

SIXTH FRAMEWORK PROGRAMME
PRIORITY 2
Information Society Technologies IST



SPECIFIC TARGETED RESEARCH OR INNOVATION PROJECT

Project Technical Description

Project acronym: **PHRIENDS**

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Physical Human-Robot Interaction: DepENDability and Safety



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1. Objectives of the project

This project aims at developing robots that can co-exist and co-operate with people, enabling a physical human-robot interaction which is dependable and safe: in a word, to make robots and humans PHRIENDS

Scientific and Technological Objectives

The next generation of robots will interact with people directly. Human-Robot Interaction (HRI) will certainly happen at the cognitive level (cHRI), fundamentally concerning communication between human and robot through the many channels available to us (video displays, sounds, watching each other's motions, spoken language, or even gaze direction or facial expression). However, robots are distinct from computers in that they physically embody the link between perception and action. Hence, the most revolutionary and challenging feature of the next generation of robots will be **physical Human Robot Interaction (pHRI)**. In pHRI, humans and robots share the same workspace, come in touch with each other, exchange forces, and cooperate in doing actions on the environment.

Robots designed to cooperate with humans, such as e.g. in assisted manipulation, collaborative assembly, domestic, entertainment, rehabilitation or medical applications, must fulfill different requirements from those typically met in conventional industrial applications. Typical conventional robot systems and applications require fast motions and absolute accuracy in positioning and path following and avoid using expensive and error-prone sensors at the tradeoff of having carefully designed and modeled environments. In sharp contrast, the before-mentioned future application areas could use (extra) internal and external sensor systems and could trade in certain performance characteristics of the robot system to drastically increase dependability and overall safety in unpredictable dynamically changing environments. Given such a discrepancy in requirements **this project aims at substantially advancing the state of the art in robot design and control to enable applications that require intrinsically safe physical human-robot interaction.**

PHRIENDS is about **developing key components of the next generation of robots, which have to meet the strictest safety standards, yet also to deliver useful performance.** This poses new challenges to the design of all components of the robot, including mechanics, control, planning algorithms and supervision systems. The approach advocated by this project consists in an integrated co-design of robotic systems for safe pHRI, which revolutionizes the classical design paradigm of industrial robots – rigid design for accuracy, active control for safety – into a new one: **design robots that are intrinsically safe, and control them to deliver performance.**

Although the scope of this STREP proposal cannot encompass the integration of complete robot systems, **PHRIENDS'** scope is to achieve fundamental advancement in the direction of safe pHRI, for it will **create and deliver:**

- A. new actuator concepts and prototypes
- B. new dependable algorithms for supervision and planning



- C. **new control algorithms for handling safe human-robot physical interaction and for fault-tolerant behaviour**

Furthermore, **PHRIENDS** will:

- D. **integrate these components in functionally meaningful subsystems**
- E. **evaluate quantitatively components and subsystems via experimental testing**
- F. **contribute to the ongoing effort of international bodies towards the establishment of new standards for collaborative human-robot operation**

2. State-of-the-art before **PHRIENDS**

From the beginning of industrial robotics to the present, the first line of defense in robot safety has been to take all necessary measures to enforce segregation between live robots and people. It is on such philosophy that most of the early technical literature on the topic is based, as well as the existing robotics safety regulations and standards. Strict robot safeguarding has not always been effective in preventing human fatalities, especially during operations such as programming, maintenance, repair, testing. In these and many other cases, segregation just does not work. An automatically guided vehicle (AGVs) is an example of a robot that cannot be put behind fences. Even more difficult are cases where successful task completion requires people and robots to collaborate directly in a shared workspace.

Attention towards safe operation of robots near and with humans is rather recent, with some of the earliest contributions dating back to the 1990's. Safety of robots involves several different considerations and depends on many factors, ranging from software dependability, to possible mechanical failures, to human errors in interfacing with the machine, etc. A thorough hazard analysis and risk evaluation must be performed according to procedures specifically designed for different domains of application: these methods are receiving a growing attention from the scientific community, international standardization bodies, and industry.

For instance, KUKA Roboter GmbH has developed new technologies, called *KUKA Safe Operation* and *KUKA Safe Handling*, which allow a safe and redundant monitoring of the robot's position, velocity and acceleration with safety level SIL 2 or EN Category 3. Such a technology provides the basis for safe human-robot cooperation and can be used, e.g., for manual robot guidance with safely reduced speed. In the case of a malfunction (hardware or software) the robot is stopped immediately. **However, more advanced safety methods and strategies are required, e.g., for cooperative assembly in which robots and humans work independently and autonomously in the same workspace to jointly assemble a work piece.**

One important aspect in designing for safety is the ability to quantitatively evaluate the risk of injuries in accidents that cannot be avoided. While the literature on robot-specific injuries is not rich, much can be learned from biomechanics and automotive applications, where several "Abbreviated Injury Scaling" factors are proposed, among which the Head Injury Coefficient (HIC) is the most often used. More recent indices, such as the Maximum Power Index (MPI) and Maximum Mean Strain Criterion (MSC), are compared and reviewed in work done at DLR.

