es eficaz, se ajusta rápidamente a las circunstancias externas y es robusta al ruido [31]. Además, el control de una mano humana emplea mecanismos biológicos para producir un alto nivel de adaptabilidad funcional en una amplia gama de situaciones. Los sistemas robóticos deberían adquirir estas capacidades para poder establecer contacto físico con el entorno y realizar tareas cotidianas básicas, evitando posibles lesiones provocadas a humanos [35]. Por lo tanto, los robots necesitan adquirir capacidades de percepción háptica y desarrollar algoritmos para interpretar la información percibida y actuar en consecuencia.

Se han propuesto múltiples soluciones para implementar la percepción táctil artificial. Los sensores táctiles existentes pueden clasificarse en función de su tecnología de detección, por ejemplo, sistemas piezorresistivos [36] que detectan las variaciones de resistencia eléctrica cuando se deforma el material; sensores ópticos [37] que se basan en las reflexiones entre medios con índices de refracción diferentes; o los sistemas piezoeléctricos [38] que, cada vez que un material cristalino es deformado por una presión externa, el sensor puede detectar la generación de carga eléctrica que se produce. Los sensores táctiles ya han demostrado su eficacia en sistemas robóticos [39]. La opción más utilizada entre los sensores táctiles es la basada en unidades sensitivas independientes (tactels) que, combinadas, forman una matriz táctil [40]. Existen varias opciones comerciales para este tipo de sensores, como el sensor BioTac, desarrollado por SynTouch [41], las soluciones de sensores de mapeado de presión Tekscan

[42], las almohadillas de sensores de presión TactArray [43], o los sensores de presión Takktile de Righthand Labs [44]. Múltiples trabajos han utilizado matrices de datos táctiles de forma similar a las imágenes, ya que ambas tienen la misma estructura, siendo el táctel de una matriz táctil análogo a un píxel de una imagen. En consecuencia, a los datos de salida de este tipo de sensores se les suele denominar imagen táctil. Los métodos de aprendizaje automático que han dado excelentes resultados con imágenes convencionales también se han aplicado a las imágenes táctiles en multitud de trabajos. Redes neuronales convolucionales (Convolutional Neural Networks (CNNs)) se han utilizado con imágenes táctiles para clasificar objetos [45–47], para predecir el deslizamiento de los objetos agarrados [48], o para el reconocimiento de formas [49].

La percepción háptica también está compuesta por la información kinestésica percibida en las articulaciones. En las pinzas robotizadas, los datos kinestésicos se definen como la posición relativa de las falanges y su velocidad [50]. Las articulaciones se mueven gracias a sistemas de actuación. Los más utilizados en este caso son motores rotativos [51]. Por otro lado, para medir la posición angular de las articulaciones se utilizan encoders. Son sensores digitales que permiten conocer la posición relativa o absoluta de una articulación. Los más usados son los encóders ópticos. La resolución mínima de un encóder para un sistema háptico viene determinada por la relación entre la distancia angular de un tick del encóder y el desplazamiento del punto final en el espacio cartesiano. Medir la velocidad es necesario para muchas aplicaciones hápticas y suele obtenerse mediante la diferenciación numérica de los datos de posición del encóder. Es necesario elegir un algoritmo de estimación de velocidad sin ruido que reduzca el desfase en las frecuencias de interés [52]. También se han estudiado métodos de aprendizaje automático utilizando datos propioceptivos para el reconocimiento de objetos [53], estimación de fuerzas intrínsecas y extrínsecas [54], o para predecir la configuración 3D de un robot blando [55].

Además, los datos hápticos se utilizan a menudo con la ayuda de otros sistemas de detección, como los sensores de visión. En [56], se estima la pose 6D de varios objetos utilizando tanto datos táctiles como de visión. Se ha desarrollado un algoritmo de localización y detección de grietas superficiales con información visual-táctil en [57]. Por otro lado, en [58] se presenta un método para detectar el deslizamiento utilizando información háptica y visual. No existen apenas trabajos que se hayan centrado en el uso simultáneo de ambas fuentes de información háptica.

Medición de fuerzas en el agarre

El campo de la robótica en el que los robots interactúan con humanos ha sido ampliamente estudiado. Algunas investigaciones sobre interacción humano-robot (Human Robot-Interaction (HRI)) se han centrado en la robótica social [59, 60], cuyo objetivo es lograr resultados positivos de la interacción en diversos temas, como la educación, la comunicación o el entretenimiento. Los robots han demostrado ser beneficiosos para el tratamiento terapéutico de niños con Trastorno del Espectro Autista (TEA). En [61], un robot enseña reconocimiento de gestos a niños con TEA, y en [62] un robot humanoide actúa como mediador social, incitando comportamientos específicos en niños con TEA. Otros investigadores centraron sus estudios de HRI en aplicaciones sanitarias. Bauer et al. presentaron un robot móvil para vigilar el estado de salud de pacientes ancianos y residentes. El robot también puede avisar de que se están produciendo situaciones inusuales, detectar pacientes caídos y enviar señales de advertencia [63]. Otro ejemplo es Lio [64], un robot móvil para tareas de asistencia al personal y a los pacientes en hospitales.

