2. Publishable summary

CogLaboration (Successful real World Human-Robot Collaboration: from the cognition of human-human collaboration to fluent human-robot collaboration) is a specific targeted research project (STReP) funded by the European Commission under the ICT Challenge 2 "Cognitive systems and robotics" of the Seventh Framework Programme (FP7). The project started on November 1st, 2011 with a duration of three years.

The project coordinator is Treelogic (TREE, Spain), represented by Mr. Víctor Fernández-Carbajales Cañete. The other beneficiaries are the Foundation Tecnalia Research & Innovation (TECNALIA, Spain), the University of Birmingham (UB, United Kingdom), The Scuola Superiore Di Studi Universitari e di Perfezionamento Sant'Anna (SSSA, Italy) and R.U.Robots Limited (RUR, United Kingdom).

More details about the CogLaboration project can be found on the project's website at http://www.coglaboration.eu. The contact details are Mr. Víctor Fernández-Carbajales Cañete, Phone: +34 902 286 386, e-mail: victor.fernandez@treelogic.com.

2.1. Summary and objectives

Recent advance in robotics are increasingly pushing the boundaries of robot applications from the classic machine environment of industrial production lines towards ever closer interaction with human users. A key aspect of this development is the desire for robots and humans to effectively perform actions together in the shared environment. This is demonstrated by the current work being performed in the development of a specific ISO standard (robot and robotic devices) to cover the emerging applications characterized by a sophisticated human-robot interaction.

The CogLaboration project is totally aligned with this expectation of extensive human-robot collaboration in the near future, and aims to make such collaboration to be fluid and effortless. Indeed, collaboration among people frequently involves dexterous object manipulation, and the effortless object handover between people is a key factor for smooth collaboration. CogLaboration is therefore working to enable fluid object exchange between a human user and a robotic arm.

Current techniques of human-robot object transfer are largely based on having the robot following a trajectory that is predefined before the motion is initiated, thus limiting the ability to adapt to unanticipated changes in human behavior. Furthermore, movements produced by current existing robots usually do not sufficiently incorporate characteristics of human movements resulting in behavior which may be experienced as not user-friendly. In addition, the human-robot object exchange is generally performed without haptic feedback, while evidence suggests that humans strongly rely on tactile information to support object manipulation.

Thus, CogLaboration is addressing the challenging task of fluid object exchange with the objectives of facilitating effortless human-robot collaboration. To reach this outcome, CogLaboration is:

1. Conducting empirical studies of fluent object exchange between human partners, in industrial and domestic settings, covering variations of the nominal exchange case with various objects.
2. Extracting the basic capacities needed for fluent, safe and effective object exchange.
3. Developing a model of human-human object exchange including all the faculties needed to characterize, monitor and coordinate the exchange.

Based on these scientific pillars, CogLaboration is developing a prototype robotic platform for human-robot object exchange and evaluating its validity and reliability in terms of performance and user experience. The underlying technical objectives are:

1. To develop a set of vision modules to provide to the robot controller with the necessary awareness of the situation, including the perception of the human partner and the object of interest.
2. To develop an advanced robotic hand equipped with compliant fingers providing sensing capacities to enhance the perception of the object handover
3. To demonstrate robotic implementation of fluent object exchange in realistic industrial and domestic settings including typical task variation and unpredictability
4. To provide practical benchmark tasks of object exchange and evaluation criteria that can be used by the community to evaluate related approaches and future developments.