The inherent danger to humans of conventional arms can be mitigated by drastically increasing their sensorization or by increasing the energy-absorbing properties of protective layers (adding enough soft and compliance coverings or placing airbags around the arm). Such solutions however seem to be hardly viable from both an economic and practical viewpoint.

An approach that has been intensely explored since the early 80's is to design active force controllers, e.g. Salisbury's stiffness control or Hogan's impedance control schemes, to introduce



compliance with respect to sensed interactions. However, **these approaches may not prove robust with respect to impacts on portions of the arm that are not equipped with force/torque sensors. Also, it is well known in the robotics literature that there are intrinsic limitations to what the controller can do to alter the behavior of the arm if the mechanical bandwidth (basically dictated by mechanism inertia and friction) is not matched to the task. In other words, making a rigid, heavy robot to behave gently and safely is an almost hopeless task, if realistic conditions are taken into account.**

PHRIENDS is about **developing key components of the next generation of robots**, ranging from industrial robots to assist devices (in particular, robots for the emerging market of non-industrial applications, e.g. for service, health-care, and entertainment), designed to share the environment and to physically interact with people. Such machines have to **meet the strictest safety standards, yet also to deliver useful performance**: this poses new challenges to the design of all components of the robot, including mechanics, control, planning algorithms and supervision systems. We propose an integrated approach to the co-design of robots for safe physical interaction with humans, which revolutionizes the classical approach for designing industrial robots – rigid design for accuracy, active control for safety – by creating a new paradigm: **design robots that are intrinsically safe, and control them to deliver performance.**

3. Results

VSA-II Actuators (University of Pisa)

Safety and dependability: adopting a new paradigm

Robots designed to share an environment with humans, such as e.g. in domestic or entertainment applications or in cooperative material-handling tasks, must fulfill different requirements from those typically met in industry. It is often the case, for instance, that accuracy requirements are less demanding. On the other hand, concerns of paramount importance are safety and dependability of the robot system. According to such difference in requirements, it can be expected that usage of conventional industrial arms for anthropic environments is far from optimal.

The classical approach adopted by robotics so far deals first with the kind of task requested to the machine, building the robot structure in conformity with the task. Just in a second moment the safety problem is taken into consideration, by adding to the robot active controls.

In this approach, the inherent danger to humans of conventional arms can be mitigated by drastically increasing their sensorization (using proximity-sensitive skins and/or by modifying their controllers). Active stiffness and impedance control could be employed to introduce compliance with respect to sensed interactions.

However, these approaches may not prove robust with respect to impacts on portions of the arm that are not equipped with sensors. Also, it is well known in the robotics literature that there are intrinsic limitations to what the controller can do to alter the behavior of the arm if the mechanical bandwidth (basically dictated by mechanism inertia and friction) is not matched to the task. In other words, making a rigid, heavy robot to behave gently and safely is an almost hopeless task if realistic conditions are taken into account.



The approach adopted by PHRIENDS revolutionizes the traditional approach adopted by the classical robotics, by creating a new conceptual paradigm: the new robot is projected to be intrinsically safe in its structure, and safety is implemented by purely mechanical and passive means. Conversely, the active control is adopted to guarantee the performance. PHRIENDS has opened up new directions, where a robotic manipulator is designed and/or optimally controlled to recover the lost performance in presence of compliance for intrinsic safety. A paradigm shift thus gets established “design for safety and control for performance”.

VSA-II Actuator

The new direction taken by PHRIENDS leads to an actuation method, called Variable Stiffness Approach and its generalized form as Variable Impedance Approach. Briefly, this approach relies on the possibility to vary the mechanical impedance (i.e. stiffness, damping and/or gear-ratio parameters) of the actuation subsystems in a way that guarantees mechanical safety during fast motions.

To make this possible, a new class of actuators was developed, called Variable Stiffness Actuator (VSA). The main characteristic of VSA is to mechanically decouple the rotary inertia of the torque source from the inertia of the actuated joint shaft by varying the mechanical impedance of the transmission.

The primary aim of VSA is to change in Real-Time transmission stiffness during motion of the joint shaft in a manner that guarantees low levels of injury indexes. **The source of inspiration is the muscular system of humans and animals:** the simultaneous control is indeed achieved by using two motors antagonistically, via use of so-called nonlinear spring as an elastic transmission between each of the motors and the actuated link. The concept of antagonistic actuation has been analyzed in theory and implemented in its first prototype, namely Variable Stiffness Actuator-1 (VSA-I).

