PACO-PLUS
Perception, Action & Cognition through Learning of Object-Action Complexes

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***Abstract*— This communication contains excerpts from the PACO-PLUS proposal to the EU, giving a detailed overview of the project, and depicting the contribution from IRI. The PACO-PLUS project aims at the design of a cognitive robot that is able to develop perceptual, behavioural and cognitive categories in a measurable way and communicate and share these with humans and other artificial agents. Objects and Actions are inseparably intertwined; the so-called Object-Action Complexes are the building blocks of cognition.**

***Index Terms*—PACO-PLUS, object-action complexes.**

I. Introduction

The objective of the PACO-PLUS project is to develop a new principle and methods to endow an artificial robotic system with the ability to give meaning to objects through perception, manipulation, and interaction with people. The paradigm of Object-Action Complexes, which is at the core of the project, will be investigated to address hard problems such as learning, decision making, and memorisation for situated agents. An anthropomorphic robotic platform will be designed to validate the proposed approaches. The ultimate goal is to provide an artificial system with higher-level cognitive abilities than state of the art systems proposed in AI and robotics. As such PACO-PLUS addresses the basic issues of the EU IST call on Cognitive Systems, which are to develop artificial systems that can interpret data arising from real-world events and processes, acquire situated knowledge of their environment, act, and make or suggest decisions and communicate with people on human terms.

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II. Project Overview

The successful design of a cognitive system must rely on a theoretical and measurable basis which on the one hand applies to humans and on the other hand to an artificial system, ultimately allowing for its construction. PACO-PLUS aims at the design of a cognitive robot that is able to develop perceptual, behavioural and cognitive categories in a self-emergent and measurable way and communicate and share these with humans and other artificial agents. PACO-PLUS brings together a consortium of robotics researchers, engineers, computer vision scientists, linguists, theoretical neuroscientists and psychologists, which is reflected in the management organization. Central to the approach are three almost axiomatic assumptions which are linked to each other and which are the building blocks of a new approach required to create cognitive artificial agents:

- Objects and Actions are inseparably intertwined; the resulting, so-called Object-Action Complexes are the entities on which cognition develops.
- Cognition is based on self-emergent recurrent processes involving nested feedback loops operating on and re-interpreting object-action complexes. This is done while actively closing the perception-action cycle which involves the loop through the environment.
- Unified measure of success and progress exist through minimization of contingencies which an artificial cognitive system experiences while interacting with the environment.

To demonstrate the feasibility of our approach we will build robot systems with advanced cognitive capabilities that operate in real-world scenarios and that are able to learn to interact and perform basic communication with humans:

1. a robot system to augment human action, and
2. a robot system that is able to explore and manipulate a limited set of objects in an unconstrained environment.

The project will run from February 2006 until January 2010, and has the following partners: Universität Karlsruhe (Prof. R. Dillmann, Dr. T. Asfour), Kungliga Tekniska Högskolan (Prof. J.O. Eklund), Universität Göttingen (Prof. F. Wörgötter), Aalborg University (Prof. V. Krüger, Prof. N. Krüger), Jozef Stefan Institute (Prof. A. Ude), Leiden University (Prof. B. Hommel), University of Edinburgh (Prof. M. Steedman), ATR Computational Neuroscience Laboratories (Prof. M. Kawato, Dr. G. Cheng), and Institut de Robòtica i Informàtica Industrial CSIC-UPC (Prof. C. Torras, Dr. J. Andrade-Cetto).

III. The approach and its general objective

PACO-PLUS aims at the design of a cognitive robot that is able to develop perceptual, behavioural and cognitive categories in a self-emergent and measurable way and communicate and share these with humans and other artificial agents. The main paradigm of PACO-PLUS is that Objects and Actions are inseparably intertwined and that categories are therefore determined (and also limited) by the action an agent can perform and by the attributes of the world it can perceive; the resulting, so-called Object-Action Complexes (OACs) are the entities on which cognition develops (action-centred cognition). Entities (*things*) in the world of a robot (or human) will only become semantically useful *objects* through the action that the agent can/will perform on them. We note that other agents can here take the role of an *object with active properties* without violating the general ideas as shall be detailed below. Objects are not just "things" upon which active agents act, but may be able to execute their own actions. Thus each active agent is just another instance of an OAC. This paradigm of OACs offers two novel key issues which will assure that a system with advanced cognitive properties can be developed.

A. Continuous path to cognition and language

We will demonstrate that the concept of OACs leads to a natural and uninterrupted (continuous) path from early perception-action events towards complex cognitive properties as well as to the development of language by the following, here abbreviated steps.

1. As explained above, Object-Action complexes are categories with inherent semantics. The modification of OACs through exploration, interaction and learning leads to new OACs (novelty, creativity).
2. The combination of OACs to more complex ones can be seen as an internal, implicit reasoning process leading to higher levels of abstraction and more abstract categories.
3. The sharing of the same OACs between human and agent through their interaction will set the basis for the development of shared, hence mutually grounded, symbols (e.g.; replacing an action on an object with a *pointer* to it that both understand.
4. The making-explicit of these symbols will create a simple language (ranging from signs to verbal).
5. Shared language developed from shared symbols which came from shared OACs will allow for explicit reasoning and communication; creating an advanced cognitive human-robot interaction system. We believe that this path will allow us to approach the signal-symbol problem in a rather fundamental way (how to arrive at meaningful symbols from bare signals).