2.2. Main achievements

WP2: Cognitive Principles of Human-Human Collaborative Object Exchange

Two robot assistance scenarios are being used in the Coglaboration project; assistant to a car mechanic who is working in lying or standing postures requiring various tools and assistant to a seated or standing elderly person who needs objects for activities of daily living (ADL). Major achievements in the second period of the project in WP2 have included quantitative and qualitative characterization of the ADL task. Quantitative analyses have included an account of the tendency for two people to copy aspects (eg speed) of each other's behaviour during object handover in the car mechanic task when handing objects to each other, a mathematical formalization of grasp postures for the ADL task, and descriptions of grip force control during the handover task. Qualitative analyses of the handover task included ratings data obtained in the ADL task. These showed that the use of unusual locations or postures at handover have a negative impact on user experience which is unaffected by standing or sitting or by who initiated the handover. A questionnaire survey comparing Northern and Southern European elderly respondents shows both recognize potential benefits of robot assistance, particularly in the kitchen but with a cautious approach to handovers, in a similar manner to how they would engage in handover actions with a child. Interestingly, Southern Europeans were found to be more inclined to use both hands in handover tasks.

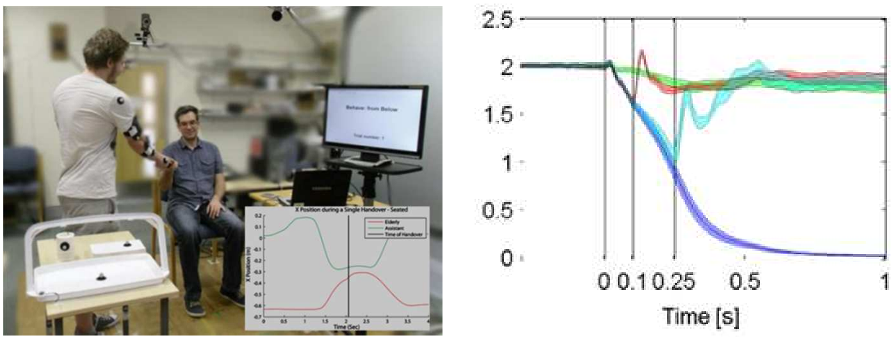

Figure 1. Left: Left: example of Human-Human handover. The tracked trajectory of the participants hands are shown on the bottom right of the figure. Right: time course of the forces recorded during the handover task

WP3: Scene and situation understanding

In WP3, the vision system has been redesigned and improved to make it more efficient and reusable, having one different component for each task of the perception pipeline, and a facade to centralize the communications of all these components with the rest of the system. The object pose estimation has been implemented using several approaches, including *i)* RANSAC initial alignment *ii)* Iterative Closest Point and *iii)* Correspondence grouping using Hough voting.

Regarding the human perception, the most efficient tracking of the human hand has been obtained with a combination of colour filtering in different spaces. The localization of the human hand is on its own an input data for the cognitive controller. The hand location along time is also used for detecting the main events of the interactions, such as the movement start or the reaching of the exchange location. We implemented a human behaviour analysis to detect such events that permit to get the robotic system reactive and synchronized with the human partner.

The hand location is also used for the recognition of dynamical and static gestures. We implemented a gesture recognition based on Hidden Markov Models for the dynamic gestures and on Gaussian Mixture Models for the static gestures. Static gesture recognition are used in R→H exchanges to deduce from the recognized hand posture the way the robot should deliver the object to the human partner. Gesture recognition has been validated on standalone applications, and the static gesture recognition has been embedded within the overall robotic system.

Regarding the object knowledgebase for the project, the final data model was designed and implemented. We explored the concept of object affordances within the task of modelling the object ontology, classifying the object's classes according to their grasp area, as humans are used to grasp them. Also, we complemented the data model with more specific information, describing attributes of these affordances that will contribute to a better situation understanding. We have worked on the knowledgebase in close collaboration with the partner in charge of the control system architecture (WP4), taking their specifications and expectations in mind, by means of an iterative process, performing continuous integration and validation during the whole development phase, which led us to the envisioned object handling knowledgebase. During the integration phase of the knowledgebase, there were several issues that requested some additional efforts that led in innovative actions and improved the value of this component within the whole system, including *i)* a handling strategy assessment module, used by the knowledgebase's reasoning engine for assessing the suitability of a proposed strategy for grasping or delivering any object *ii)* a handling strategy simulation tool, which served us for pre-visualizing the strategy to be executed by the robot before performing it effectively and *iii)* a web-based application, serving as front-end for the knowledgebase datastore, in order to ease the data management tasks and automate the object data characterization process. Finally, the knowledgebase module was successfully integrated evaluated when working jointly with the perception and cognitive control systems.