Sin embargo, ninguno de los trabajos mencionados ha abordado el contacto físico entre los participantes. El campo de investigación que se basa en la interacción física humano-robot (pHRI) investiga lo que ocurre cuando ambos establecen contacto directo mientras operan juntos en el mismo lugar. Los problemas de software, los errores del operador o las averías mecánicas pueden afectar a la seguridad de los intervinientes. Por lo tanto, como requisito previo para la interacción física entre robots y humanos, hay que diseñar robots que sean seguros y que tengan un control robusto [65]. Algunas investigaciones existentes presentan sistemas robóticos que tienen contacto físico directo con las personas para su rehabilitación, como los exoesqueletos [66] o las prótesis [67]. Otros trabajos presentan pHRI pero con el humano iniciando el contacto. En [68], un robot social recibe abrazos para fomentar el aumento de la confianza del sujeto que abraza. Además, en [69], sus autores se centraron en una interacción social concreta, el apretón de manos, y analizaron la presión ejercida por los participantes para determinar su estado de ánimo. Por otro lado, otros trabajos se desarrollan con una tercera persona supervisando todo el proceso, como en los robots de asistencia médica [70, 71] que ofrecen a los cirujanos la posibilidad de realizar operaciones quirúrgicas con mayor precisión.

No hay muchos trabajos que se hayan centrado en que el robot inicie el contacto con el humano, teniendo en cuenta la complejidad de la tarea. Las principales barreras son las elevadas capacidades sensoriales requeridas en el robot, el riesgo de lesionar no intencionadamente al humano, y la adaptación a una hipotética no colaboración de los sujetos [72]. Se han realizado algunos estudios en humanos para analizar su comodidad durante este tipo de interacción [73, 74]. Para que la interacción sea segura siempre que el robot inicie el contacto, es fundamental medir las fuerzas entre el ser humano y el robot. Los métodos de control de admitancia, utilizados habitualmente en manipuladores móviles en aplicaciones pHRI [75, 76], necesitan de realimentación de fuerzas. Los sensores de fuerza o de par son una solución potencial para medir las fuerzas de interacción, pero su coste suele ser muy alto, lo que los hace económicamente inaccesibles para muchos investigadores y organizaciones. Como alternativa, se han diseñado varios métodos de estimación basados en las capacidades de detección de los robots, por ejemplo, el algoritmo del observador de perturbaciones (Disturbance Observer) [77, 78], o en el error detectado en un control de posición [79]. Otras técnicas de estimación se basan en el esquema estimación de tiempo de retardo (Time Delay Estimation), que puede proporcionar una estimación precisa de la dinámica no lineal del robot, incluidas las fuerzas externas [80].

La detección de fuerzas con pinzas es una tarea ardua. Muchos estudios se han centrado en el desarrollo de pinzas avanzadas. Se pueden clasificar de diferentes maneras, por ejemplo, por el número de dedos y su configuración, según la aplicación prevista, o en función de su tipo de accionamiento [81]. Considerando en este caso la clasificación según la aplicación, las pinzas se han utilizado para un amplio abanico de posibilidades. Las primeras pinzas se desarrollaron para soluciones industriales. Presentan altas capacidades de carga, así como sensores externos para disminuir la incertidumbre en la operación [82]. Por otra parte, se ha presentado una amplia variedad de pinzas para aplicaciones médicas, como en [83], donde se diseñó una pinza robotizada blanda como herramienta para cirugía mínimamente invasiva, considerando las ventajas de su diseño blando para proporcionar interacciones seguras. Otros trabajos han centrado sus esfuerzos en la robótica asistencial, diseñando pinzas para personas con discapacidad para actividades de la vida diaria [84].

Algunos investigadores han utilizado métodos de aprendizaje automático con los datos proporcionados por los sensores de la pinza como entrada para obtener información sobre el cuerpo agarrado o el estado del procedimiento de agarre. En [85], una pinza está equipada con un electroimán para mejorar las técnicas de ayuda para vestirse. Por otro lado, en [86], un robot submarino equipado con una pinza robotizada utiliza un sensor de par y la información kinestésica para alimentar un modelo de Markov y predecir tres estados de contacto. Las pinzas con sensores táctiles también han demostrado ser válidas para las tareas de clasificación basadas en técnicas de aprendizaje automático. En [87], un sistema robótico es capaz de distinguir objetos utilizando la información proporcionada por dos sensores táctiles piezoresistivos mediante los enfoques de Árbol de Decisión (Regression Tree) y Bayesiano (Bayesian).

Interacción robot humano en escenarios de búsqueda y rescate

En situaciones de catástrofe como tsunamis, terremotos, huracanes, erupciones volcánicas o atentados terroristas, las operaciones de búsqueda y rescate (Search and Rescue (SAR)) son cruciales. El principal objetivo de estas operaciones es encontrar a personas atrapadas en lugares peligrosos o heridas y recuperarlas para estabilizarlas médicamente. Los equipos de rescate tienen aproximadamente 48 horas para localizar a víctimas atrapadas; pasado ese tiempo, sus posibilidades de encontrar supervivientes disminuyen drásticamente [88]. En los escenarios de búsqueda y rescate, se ha demostrado que el uso de sistemas robóticos es beneficioso. Su resistencia a condiciones extremas de calor [89] y a ambientes tóxicos [90], así como a su capacidad para entrar en espacios inaccesibles para los miembros del equipo de rescate de mayor tamaño [91], les hacen un accesorio extremadamente útil. La eficacia y la seguridad propia de los equipos de rescate también es una cuestión crítica en la que los robots pueden ayudar con su presencia. Aproximadamente el 48% de los rescatadores que perecieron en el terremoto de Ciudad de México de 1985 murieron mientras buscaban supervivientes en espacios cerrados que se inundaron [92]. Sin embargo, cabe destacar que los robots son reemplazables, y solo se producen pérdidas económicas si se pierden o se dañan. Además, rescatar a una víctima en condiciones adversas, como atrapada en un agujero, requiere una media de diez horas, con una media de diez miembros del equipo de rescate [93], y que haya suficientes expertos en un escenario de búsqueda y rescate es poco común. Por lo tanto, que los robots sustituyan a algunos miembros del equipo podría hacer posible el rescate simultáneo de un mayor número de víctimas.

