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Project activity in Central Italy: research projects at the University of Perugia and Siena

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This paper highlights the activities of the Laboratory of Mechanics of Machines at the University of Perugia and the Human Centered Robotics Group at the University of Siena, where certain research projects are carried out collaboratively.

The research conducted at the University of Perugia, under the leadership of Prof. Maria Cristina Valigi and in collaboration with Prof. Silvia Logozzo, primarily focuses on robotic manipulators and tribological issues. The focus of the robotics research is on the development of underactuated monolithic grippers for industrial applications, designed to perform both compliant and powerful grasps. The ongoing development of these grippers remains a central aspect of the research, involving the design and prototyping of new models through experimental, numerical, and theoretical approaches. Recently, some rigid gripper prototypes have been studied for potential applications in the aerospace industry. In addition, leveraging extensive experience in tribological models and analysis, the research addresses specific tribological challenges in robotic fingers, particularly those related to precision grasping. This includes evaluating the contact issues of sensorized fingertips and proposing an innovative method for assessing contact imprints using 3D scanning technologies. The research at the University of Perugia also focuses on tribological issues related to contact analysis, wear, and lubrication of industrial and biomechanical components. Among these, it is worth mentioning the experimental 3D wear analysis of knee and hip prostheses, including retrieved implants, as well as the modeling of friction instabilities in mechanical face seals.

The University of Siena research group coordinated by Prof. Malvezzi focuses on robotics, haptics, and mechanical systems. The research is interdisciplinary, blending mechanical design, control systems, advanced robotics, as well as aspects related to human factors and user studies. The main contributions lie in the development of innovative robotic hands, soft robotic systems, and human-robot interaction. A significant aspect involves the design of underactuated robotic hands and grippers. incorporating compliant mechanisms and modular designs, which improve adaptability and reduce control complexity. The Siena research group is very active in haptics studies. Recent projects include the design of wearable devices enhancing tactile sensations and facilitating interactions in virtual environments. Siena research group contribution is also on theoretical methodologies in robotics, including the study of hand synergies, a concept inspired by the coordination of human hand movements, where a reduced set of control inputs can effectively manage complex robotic actions, an approach that enhances the efficiency and usability of robotic hands in tasks like grasping and manipulation. Recent studies improve robot sensing and actuation through twisted string actuators and soft pneumatic pads, with applications in healthcare and industry.

University and Siena and University of Perugia research groups coordinated by Prof. Valigi and Prof. Malvezzi have collaborated extensively in underactuated mechanisms and soft robotics exploring the design and control of modular, compliant robotic grippers and hands, with an emphasis on tendon-driven, underactuated wearable robotic fingers. They work on integrating soft and rigid elements to improve performance in dynamic environments, with applications in healthcare, industrial automation, and human-robot interaction. Additionally, they develop software tools for modeling and prototyping robotic devices and have applied their research to wearable robotics for rehabilitation, including physiotherapy protocols.

1 Introduction

The research groups led by Professors Monica Malvezzi and Maria Cristina Valigi have established a strong and productive collaboration in the field of robotics, particularly in the areas of assistive technologies and robotics education. Their joint research is driven by the goal of enhancing human-robot interaction through the development of innovative solutions that improve accessibility, functionality, and learning experiences. By integrating expertise in mechanical engineering, control systems, and artificial intelligence, they address both theoretical advancements and practical challenges in robotics.

A key aspect of their collaboration is the focus on assistive robotics, where they explore technologies designed to support individuals in performing everyday activities. Their research emphasizes the development of robotic systems that can operate safely and efficiently in human environments, incorporating advanced control strategies and adaptive mechanisms. Their work contributes to the growing field of rehabilitation and assistive devices, striving to improve the quality of life for individuals with physical impairments.

Beyond assistive robotics, the Siena and Perugia groups have also made contributions to robotics education. Their research includes the development of educational tools and methodologies aimed at enhancing the learning experience for students in robotics and mechanical engineering. By designing interactive platforms and case studies, they facilitate a deeper understanding of complex kinematic and control concepts, ensuring that students and researchers can effectively engage with modern robotic technologies.

This document highlights the various research activities carried out by the Laboratories of Mechanics of Machines, operating both at the University of Siena and the University of Perugia. The collaboration provides a shared opportunity where numerous researches are conducted by faculty and researchers from the research groups led by Prof. Monica Malvezzi at Univeristy of Siena and Prof.ssa Maria Cristina Valigi at Univeristy of Perugia.