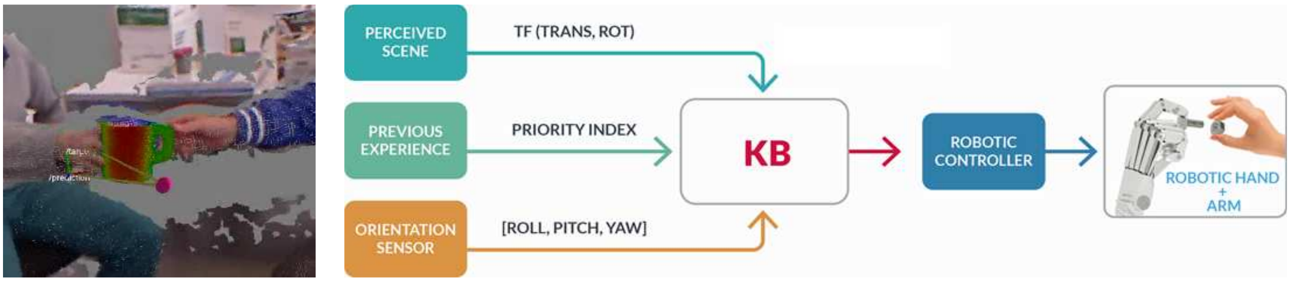

Figure 2. Left: Dynamic object pose estimation. The sensorized object (a coffee mug in this example) is exchanged between two human subjects. The perception system delivers the object location within the scene and the estimated pose. Thanks to the orientation sensor, higher precision levels are achieved. Finally, those inputs are provided to the knowledgebase reasoning engine (right), which uses them for suggesting the most suitable strategy to be executed by the cognitive control system.

WP4: Design and implementation of a control architecture based on concepts from cognitive neuroscience

In WP4, we have modified the control law based on the bio-inspired DMP framework to handle the main limitations observed during the first experimentation. We have proposed an action plan definition that takes into account the physical and dynamical limitations of the robotic arm being used, to make sure that the plan to reproduce is effectively achievable by the arm, by the introduction of velocity and acceleration constraints. We have incorporated a management of the previous exchange locations, so that the system can directly move towards the exchange site observed during the previous exchanges, while keeping the possibility to adjust online to a new exchange site. We have also implemented an action execution monitoring to detect early on any potential violations of the software velocity and accelerations limits defined, requested thus an online plan redefinition. Finally we have also added the possibility to handle object transport constraints and online adjustments of the grasping or delivery strategy, if the perception detects that the a priori strategy does not fit with the observed human expectation and object orientation. All these extensions have been studied and validated in simulation before being deployed onto the robotic platform for experimental validation performed in the framework of WP5.

The hand controller has been also extensively improved mainly to ease the extraction of the status of the hand and to provide to it more autonomous capabilities. The high-level and low-level layers have been extended to provide a direct access to the status of all motors with a single request, on demand or through an automatic streaming. A specific status has also been prepared for the grasping procedure, to make easier the understanding of the handover advancement. The access to the contact sensors in the palm and in the fingertips has also been included. Finally, an analysis of the forces observed during object handovers in a stand-alone prototype has also been conducted to detect the beginning of the handover as well as its different phases, with the objective to design an automatic grasping procedure.