Sin embargo, a pesar de todas las ventajas que generan los robots de rescate, las soluciones totalmente autónomas aún no existen con la tecnología actual, teniendo en cuenta que siguen necesitando cooperar con algún miembro del equipo de rescate. Como ya se ha mencionado, uno de los principales objetivos en un escenario de rescate es encontrar a las víctimas entre los escombros de la forma más eficiente y segura posible [94]. Los vehículos aéreos no tripulados (Unnamed Aerial Vehicles (UAVs)) se han utilizado para este fin teniendo en cuenta sus múltiples ventajas, como su bajo coste, su buena maniobrabilidad, la reducción de los recursos humanos en materia de rescate y su rápido despliegue [95]. Los equipos de rescate son capaces de empezar a buscar víctimas casi al instante en zonas a las que los humanos no pueden acceder fácilmente gracias a los UAVs [96]. Varios trabajos han utilizado enfoques de aprendizaje automático para encontrar víctimas [97–100]. Redes neuronales convolucionales se han utilizado para detectar víctimas en paisajes mediterráneos [97] o para identificar a un ser humano con imágenes térmicas [100]. Otros trabajos presentan métodos para rastrear a múltiples víctimas a la vez [99]. Los métodos de detección de teléfonos móviles también han demostrado su eficacia para localizar a las víctimas [101, 102].

Los robots terrestres también se utilizan habitualmente en escenarios de rescate. El principal reto de estos robots es que deben superar obstáculos en el entorno, que normalmente no está estructurado y se desconoce de antemano, para alcanzar su posición objetivo [103]. En relación con estas necesidades, se han diseñado varios robots de orugas y ruedas [104–108] teniendo en cuenta estas claves que deben cumplir los robots de rescate: supervivencia, movilidad, detección, comunicabilidad y operatividad [109]. Los robots terrestres para rescate suelen presentar varios sensores para percibir la máxima cantidad de información. Algunos trabajos [104, 107, 108] se centran en realizar localización y mapeo simultáneos (SLAM) en entornos desconocidos, mientras que otros se especializan en dotar de las máximas capacidades mecánicas al robot [104, 106]. Se han diseñado algunas aplicaciones para utilizar robots de rescate interactuando con las víctimas. En [110], se presentaron robots equipados con comunicación bidireccional de vídeo y audio para interactuar con las víctimas atrapadas, y en [111], se diseñó una mano robótica para realizar un novedoso sistema de triaje borroso con el fin de leer los signos vitales de las víctimas.

No obstante, entre los trabajos que se ocupan de la aplicación de robots a misiones de rescate, pocos abordan el problema de gestionar eficazmente el contacto físico de los mismos con las víctimas. En [112] un robot semihumanoide equipado con sistemas de motorización de alta potencia realiza evacuaciones de heridos, gracias a su diseño con dos brazos. Además, en [105], un robot terrestre se equipa con una camilla. Con esta configuración, la plataforma robótica realiza una aproximación a la víctima y la transporta a una zona segura.

Objetivos

El campo de la investigación sobre pinzas robotizadas es muy amplio y no puede abarcarse en solo una tesis. Sin embargo, sí que pueden tratarse algunas de las tareas derivadas. Esta tesis se enfoca en varios conceptos, desde el diseño de pinzas que tengan capacidades hápticas y el análisis posterior de los datos obtenidos con cada agarre, hasta el proceso de interactuar iniciando el contacto con pinzas en humanos. Los principales objetivos de la tesis están señalados a continuación.

1. **Mejora de las capacidades de percepción háptica de las pinzas robotizadas.** Los humanos podemos discernir fácilmente entre varios objetos y manipularlos usando percepción táctil y kinestésica a la vez. Las pinzas robotizadas hasta ahora han usado las dos fuentes de información háptica por separado para realizar estos procedimientos de reconocimiento y manipulación. Sin embargo, todavía no se ha considerado el fusionar las dos fuentes para mejorar el resultado final. En esta tesis se desarrollan métodos que fusionan la información háptica recibida a través de las pinzas robotizadas.

2. **Desarrollo de métodos para reconocer las intenciones de los humanos una vez han sido agarrados por una pinza.** Los propósitos de los humanos a veces pueden ser impredecibles para los robots, especialmente si se les está agarrando. Por lo tanto, los robots deben de tener la capacidad de reconocer que el humano está incómodo y actuar en consecuencia, mostrando una forma primitiva de empatía. Esta tesis se enfoca también la capacidad de reconocer las fuerzas de interacción que ocurren en una pinza que está agarrando a una persona. El reconocimiento de las fuerzas se realiza con la ayuda de técnicas basadas en aprendizaje automático.