In the following we summarize these collaborative efforts, encouraging the exchange of knowledge, resources, and expertise, fostering an environment of innovation and contributing to the advancement of mechanical engineering research. Through these partnerships, the laboratory aims to address complex challenges in the field, with a particular focus on enhancing the design and functionality of mechanical systems, exoskeletons, robotics, and tribology.

1. Research activities at the University of Siena

The research group at the Human Centered Robotics Laboratory at the University of Siena is specialized mainly in robotics, mechanical engineering, and haptics. In the following, the main research topics are briefly introduced.

1.1. Robotic Grasping and Manipulation

The Siena group's contributions to robotic grasping and manipulation primarily aims at improving the ability of robots to replicate human-like dexterity and efficiency in handling objects. One key aspect of their work concerns the study of human hand synergies [1] [2] and their mapping to robotic hands with dissimilar kinematics [3]. This research aims to transfer the efficient, coordinated movements of the human hand to robots, even when the robotic hand has different kinematic structures or degrees of freedom. By focusing on object-based approaches, the group explored how robotic hands can better mimic the way humans naturally grip and manipulate objects. This enhances the robot's ability to perform complex tasks that require fine motor skills, such as grasping and handling delicate or irregular objects. A Matlab toolbox including functions for human and robotic hands actuated with synergies has been released by the Siena research team [4].

Additionally, their work also aims at providing the grasping abilities of soft robotic hands by exploring how their flexibility and adaptability can be applied to real-world manipulation tasks. The research highlights the potential for robotic systems to become simpler, more intuitive and versatile in a variety of scenarios, from industrial automation to rehabilitation, by adopting more human-like grasping strategies, advancing more adaptive, effective, and human-inspired robotic grasping and manipulation capabilities.

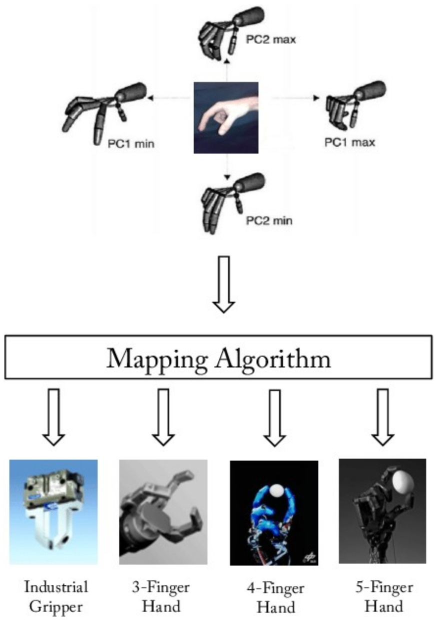

Figure 1: Mapping human synergy on robotic hands with dissimilar kinematics [3]

1.2. Haptic Feedback Systems

The work in haptics focuses on enhancing tactile feedback systems, particularly in the context of robotic and wearable devices, improving tactile interaction by designing more efficient, comfortable, and realistic feedback systems, which are critical for applications in robotics, virtual reality, and human-robot interactions [5].

A significant part of the research has been the development of wearable devices for different parts of the body (Fig. 2) that provide cutaneous force feedback. One of the most relevant contribution is in the development of haptic devices providing different types of haptic feedback to the fingertips, a part of the body that is fundamental for tactile exploration of the environment. A 3-DOF (degrees of freedom) wearable fingertip devices is presented in [6]. These devices are designed to provide tactile feedback to the user, simulating touch sensations in a way that enhances the interaction between the user and the robot or virtual environment [7]. By improving the force feedback at the fingertip, her work seeks to make haptic technology more practical and immersive, especially in fields like teleoperation, robotics, and virtual reality. The research also emphasizes the wearability aspect of haptic devices, ensuring that the feedback system is not only effective but also comfortable for prolonged use. This balance of functionality and comfort is crucial in applications where users need to engage with robotic systems or virtual environments for extended periods, such as in rehabilitation or remote operation tasks [8].