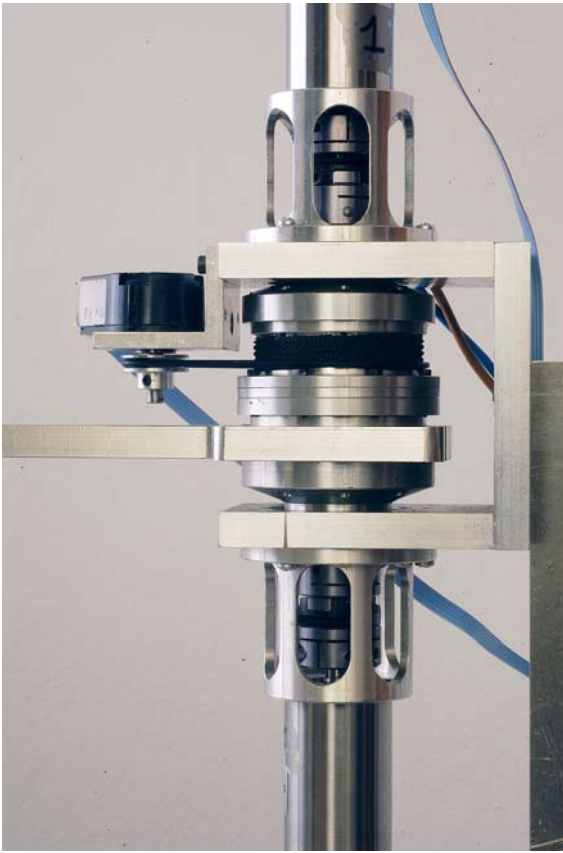
VSA-I as a demonstrator for variable stiffness actuation has established the principle and purpose. However, it finds limitation in torque capacity and in practical implementation in a robotic arm.

Recently, the University of Pisa has presented an improved actuator: VSA-II, based on simpler antagonistic concept for a direct robotic joint actuation. **VSA-II overcomes the problem of implementability with higher capacities and robustness in design for longer life.**

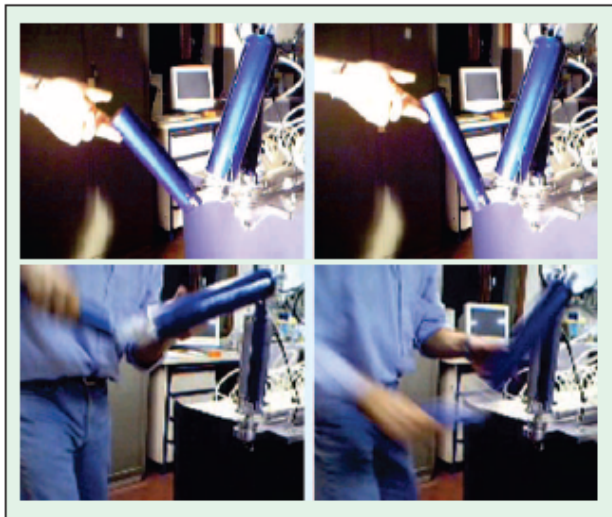
VSA-II has been recently presented at the International Conference of Automation and Robotics (ICRA 2008) in Pasadena, raising the interest of the whole community of research in robotics. The paper presenting VSA-II ("VSA-II: A Novel Prototype of Variable Stiffness Actuator for Safe and Performing Robots Interacting with Humans" by Riccardo Schiavi, Giorgio Grioli, Sen Soumen, Antonio Bicchi) won the KUKA Service Robotics Paper Award.

Future work will address further improvement of the VSA class of actuators, for what concerns stiffness range, encumbrance and weight reduction, etc. Moreover an integrated design of a 3-DOF variable stiffness arm is undergoing.





VSA-II



The University of Pisa SoftArm has a 3-DOF anthropomorphic and lightweight structure, actuated by McKibben artificial muscles in antagonistic pairs. The arm can interact closely with a human operator in both low- (top) and high-frequency (bottom) ranges. The arm, called GioSte, has been developed to test the functioning principles of VSA.

Impact detection and reaction (DLR)

[already on a prototype of Kuka that will be put on the market soon]

A robot manipulator sharing its workspace with humans should be able to quickly detect collisions and safely react for limiting injuries due to physical contacts. In the absence of external sensing, relative motions between robot and human are not predictable and unexpected collisions may occur at any location along the robot arm.