3. **Desarrollo de aplicaciones basadas en interacción física robot humano para rescate.** Muy pocos trabajos han considerado a un robot iniciando contacto físico con una víctima en un escenario de rescate, debido a la gran cantidad de desafíos que hay que superar. Esta tesis tiene como objetivo el desarrollar un sistema robótico autónomo que sea capaz de interactuar físicamente con una víctima y monitorizar su estado usando una pinza. Esta pinza se separa del robot y se fija en una persona gracias a su diseño novedoso y al uso de sensores de visión.

Contribuciones

Las principales contribuciones de esta tesis están divididas en los capítulos 2, 3, y 4.

- **Fusionando información háptica percibida con pinzas:**

  Esta contribución presenta los beneficios de combinar varias fuentes de información. En concreto, datos táctiles y kinestésicos se han entrenado con métodos de inteligencia artificial basados en redes LSTM (Long-Short Term) para resolver problemas de clasificación y de regresión. Esta tesis aporta dos trabajos a este campo de investigación. Además, se ha contribuido con dos conjuntos de datos (datasets) que contienen información háptica grabada con una pinza. En la sección 2.3, la primera contribución presenta un método de reconocimiento de objetos que usa las dos fuentes de información háptica por separado, y luego fusiona los resultados usando dos enfoques: Bayesiano y de inferencia neuronal. La segunda contribución está incluida en la sección **??** y en ella se presenta una estimación de la zona del antebrazo por donde una pinza robotizada te ha cogido. Los experimentos de ambas contribuciones han probado que, como se esperaba, los resultados de la fusión de datos son más robustos y en general mejores que los resultados que usaban la información por separado. Es también importante mencionar que el artículo que fue resultado de la contribución 2.3 ha sido relevante para la comunidad científica, generando diecinueve citas de artículos (hasta la publicación de esta tesis) de autores no pertenecientes a la Universidad de Málaga. Además, los conjuntos de datos generados se han subido a la plataforma GitHub, resaltando que el conjunto de datos de la sección 2.3 tiene más de ochocientas visitas y tres forks.

- **Sintiendo mientras se agarra en interacción física entre robots y humanos (pHRI):**

  Esta tesis aborda el problema de reconocer las intenciones de los humanos cuando están siendo agarrados por un robot. La sección 3.3 presenta una pinza que, mediante sensores kinestésicos y el desarrollo de técnicas de aprendizaje automático es capaz de reconocer las fuerzas que se ejercen entre el humano y la pinza que le está cogiendo. Los resultados de los experimentos que se llevaron a cabo prueban que el método de estimación es capaz de descifrar con fiabilidad la dirección y el módulo de las fuerzas de interacción. Esta contribución ha servido de inspiración para el desarrollo de una nueva pinza robotizada con mayor capacidad de agarre, y ha sido presentada en [7], así como un nuevo método para estimar fuerzas de agarre en la nueva pinza [8].

- **Interacción entre un robot y un humano en escenarios de búsqueda y rescate:**

  Se presenta como contribución de la tesis una aplicación donde hay interacción física entre un robot y una víctima en un escenario de búsqueda y rescate. En la sección 4.3 se presenta un método para, de forma autónoma, sensorizar a víctimas mediante una pinza y el mecanismo de liberación de la propia pinza basado en dos estados estables. La pinza se coloca usando un sensor de visión y un robot manipulador. El sensor de visión es capaz de detectar la pose de la muñeca gracias al uso de redes neuronales y el algoritmo de Horn. El brazo manipulador es capaz de, usando un control predictivo por modelo (Model Predictive Controller (MPC)), replanificar la trayectoria en función de la pose detectada y finalmente colocar la pinza en el antebrazo de la víctima. Se llevaron a cabo dos experimentos de forma satisfactoria. El primero en el laboratorio, con las condiciones de contorno controladas, y el segundo como parte de un ejercicio a gran escala en las Jornadas Internacionales de Seguridad, Emergencias y Catástrofes en Málaga, 2021.

Publicaciones que avalan la tesis

El núcleo de la tesis está compuesto por un compendio de artículos que constituyen la principal contribución de este trabajo. A continuación se exponen los cuatro artículos que avalan a esta tesis.

- J. Ballesteros, F. Pastor, J. M. Gómez-de-Gabriel, J. M. Gandarias, A. J. García-Cerezo and C. Urdiales “Proprioceptive Estimation of Forces Using Underactuated Fingers for Robot-Initiated pHRI", Sensors, vol 20(10), pp. 2863, 2020 (Q2, T1) [17] DOI: 10.3390/s20102863

- F. Pastor, J. García-González, J. M. Gandarias, D. Medina, P. Closas, A. J. García-Cerezo, J. M. Gómez-de-Gabriel, “Bayesian and Neural Inference on LSTM-based Object Recognition from

Tactile and Kinesthetic Information", IEEE Robotics and Automation Letters, pp. 231–238, 2020 (Q2, T1) [18] DOI: 10.1109/LRA.2020.3038377