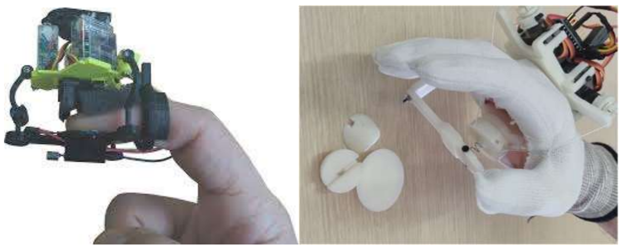

Figure 2: examples of wearable haptic devices for the fingertip [6] and for the hand palm.

1.3. Soft Robotics

Another important branch of Siena group's research activity is the development of robotic grippers, particularly in the integration of soft and rigid elements to enhance adaptability and functionality.

A notable contribution it this research topic is the development of a methodology for compliant gripper design, prototyping, and modeling using screw theory, as detailed in [10]. This article explores the design, modeling, prototyping, and testing of soft–rigid tendon-driven grippers. The research applies of screw theory to model the kinematics and compliance of these grippers, providing a framework for their development and analysis.

Recent studies focused on developing an optimization-driven design methodology for monolithic soft-rigid grippers. In these studies a novel methodology that combines advanced rapid prototyping techniques with an efficient optimization strategy is presented. This approach aims to mitigate deviations from simulated designs caused by manufacturing processes like 3D printing and molding, reducing the need for multiple prototypes to achieve functional systems [11].

1.4. Human-Robot Interaction:

The Siena group work extensively on different applications and scenarios of human/robot interaction, both in work and social contexts. Recently the group proposed a solution for soft human-robot handover using vision-based pipelines, and exploiting the soft physical contact between the human and the robot, contributing to more intuitive and efficient interactions between humans and robots [12].

In social contexts, the Siena research group investigated the role of closed-loop hand control in human-robot handshaking interactions [13]. The research aimed to understand how haptic feedback influences the quality of handshakes between humans and robots. The findings suggest that incorporating sensorimotor delays, mimicking human reaction times, can make robotic handshakes more natural and positively affect the perceived personality traits of the robot.

1.5. Robotic Rehabilitation:

The neurorehabilitation robotics landscape is evolving rapidly, where continuous innovations in robotics, AI, and VR are playing pivotal roles in driving the sector forward. Robotic devices, integrated with AI can support and monitor patient progress in real-time, adjusting therapy sessions according to individual needs and performance. The Siena research group is working the field of robotic rehabilitation, researching and developing innovative assistive devices. In particular they developed a modular hand exoskeleton that facilitates the flexion and extension of fingers. The exoskeleton's adaptable design enhances wearability and provides bidirectional force application, assisting both in opening and closing the fingers [14]. An underated version of the exoskeleton employing a gear-based differential mechanism, enabling the coupling of adjacent fingers' movements while minimizing complexity and cost is presented in [15], while in [16] a tendon actuated glove employing Twisted String Actuators, TSA, is introduced.

The research group explored the development of supernumerary robotic devices to support individuals with upper limb impairments. One such innovation is a soft supernumerary robotic finger combined with a mobile arm support. This system compensates for grasping deficiencies and aids in the rehabilitation of hemiparetic upper limbs, offering users enhanced autonomy in daily activities [17].

2. Research activities at the University of Perugia

The research conducted at the University of Perugia, led by Prof. Maria Cristina Valigi primarily focuses on advancing robotic manipulators and exploring tribological issues.

2.1. Underactuated monolithic grippers for industrial application

One of the the research is the development of underactuated monolithic grippers specifically designed for industrial applications. These grippers are engineered to perform a wide range of tasks, combining both compliant and powerful grasps, and also focusing on precision grasping with sensorized fingertip. They could beversatile tools in various industrial environments. The continuous development and enhancement of these grippers remain at the heart of the research efforts, with the team actively engaged in designing and prototyping new models. The development process is encompassing experimental, numerical, and theoretical approaches to ensure the grippers meet performance. Examples of newly proposed designs for underactuated monolithic grippers are found in [18][22,25,26], where the joint design is characterized by waves (Fig3), with their geometry and materials determining the stiffness of the grasp. Numerical and experimental characterization of the joints, crucial for designing grippers, is evaluted with different geometrical variables of sinusoidal wave, achiening a large variety of stiffness values useful for different tasks.