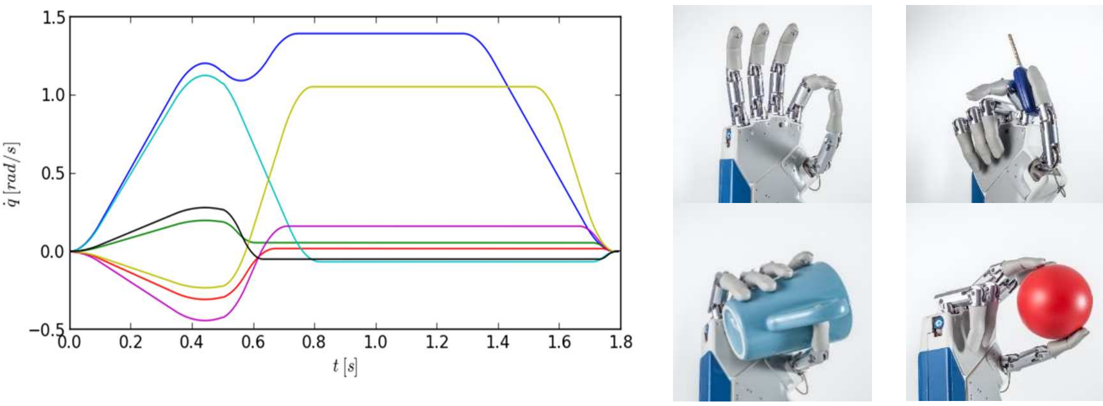

Figure 3. (left) Illustration of the robotic arm velocity variation when a motion plan switch is performed online (at t=0,5) (right) illustration of the various hand grasping modes implemented onto the hand.

WP5: Artificial Cognitive Systems Integration

In WP5, we have integrated the different hardware components with their related software modules developed within WP3 and WP4 to get the final prototype. The latest tactile and force sensors developed for perceiving contact information onto the hand have been inserted into the hand, and the hand driver has been updated to deploy such added information to the ROS environment into which the global system is handled. The latest developments for the perception and the system control have been deployed onto the robotic system equipment and the communication interfaces have been actualized to get all these different modules interacting accordingly to the application needs. The integration of these different components has been experimented and validated through the automatic acquisition of static object and through the realization of pilot interactions between the robotic platform and human operators. The recorded logs have permitted to improve the general behaviour during the lifetime of the Work Package, to get the final prototype that has been later on evaluated through interactions with 10 Tecnalia staff subjects and 5 elderly persons, in the context of Work Package 6.

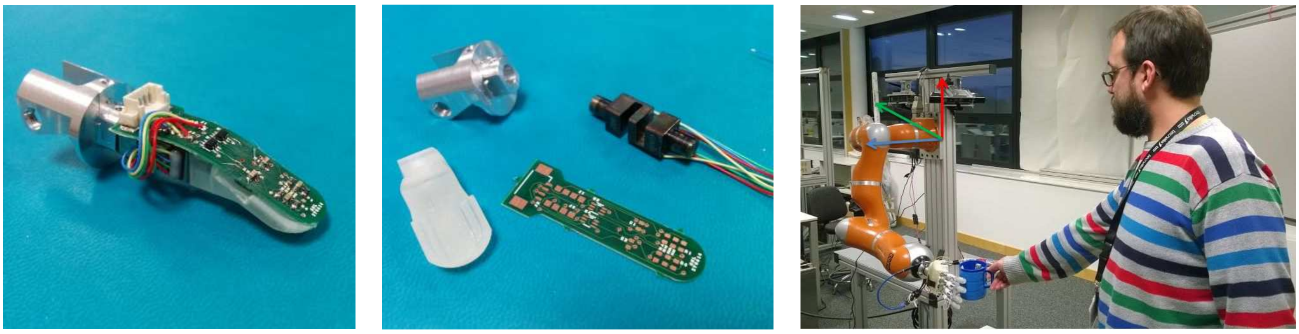

Figure 4. (left & middle) fingertip tactile sensors mounted onto the hand (right) object interaction in between an operator and the robotic arm