- F. Pastor, F. J. Ruiz-Ruiz, J. M. Gómez-de-Gabriel, A. J. García-Cerezo, “Autonomous Wristband Placement in a Moving Hand for Victims in Search and Rescue Scenarios With a Mobile Manipulator", IEEE Robotics and Automation Letters, pp. 11871–11878, 2022 [19] DOI: 10.1109/LRA.2022.3208349
- F. Pastor, D. Lin-Yang, J. M. Gómez-de-Gabriel, A. J. García-Cerezo, “Dataset with Tactile and Kinesthetic Information from a Human Forearm and its Application to Deep Learning",Sensors, vol 22(22), pp. 8752, 2022 [20] DOI: 10.3390/s22228752

Marco y desarrollo de la tesis

Esta tesis comenzó en noviembre del 2017 como parte del trabajo del autor como miembro del Grupo de Robótica y Mecatrónica (Robotics and Mechatronics Group) [1], en la Universidad de Málaga. Aun siendo el conjunto de publicaciones que avalan esta tesis imprescindible, el concepto de tesis es mucho más que eso. Otro tipo de actividades de investigación, como colaborar con compañeros de laboratorio en otras publicaciones, organizar eventos para promover los resultados de la tesis, o participar en congresos internacionales de renombre con la intención de compartir ideas se han realizado. Todas estas actividades forman también parte crucial de esta tesis.

Publicaciones adicionales

Las siguientes publicaciones son del autor de esta tesis. No están incluidas en el compendio de artículos, pero están dentro del ámbito de la tesis y relacionadas con el tema de investigación, por lo que también se las considera como una contribución. Cada publicación viene acompañada de una breve descripción de cada trabajo.

Artículos de revistas

- F. J. Ruiz-Ruiz, J.M. Gandarias, F. Pastor, J.M. Gómez-de- Gabriel “Upper-limb kinematic parameter estimation and localization using a compliant robotic manipulator" IEEE Access, 9, 48313-48324, 2021. (Q2, T1). [21]

  En este trabajo los autores desarrollamos un método para estimar los parámetros cinemáticos y la pose de un brazo humano usando un robot manipulador y sin el uso de sensores externos. El método se basa en usar la información proprioceptiva del manipulador y en el control de impedancia cartesiano, que genera una trayectoria que se adapta a las restricciones cinemáticas del brazo. Dos métodos de estimación se implementaron y se probaron usando un brazo artificial que podía cambiar su longitud. Los resultados probaron que ambos métodos realizaban estimaciones correctas.

- F. Pastor, J.M. Gandarias, A.J. García-Cerezo, J.M. Gómez-de-Gabriel, “Using 3D convolutional neural networks for tactile object recognition with robotic palpation", Sensors, vol. 19(24), 5356, 2019. (Q1, T1). [22]

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[1] `https://www.uma.es/robotics-and-mechatronics`

Este trabajo presenta una pinza robótica con tres dedos y dos actuadores para realizar palpación activa. Un sensor táctil se fija en uno de los dedos, registrando datos durante el procedimiento de apretar y soltar. Se entrena una red neuronal de convolución 3D en un conjunto de datos de 24 objetos con características internas variables, y los resultados mostraron un rendimiento mejorado en comparación con las redes neuronales de convolución 2D tradicionales.

Artículos de conferencias

- F. Pastor, F. J. Ruiz-Ruiz, J. M. Gómez-de-Gabriel, A. J. García-Cerezo, “Autonomous Wristband Placement in a Moving Hand for Victims in SAR Scenarios With a Mobile Manipulator", IEEE International Conference on Robotics and Automation (ICRA), 2023, aceptado

  Este artículo ha sido propuesto para su publicación en la conferencia International Conference on Robotics and Automation (ICRA), siguiendo las recomendaciones de los editores de la revista IEEE Robotics and Automation Letters. El congreso ha sido aceptado y se presentará entre el 29 de mayo y el 2 de junio de 2023.

- A. Mandow, J. Serón, F. Pastor, A.J. García-Cerezo, “Experimental Validation of a Robotic Stretcher for Casualty Evacuation in a Man-Made Disaster Exercise", IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), 2020 [23]

  En este artículo se describe como un equipo de militares utilizó un robot móvil (Rambler) para evacuar heridos en un escenario de búsqueda y rescate. En el ejercicio se usó una camilla con un mecanismo de fijación rápida para asegurarse al robot y se probó el sistema en un ejercicio real con miembros del equipo de rescate sin experiencia previa con el dispositivo.

- J.M. Gandarias, F. Pastor, A.J. Muñoz-Ramírez, A.J. García-Cerezo, J.M. Gómez-de- Gabriel, “Underactuated Gripper with Forearm Roll Estimation for Human Limbs Manipulation in Rescue Robotics", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019. [24]

  En esta publicación de congreso se introduce una pinza robotizada y una estrategia de agarre para realizar un agarre estable a una persona que esté tirada en el suelo. También se usan métodos basados en aprendizaje automático para estimar el ángulo de la muñeca con respecto al antebrazo una vez se ha cogido, permitiendo así realizar manipulación segura y estable.

- F. Pastor, J.M. Gandarias, A.J. García-Cerezo, J.M. Gómez-de-Gabriel, “Grasping Angle Estimation of Human Forearm with Underactuated Grippers Using Proprioceptive Feedback", ROBOT 2019: Fourth Iberian Robotics Conference, Springer, 2019. [25]

  Este artículo presenta un método para estimar el ángulo del antebrazo con respecto a una posición de reposo. La estimación se realiza mediante el agarre al antebrazo de una pinza subactuada robotizada. Varios métodos de regresión fueron entrenados con la información propioceptiva proporcionada por las falanges de la pinza robotizada. Se llevaron a cabo varios entrenamientos y pruebas con sujetos conocidos y no conocidos, obteniendo buenos resultados en cada uno de los experimentos.