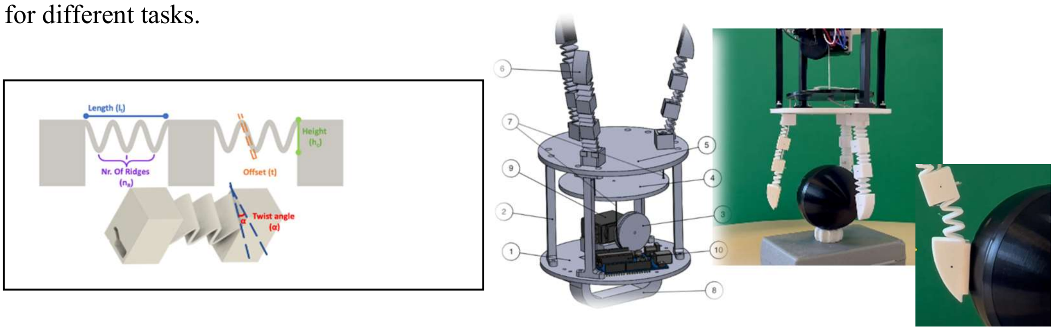

Figure 3:The Wave-Joint (on the left) and modelling and prototype of a gripper with 3-finger for precision grasping (on the right)

Sensorized grippers have been prototyped for precision grasping. The proposed gripper, featuring a monolithic joint, consists of four tendon-actuated soft fingers, allowing high adaptability for grasping objects of various shapes [27]. Force Sensing Resistors (FSRs) are integrated into the fingertips to measure and calibrate the forces during grasping. This sensor feedback enhances the precision of the gripper, making it particularly suitable for handling delicate objects. The study focused on the characterization, calibration, and validation of the system to ensure accurate force detection and control. Experimental tests were conducted to determine the threshold force required to support, deform, or, when necessary, break specific object (Fig.4).

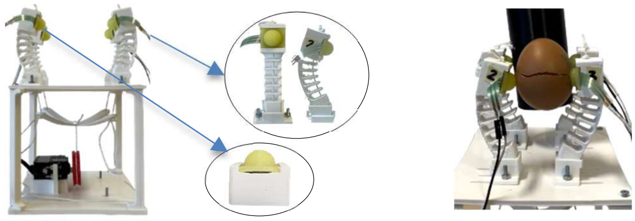

Figure 4: 3D-printed underactuated soft gripper with sensors on fingertips

2.2. Rigid gripper prototypes for aerospace application

Recently, the research team has explored the application of these grippers in the aerospace industry, focusing on rigid gripper prototypes designed for the collection of space debris. The concept involves developing a biomimetic gripper inspired by the natural world, particularly by the plant structures used by carnivorous plants to capture prey, such as the Venus flytrap. Drawing inspiration from the capturing process, the gripper design is based on distinct phases: the initial snap phase, the clamping phase, and the sealing phase [28].

2.3. The human and robotic touch

In parallel, the research benefits from the team's extensive experience in tribological models and analysis. They are actively addressing tribological challenges related to human and robotic fingers, with a particular focus on precision grasping[29-31]. This involves assessing the contact behaviors of sensorized fingertips, crucial for the accuracy and reliability of robotic gripping. A key innovation emerging from this research is the development of a novel method for evaluating contact imprints, which involves the use of advanced 3D scanning technologies. This method offers a highly detailed and precise way to analyze the interaction between the gripper and the objects it handles, pushing the boundaries of how we understand contact mechanics in robotic systems. The idea also stems from the collaboration with Prof. Malvezzi, an expert in haptic devices, who has contributed to integrating these advanced technologies into the context of robotic applications. Fig.5 shows the proposed method applied to human fingertip.

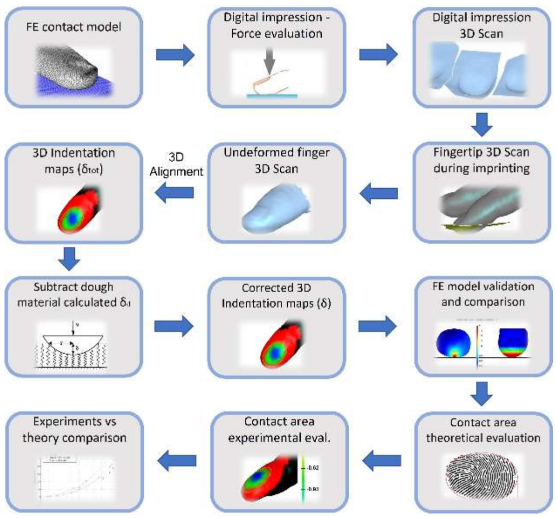

Figure 5: Modelling the human touch by 3D scanner technology.