WP6: Artificial Cognitive Systems Evaluation

In WP6, we first designed and then performed evaluation on the two main prototypes developed by WP5 within the CogLaboration project. The evaluation centred on the actual passing task itself, rather than evaluating the performance of the individual sub-system components, although it is fairly obvious that these have to be working well in order to achieve a high quality and fluent passing behaviour. The evaluation of the first prototype investigated the correct functioning of the prototype, and highlighted its achievements in terms of ability to sustain multiple handover for a prolonged time (7 hours), and usability in performing handovers under three different experimental setups belonging to a car mechanic scenario (engine bay, lying under the car, hydraulic lift) . Moreover, it compared Human-Robot (HR) interaction with Human-Human (HH) interaction providing correlations between the quantitative features of the interaction and the users' preferences, gathering insights on what to improve in the final prototype. The second evaluation confirmed the achievements obtained during the first evaluation and tested the usability of the system, validating its improvements in a domestic setup, both on elderly users and younger adults. It therefore provided guidelines on the how to improve the system depending on the population of interest.

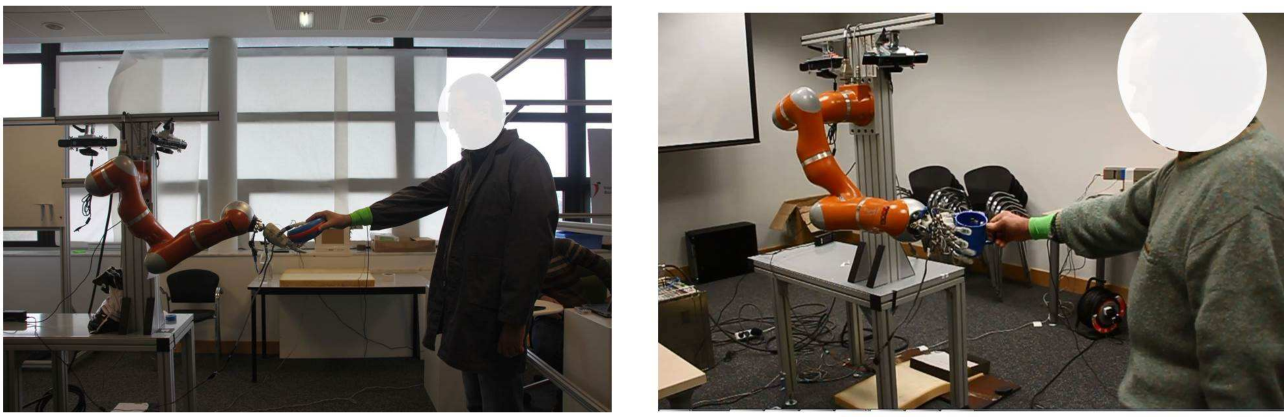

Figure 5. (left) HR Experimentation with Tecnalia staff (right) experimentation with elderly subjects.

WP7: Dissemination and Exploitation

With regard to the project in its entirety, the project has achieved a major step forward with regard to the achievement of fluent transfer of objects and people, as well as developing products with near-market exploitation potential. The major step forward has been in terms of the development of a demonstrator at TRL 5-6 of the principles of fluent transfer, together with a body knowledge collected from human trials that underpin those principles. In terms of products with short term exploitable potential there are at least two, these being:

- The fingertip which human-like qualities from SSSA. This has potential to be used in both artificial robot hands and in human hand prostheses to increase the sensitivity and stability of grips and is already being used by Microsoft to test the durability of their new "surface" product to prolonged usage (such is the similarity between the SSSA fingertip and the real thing).
- The object sensor developed by RUR which has the potential to become a 'standard' instrumentation device for tracking object movements in both robot oriented and human oriented trials, and indeed in any further human-robot trails. The cost-effective package is available in both a stand-alone mode with on-board data collection of in a real-time mode with data streaming over blue-tooth. Together with the data analysis software this has the potential for supporting a wide range of instrumentation tasks. The touch sensor inputs increase the range of flexibility of this product and could be modified in future versions to accommodate almost any type of analogue inputs.