- J.M. Gandarias, F. Pastor, A.J. García-Cerezo, J.M. Gómez-de-Gabriel, “Active Tactile Recognition of Deformable Objects with 3D Convolutional Neural Networks", IEEE World Haptics Conference (WHC), 2019. [26]

Este artículo de conferencia presenta una red neuronal convolucional 3D llamada TactNet3D que puede clasificar un conjunto de objetos en base a los datos tomados de forma activa de un sensor táctil. El sensor registra tensores táctiles 3D, que son secuencias de imágenes táctiles tomadas a lo largo del tiempo cuando se le aplican diferentes fuerzas incrementales, lo que resulta en una matriz de $[28 \times 50 \times 10]$. La red TactNet3D fue capaz de lograr una precisión del 96,39% en la clasificación de 9 objetos deformables con diferentes rigideces y características internas.

- T. Sánchez-Montoya, J.M. Gandarias, F. Pastor, A.J. Muñoz-Ramírez, A.J. García-Cerezo, J.M. Gómez-de-Gabriel,“Diseño de una pinza subactuada híbrida soft-rigid con sensores hápticos para interacción física robot-humano", XL Jornadas de Automática, 2019. [27]

  En este trabajo se presenta el diseño de una nueva pinza con características híbridas, teniendo componentes rígidos y de robótica blanda. La pinza tiene dos dedos paralelos rígidos subactuados con sensores proprioceptivos, y un dedo subactuado blando que contiene un sensor táctil. Por lo tanto, la pinza puede obtener tanto información kinestésica como táctil. Se realizaron experimentos con dos configuraciones para agarrar un brazo humano y, finalmente, se discutieron los resultados.

- F.J. Ruíz-Ruíz, J.M. Gandarias, A.J. Muñoz-Ramírez, A.J. García-Cerezo, F. Pastor, J.M. Gómez-de-Gabriel, “Monitorización de víctimas con manipuladores aéreos en operaciones de búsqueda y rescate", XXXIX Jornadas de Automática, 2018. [28]

  En esta publicación se presenta un dispositivo para monitorizar las constantes vitales de un ser humano utilizando un vehículo aéreo no tripulado equipado con un manipulador delta. El dispositivo ha sido diseñado para ser utilizado en operaciones de búsqueda y rescate, donde el triaje rápido de víctimas es crucial para implementar una estrategia de rescate efectiva. Las constantes vitales recogidas se transmiten al equipo de rescate a través de la internet de las cosas. Para demostrar la viabilidad del dispositivo, se llevó a cabo un experimento en un ejercicio de rescate simulado y los resultados fueron satisfactorios.

- F. Pastor, J.M. Gandarias, J.M. Gómez-de-Gabriel, “Cinemática y prototipado de un manipulador paralelo con centro de rotación remoto para robótica quirúrgica", XXXVIII Jornadas de Automática, 2017. [29]

  En este trabajo se presenta el diseño y la cinemática de un robot paralelo con dos grados de libertad para cirugía laparoscópica. El robot está basado en un mecanismo de cinco barras, pero los ejes no son paralelos entre sí, sino que todos se cortan en un centro remoto de rotación, en torno al que el efector final del robot pivota. El diseño y la cinemática se validaron con la construcción de un prototipo real, el cual se sometió a varios experimentos que se llevaron a cabo de manera satisfactoria.

Patentes

Se ha desarrollado una patente como parte del trabajo de esta tesis:

- J.M. Gómez-de-Gabriel, A.J. MuñozRamírez, J.M. Gandarias, F. Pastor, J. Ballesteros, A.J. García-Cerezo. “Dispositivo, sistema y método de fijación controlable mediante un brazo mecánico"

Otras actividades

Durante el desarrollo de esta tesis, el autor ha tenido la oportunidad de colaborar con la empresa de robots manipuladores KUKA en el diseño de una demo para el Congreso de Robótica Europeo (European

Robotics Forum (ERF)) en Málaga en el año 2020, formando parte también del comité organizador de dicho evento. El autor también ha tenido la oportunidad de publicar en dos trabajos en progreso (Work In Progress (WIP)) en dos conferencias: IROS 2018 y el World Haptic Conference (WHC) 2019. También ha sido revisor de varias revistas y conferencias de prestigio: IEEE Transactions on Instrumentation & Measurement, IEEE Robotics and Automation Letters, IEEE Sensors Journal, IEEE Access y la Iberian Robotic conference, donde además ha sido miembro del comité organizador. Se han cotutorizado a dos estudiantes con sus trabajos finales de grado. Además, se han ejercido funciones docentes para el departamento de Ingeniería de Sistemas y Automática en el Grado en Ingenierías industriales y en el de Ingeniería Electrónica, Robótica y Mecatrónica. En concreto, el autor ha sido profesor de la asignatura Regulación Automática desde 2020 a 2022. El autor también ha participado en varios proyectos nacionales, siendo los más importantes: FIRST-ROB (DPI-2015-65186-R) y TRUST-ROB (RTI2018-093421-B-100).