2.4. Innovative method for 3D wear anlysis using 3D optical scanner

The scope of the research also extends to a broader range of tribological issues, particularly those related to industrial and biomechanical components. These include in-depth studies on wear, lubrication, and contact analysis. Among the most notable studies is the experimental 3D wear analysis of knee and hip prostheses, including the evaluation of retrieved implants [32-37]. This research aims to understand the long-term behavior of prosthetic components under real-world conditions. The scheme of the digital procedure and example in terms of wear maps of components are showed in Fig.6.

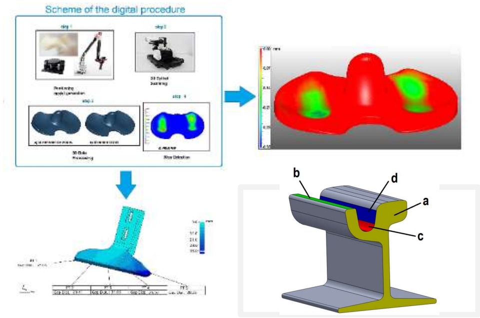

Figure 6: Scheme of digital procedure for the evaluation of wear by 3D scanner technology.

2.5. Mechanical seals and lubrication

Additionally, n our research, we are focusing on mechanical seals, which are crucial components in various industrial fields, ensuring the proper functioning of machinery and systems by preventing fluid leakage or contamination. The main objective is to improve the longevity and efficiency of seals, especially addressing phenomena related to friction, wear, and lubrication. A key aspect we are analyzing is friction instability in mechanical seals A proper model is proposed and a simulation tool is proposed to study the oinfluence of dynamic parameters on friction intabilities. Some details of the model are in Fig.7 [38-41].

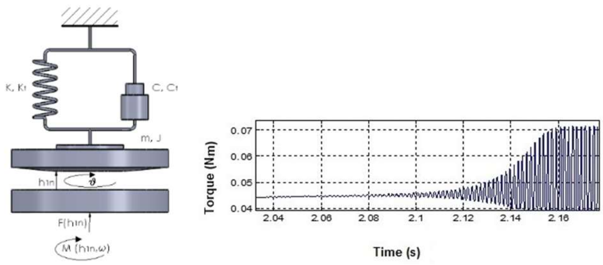

Figure 7- Lumped parameter model of a mechanical face seals and results of simulation due to friction instabilities

3. Joint research activities

Professors Monica Malvezzi and Maria Cristina Valigi have collaborated extensively in the field of robotics, focusing on the development of innovative grippers and educational tools. One notable project is the "DressGripper," a collaborative robotic gripper designed to assist individuals with physical or neurological impairments in dressing. This device combines a compliant structure with electromagnetic actuation at the fingertips, ensuring both safety and effective grasping during dressing tasks. The DressGripper exemplifies their commitment to creating assistive technologies that enhance human-robot interaction in daily activities [18]. Another interesting device that they developed in collaboration is a double extra finger that can be used as an active assistive support for people with upper limb impairments. With respect to other extra fingers previously introduced, the one presented in this work guarantee a higher grasping robustness and adaptability, while maintaining a rather compact and light structure, thanks to the fingers' mechanical coupling through a differential mechanism.

The research groups collaborated extensively in the study of robotic grasp and in the design of soft robotic grippers. Grasping and dexterous manipulation are still open challenges in robotics, above all when performed with multifingered robotic hands or underactuated grippers. The availability of simulation tools to design and test grasp and manipulation control strategies is therefore important to get functional robotic manipulation systems. The Siena and Perugia research groups collaborated in the development of a framework [21] for modeling and simulating grasps in the Simulink environment, by connecting SynGrasp [4], a well established MATLAB toolbox for grasp simulation and analysis, and Simscape Multibody, a Simulink Library allowing the simulation of physical systems (Fig. 8). The proposed approach can be used to simulate the grasp dynamics in Simscape, and then analyse the obtained grasps in SynGrasp. The devised functions and blocks can be easily customized to simulate different hands and objects.