PHRIENDS has developed an efficient collision detection method that uses only proprioceptive robot sensors and provides also directional information for a safe robot reaction after collision. The approach is first developed for rigid robot arms and then extended to the case of robots with elastic joints, proposing different reaction strategies.

Accidental collisions that may harm humans should be avoided by anticipating dangerous situations, while the effects of actual collisions should be mitigated by having the robot react promptly so as to recover a safe operative condition.

Current research on physical human-robot interaction deals with different aspects involved in robot dependability: **mechanical design**, aimed at reducing manipulator inertia and weight; introduction of **compliant components**, for reducing the severity of impacts; additional use of **external sensors**, so as to allow a fast detection of human-robot proximity; motion **planning and control** strategies, for minimizing the risks associated to collisions. Each of these aspects is relevant in one or more of the elementary phases in which a physical human-robot interaction can be divided.

When a collision occurs, the resulting contact forces during the *impact phase* may be alleviated by pursuing a lightweight robot design, by adding soft visco-elastic covering to the links, or by introducing compliance in the driving system so as to mechanically decouple the heavy motor inertia from the link inertia. Light but stiff link materials can be combined with harmonic drives, introducing thus joint elasticity, as in the DLR-III robot manipulator. Also, variable stiffness actuation can be used, stiffening the joints during low-velocity transients and relaxing them at high-velocity regimes, in such a way that tracking performance during free motion is not compromised by the introduced compliance.

Collision detection and identification signals can be efficiently generated resorting to energy arguments or based on the robot generalized momentum and by using only proprioceptive measurements. After collision has been detected, a reactive control strategy enables to reduce the effective inertia seen by the Cartesian contact forces. The robot retracts itself safely and rapidly away from the collision area, using the local directional information collected during the impact. The developed methodology covers both the case of rigid manipulators and of robots with elastic joints.

On-going work is concerned with acceleration-driven collision detection and the reduction of control communication delays in our robotic set-up, as well as with a more accurate evaluation of several severity indices of the impacts and of the beneficial inclusion of compliant coverages. Furthermore, robot redundancy will be exploited in order to devise reaction strategies that try to complete a given Cartesian motion task, despite of the detected collision.





Standardized crash tests for the evaluation of “Safety in physical Human-Robot Interaction”

4. Impact of the results

The project has a strong emphasis on research on safety indices, performance metrics, and above all on quantitative tools for **evaluation** of safety-critical robot systems and for providing **design guidelines**.

This focus aligns the project to the Call’s objective “to address some of the key challenges for the paradigm shift of robotic equipments in their evolution from a specific industrial technology to a broad enabler for a wide range of products and services that are entering the consumer, home and entertainment markets”. The strong relations with international efforts toward **revised and new standards** for robotic assistive devices is also in line with the European interests in a broader international market space for a sector such as industrial robotics, where Europe has world-wide leadership. As the call recognizes being necessary, our consortium integrates multi-disciplinary scientific research (information, mechanical, control and bio- engineering) with industrial-strength technology integration.

The **social relevance** of innovation in pHRI is enormous. **Enhanced safety and reduced fatalities in industrial manufacturing workplaces is a primary goal of our project. Reduction of musculoskeletal disorders for workers obtainable by intelligent machine assistance in lifting and manipulating heavy loads is also very important. Safety and dependability are crucial enabling attributes for critical applications of robots such as in domestic (robotic aid for the disabled and the elderly), biomedical (surgery, rehabilitation), sports training or entertainment.** The goals of PHRIENDS thus fit well the call’s ambition to pave the way to the future massive introduction of robots in everyday human environments and their close cooperation with people.

The **domestic assistance application** has obvious, if indirect, relevance also to the call theme 2.6.2, “Ambient Assisted Living (AAL) in the Ageing Society”.

More broadly, the PHRIENDS project addresses many important Strategic Objectives (SOs) of the IST thematic priority, as described in its general Work Programme. As indicated by SO 2.5.9 ‘Collaborative Working Environments’, PHRIENDS will contribute to developing next generation collaborative working environments, boosting innovation and productivity.



The working environments envisaged by **PHRIENDS** provide collaboration services to make possible the development of worker-centric, flexible applications, and enable seamless and natural collaboration amongst humans and machines. **PHRIENDS** pursues the goals of SO 2.4.3, 'Towards a global dependability and security framework', in that will build technical and scientific excellence, as well as European industrial strength in security, dependability and resilience of systems, and contribute to standardisation activities. Long-term implications of safe and dependable robotics technologies developed by **PHRIENDS** will address the concerns of SO 2.5.11 "eInclusion", by enabling the development of next generation assistive systems that will empower persons with disabilities and aging citizens to increase their autonomy and to realize their potential.

For further info about the expected results see www.phriends.eu/impact.htm.