Conclusiones

Esta tesis ha explorado y realizado contribuciones al amplio mundo de las pinzas robotizadas. El resultado de la investigación ha sido publicado en revistas científicas y en congresos internacionales de alto prestigio. Como denominador común, aplicaciones con pinzas robóticas inteligentes han sido desarrolladas en esta tesis. Además, el conjunto de trabajos presentado percibe algún tipo de información háptica, y usa métodos de aprendizaje automático como herramienta para aprender de los datos obtenidos. La tesis se puede resumir en tres contribuciones principales: I) Los beneficios de fusionar la información háptica obtenida a través de una pinza robotizada para mejorar el uso de la información, así como las tareas de clasificación y estimación. II) Detectar las fuerzas de interacción entre el antebrazo de un humano y una pinza robótica solo con información kinestésica una vez la pinza ha agarrado al humano. III) La colocación autónoma de una pinza en el antebrazo de una víctima con la ayuda de sensores de visión y un novedoso mecanismo que está incluido en dicha pinza. Después de esta descripción general, las principales conclusiones se presentan a continuación:

- En el capítulo 2 se presentaron dos artículos que usan información háptica obtenida con una pinza robotizada. Ambos trabajos han usado información kinestésica y táctil para entrenar redes neuronales, en concreto redes LSTM. Las dos fuentes de información se entrenaron por separado, y después, los resultados de esas redes neuronales se fusionaron para mejorar el rendimiento del enfoque que usa solo un tipo de información. En el primer trabajo presentado, un conjunto de datos de 36 objetos fue grabado, y se planteó un problema de clasificación de los objetos. Los resultados de las redes neuronales táctiles y kinestésicas son distribuciones de probabilidad. Usando estas dos distribuciones, se generó una distribución de probabilidad final mediante dos técnicas: un método de inferencia Bayesiana, que usó una estimación máxima a posteriori (MAP), y una inferencia neuronal, que incluye una capa densa. El segundo trabajo presentó un conjunto de datos de información háptica de un antebrazo humano completo. Estos datos hápticos tienen asociada la localización del antebrazo donde fueron agarrados. La información kinestésica y táctil fue entrenada esta vez como un problema de estimación que tiene como resultado la zona del antebrazo en dónde la pinza agarró. De forma similar al trabajo anterior, los dos resultados de ambas redes se han usado, siendo en este caso el resultado un escalar normalizado. Para la fusión se usó un método de inferencia neuronal con varias capas densas concatenadas. Los resultados de los dos trabajos demostraron los beneficios de fusionar información, y más concretamente, información háptica.

- En el capítulo 3 se presentó un trabajo dónde una pinza robotizada era capaz de medir las fuerzas de interacción con un humano una vez se había agarrado. La medición de fuerzas se lleva a cabo únicamente con información proprioceptiva. Interpretar las intenciones de los humanos que están siendo agarrados por un robot es crítico para actuar en consecuencia y mantener una interacción segura con el sujeto, interrumpiendo la tarea en caso de que fuera necesario. La pinza robotizada que se presentó en este artículo tiene dos dedos subactuados que se adaptan a la forma del antebrazo del sujeto que están agarrando. Con la información kinestésica que se grabó en numerosos experimentos, se entrenaron métodos basados en aprendizaje automático para aprender la relación entre las lecturas de los sensores proprioceptivos y las fuerzas de interacción. Varios métodos se consideraron, usando un conjunto de datos variado con información de cinco sujetos. Los métodos se probaron con datos de sujetos conocidos y desconocidos para demostrar la efectividad del método, con resultados satisfactorios.

- El capítulo 4 presentó una aplicación que consiste en colocar una pulsera sensorizada a víctimas en escenarios de búsqueda y rescate. Cuando se producen este tipo de escenarios, el personal de rescate suele ser muy limitado en cuanto a efectivos, y además suelen estar muy demandados. Por lo tanto, robots que sean capaces de ayudar con las maniobras de rescate son altamente valorados. En este artículo se presentó un método autónomo para colocar una pulsera con sensores embebidos en el antebrazo de una víctima con la ayuda de un robot manipulador y un sensor de visión. La pulsera incluye sensores vitales para poder realizar el proceso de triaje a las víctimas, priorizando la evacuación de las que tengan más posibilidades de sobrevivir, y, por lo tanto, mejorando la organización del equipo de rescate. La pulsera presenta un diseño novedoso basado en muelles para desacoplarse del efector final del robot manipulador y acoplarse en el antebrazo de la víctima cuando se aplican la fuerza suficiente. La magnitud de dicha fuerza se parametrizó y se puede establecer definiendo ciertos valores como la longitud de los muelles o su constante elástica. Además, se presentó un método novedoso para estimar la pose de una mano. El método usa redes neuronales para detectar puntos de referencia de la mano y luego, con la información de la cámara, estimar la posición 3D de ciertos puntos de referencia. Luego, con la ayuda del algoritmo de Horn, se calcula la pose 6D de la mano. Finalmente se realizaron experimentos en el laboratorio y en escenarios típicos de rescate con resultados favorables.