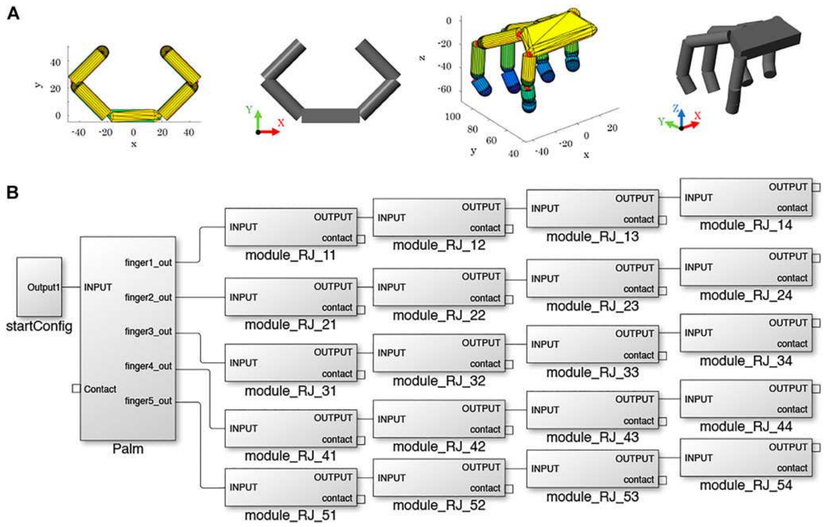

Figure 8: Modeling and simulation of robotic grasping in simulink through simscape multibody. (a) Syngrasp and Simscape models. (b) Simscape scheme of an anthropomorphic hand.

Figure 9: soft gripper with modular actuated embedded constraints.

An interesting gripper (Fig. 9) is presented in [20], in which the implementation of some specific features that can be represented as “embedded constraints” allows to reduce uncertainty and to exploit the role of the environment during the grasp. The design exploits a modular structure guarantee a suitable level of adaptability to the shape of the objects that have to be grasped. In the proposed device the embedded constraint is no rigid neither unactuated and is composed of an alternation of rigid and soft modules, which increase versatility. Moreover, the use of soft material such as thermoplastic polyurethane (TPU) reduces the risk of damage to the object being grasped. In the paper, the main design choices have been exploited and a finite element method (FEM) analysis through static simulation supports a characterization of the proposed solution.

In [22] the joined research groups presented a methodology to design soft-rigid grippers able to perform different manipulation tasks. The main idea was the introduction of wave-shaped hinges whose geometrical parameters can be designed to achieve different three-dimensional impedance characteristics. This allows one to use the same tendon-driven actuation to perform different tasks including grasping objects with different shapes and in-hand manipulation of small objects.

Their collaborative efforts are more recently joined another research group at the University of Brescia, led by Prof. Monica Tiboni, focusing on the development of design methodologies and benchmark for assistive robotics, demonstrating a shared commitment to leveraging technology for societal benefit [23]. That work proposes a roadmap (i) for both the design and selection of exoskeletons for hand rehabilitation, (ii) to discriminate among the peculiarities of soft, rigid, and hybrid devices, and (iii) with an impairment-oriented rationale. The clinical requirements expected for an exoskeleton are identified by applying a PICO-inspired approach focused on the impairment analysis; the technical features are extracted from a proposed design process for exoskeletons combined with a narrative literature review.

In addition to their work on assistive devices, Malvezzi and Valigi have contributed to develop educational resources in robotics [24]. They co-authored a study presenting an educational tool for kinematic analysis, aimed at enhancing learning experiences in robotics and mechanical engineering. This tool serves as a case study for improving the comprehension of complex kinematic concepts among students.

4. Conclusion and future works

This paper summarizes the research activities conducted individually and jointly by the Laboratory of Mechanics of Machines at the University of Perugia and the Human Centered Robotics Group at the University of Siena. It's worth to underline that the collaboration extends beyond research publications, as they actively contribute to academic discussions, conferences, and editorial initiatives in the robotics field. Through their joint efforts, they aims at fostering interdisciplinary innovation, bridging the gap between theoretical research and practical applications. Their work not only aims at contributing to scientific knowledge but also demonstrates a strong commitment to leveraging robotics for societal benefit, working both on theoretical methodologies and technological capabilities.

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