Discusión

Esta tesis ha demostrado los beneficios de fusionar dos fuentes de información, concretamente datos táctiles y kinestésicos. También se ha presentado una estimación de las fuerzas de interacción con un ser humano utilizando solo información kinestésica. Finalmente, se incluyó un método para colocar una pinza sensorizada en víctimas de escenarios de desastre. Considerando las contribuciones de esta tesis, podrían desarrollarse aplicaciones más complejas que unifiquen las metodologías presentadas. Así, se podría diseñar una pinza robotizada que, gracias a los sensores táctiles que incluya y la información kinestésica de sus falanges, pueda reconocer tanto las fuerzas de interacción entre un ser humano y la pinza, como la sección del antebrazo que está siendo agarrada. Este dispositivo podría ser utilizado para realizar procedimientos médicos como inyectar medicamentos, y ser capaz de cancelar el proceso si el ser humano presenta algún tipo de resistencia o muestra estar incómodo. También tendría sentido integrar esta solución en una aplicación para escenarios de rescate donde, una vez que se sensoriza a una víctima con la pinza desacoplable, se detecte si se necesitan con urgencia alguno de los procedimientos médicos mencionados anteriormente. Finalmente, en el caso de que sean necesarios, se realizan dichos procedimientos. La estimación de la sección del antebrazo agarrada también podría mejorarse fusionando la información captada por el sensor de visión 3D.

Trabajos futuros

Las pinzas robotizadas están muy lejos de tener la controlabilidad, la adaptabilidad y las capacidades sensoriales que tiene una mano humana. A pesar de que el campo de las pinzas robotizadas está muy avanzado, todavía hay mucha capacidad de mejorar. Esta tesis ha reflejado alguna de estas mejoras, pero todavía queda mucho trabajo por hacer. De aquí en adelante, algunas de las posibles líneas de trabajo futuras basadas en los resultados de esta tesis se presentan:

- **Mejorar las capacidades sensoriales de las pinzas robotizadas:**

  Diseño de una nueva pinza subactuada con percepción háptica. La pinza presentada en el capítulo 2, que tiene capacidades tanto táctiles como kinestésicas, presenta algunos inconvenientes que pueden solucionarse. Solo hay sensor táctil en el dedo fijo. Por lo tanto, la nueva versión debe incluir también sensores táctiles en los dedos subactuados y en el resto de la superficie de agarre. Además, tener un dedo que sea fijo limita la capacidad de agarrar de la pinza. Podría ser útil diseñar un mecanismo para que la distancia entre los dedos subactuados y el dedo táctil sea variable. Sería también beneficioso darle flexibilidad a la superficie del dedo fijo para mejorar el agarre.

- **Diseño de técnicas para realizar procesos de exploración:**

  Implementación de técnicas para realizar nuevos procesos de exploración a la pinza robotizada que es capaz de obtener datos hápticos y que ha sido presentada en el capítulo 2. El buen rendimiento del proceso de apretar y desapretar un cuerpo para discernir sus características internas ha sido demostrado. Se podría mejorar aún más los enfoques basados en redes neuronales para las tareas de reconocimiento y estimación incorporando procedimientos exploratorios adicionales, como el movimiento lateral para reconocer texturas.

- **Falanges adicionales para mejorar la información kinestésica:**

  Diseño de nuevos dedos subactuados que incluyan más falanges, lo que supondría un aumento de la complejidad del diseño de la pinza. Sin embargo, este cambio proporcionaría una mayor información sobre la forma del cuerpo agarrado gracias a una mejor adaptación de los dedos, proporcionando una información kinestésica más rica. También se traduciría en un aumento de la comodidad percibida por los usuarios que están siendo agarrados, ya que la superficie de agarre sería mayor y las fuerzas aplicadas estarían mejor distribuidas.

- **Influencia de la pose de la muñeca con respecto a la estimación de fuerzas:**

  Aunque en el trabajo de la sección 3.3 se supuso que la pose de la muñeca es estable, no tendría por qué ser así siempre. Realizar un estudio sobre cómo afecta a la estimación de fuerzas de interacción la variación de la pose del antebrazo podría ser de interés. También podría ser interesante un estudio en profundidad de la mejor pose para la estimación de ciertos requerimientos (mejor estimación en el eje X, mejor estimación en el eje Y, mejor estimación del módulo o mejor estimación de la dirección).

- **Integración de la robótica blanda:**

  Aplicación de técnicas basadas en la robótica blanda a las pinzas presentadas en esta tesis. Cabe destacar que todas las pinzas de este estudio se diseñaron para tener contacto físico directo con extremidades humanas. Por ello, se sugiere la incorporación de dedos blandos en el diseño de estas pinzas para mejorar la comodidad experimentada por los sujetos. Además, el diseño de pinzas blandas con capacidades hápticas es un tema de investigación novedoso, por lo que aportar contribuciones en este campo sería beneficioso para la comunidad científica.

- **Nuevas aplicaciones sobre interacción física robot humano en escenarios de rescate:**

  Aunque en esta tesis se han incluido algunas aportaciones sobre este campo, está todavía muy inmaduro. La ayuda de los robots cuando se produce una catástrofe sería más eficiente y tendría más impacto si estos pudieran interactuar de forma segura con las víctimas, de forma similar a como lo haría un miembro del equipo de rescate. En general, la incorporación de soluciones robóticas a los equipos de rescate ante catástrofes es una vía prometedora para la investigación que ayudará a salvar a un número mayor de víctimas.

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