B. A unified measure of success and progress

As opposed to all existing other approaches the concept of OACs (and their natural extension into the symbol/language domain) offers the advantage to formalize a general measure of success. Following their drive/motivation, agents will either seek to minimize disturbances which arrive at them from their environment, or they will actively seek to maximize some kind of reward. PACO-PLUS will develop a measure to quantify the success in disturbance minimization and/or reward maximization using the same evaluative functions at all stages 1-5 above. The process of decision making and planning, which is vital to cognition, can now be phrased in terms of how to bias the evaluating functions with respect to the context provided by environment and internal states (intentions, drives) of the agent.

IV. Humanoid Robotics

The central assumption behind our approach is that the conjoint application of Key Issues A and B will lead to a gradual, continuous and controlled emergence of cognitive properties in a process of interactions with objects and other cognitive agents by means of shared categories. Since these categories are limited by the action of agents, it is of central importance for the project to investigate how they can develop on a sufficiently complex anthropomorphic robot. Anthropomorphism is desirable because it makes interaction easier and also supports the transfer of ideas from psychology and neuroscience to robotics. Hence PACO-PLUS will undertake the development of a richly integrated robotic system with humanoid traits to support interaction with people. The theoretical assumptions which underlie this approach are that OAC representations shared between humans and the robot will lead to mutually grounded symbols facilitating language development.

V. Specific Objectives

These are centred on the notion that objects and actions cannot be separated (object-action complexes, OACs), because objects can induce actions (cup $\rightarrow$ drink), while actions can redefine objects (the action, or action-plan of putting something on top of something redefines an upside-down cup as a pedestal).

- Sensor: Design and implement a real-time computer system to process the incoming sensory information allowing explorative and interactive processes for OAC learning. Distributed and asynchronous computations will be used to ensure real-time operation of the system when learning higher-level OACs, i.e., more complex cognitive behaviours.
- Motor: Define the atomic action repertoire that is needed for the chosen scenario and design a motor control system based on established neuronal or other appropriate control algorithms. Calibrate the system's body through learning of the representations of its own actions.
- Motor (Sensor): Design and implement basic oculomotor primitives on a humanoid head and integration with real-time vision.
- Sensor-Motor Coupling: Define the mapping and context-dependent adaptation of the sensor representation of OACs (or the sensor representation of actions) to the robot motor control system.
- Memory: Endow the system with an adaptive, map-like structure in space-time on which it can by itself implement generalised representations ("categories") of OACs by means of network- and reinforcement learning techniques partly based also on imitation learning.
- Internal representation and memory: Define the relation between its own motor actions and the representation of OACs.
- Framework for measuring performance and success: Develop a formal representation scheme which can be used to represent and analyse actions while considering the uncertainty in the real-world. Base this on and extend theoretical neuroscience results on contingency minimization in neuronal systems. Bring this together with methods for goal directed learning based on return-maximization to create a conjoint measure for learning success. Employ this measure of success to all stages of sensor-motor matching, learning as well as decision making and planning.
- Early Communication: Define interaction as the process of action continuation of someone else by anticipating the other's actions from interpreting OAC categories. Communication takes place through direct demonstration and through verbal instructions.
- Advanced Communication and Language: Define the relations between generalized OAC-categories and the intended action-substitution mechanism. From this develop compositional language which leads to advanced communication.
- Learning: Investigate correlation based as well as reward based neuronal learning algorithms. Implement advanced Actor-Critic modules in a chained way to allow for action sequence learning. Modify the learning outcome by "motivations" as well as "context".
- Decision making: Derive a brain-like distributed representation of the central processing streams, including motor-planning and reasoning (decision making).

VI. Research, technological development and innovation activities

The implementation plan is centred on seven highly relevant and timely scientific problems, which define the key research activities (KRA1 - KRA7) of the project. These seven key research activities are:

- KRA1. Representation of "Things" and Actions
- KRA2. How OACs arise?
- KRA3. How OACs evolve?
- KRA4. Language, Communication and Interaction
- KRA5. Memorization, Learning and underlying theoretical concepts
- KRA6. Decision Making and Planning
- KRA7. Cognitive Robotic Systems: Integration and Control Architecture

In KRA1 we will develop the sensory representation of "Things" through peformed actions. While initially being an abstract THING (just a physically existing entity without meaning) to the agent, such a THING turns into an OBJECT through the actions it is involved in. Objects are only seen in their action context. The robotics scientists will provide an initial repertoire of sensory-motor primitives based on the biological basic motor acts. This will be the motor representation that is intrinsic to the robotic agent and will enable the agent to execute initial exploratory movements, thus providing it with the ability to acquire sensory representations of objects. We note that action becomes the context of an object, which constrains the object recognition problem and which finally gives a meaning to the object.

In KRA2 we will create first "early" object-action complexes. The formal representation of OACs will be built around three complementary hierarchical representations: stochastic grammars, probabilistic action trees and dynamic belief networks. These formalisms will allow us to combine objects and actions into meaninguf entities. The representations of OACs in KRA2 will in general be multi-sensorial. We shall design learning algorithms to acquire early OACs and define various processes on them, e.g. recognition. Furthermore, we will investigate how an action is encoded when it is physically carried out by a different agent. This will allow deducing motor information from visual sensory input and matching of sensory representations of actions to the agent's own motor representations. This process will be of vital importance for our applications on augmenting human action. Through information encoded in OACs, complex actions on objects can be generated and executed by the robotic agent.

In KRA3, we will address the aspect of how more complex OACs can arise from the early OACs and how during this process Novelty and, hence, Creativity occurs. This will be achieved by realizing that OACs are not single points on the surface of object and action representations. Instead we will implement these representations as a continuum. As a consequence we can now implement explorative mechanisms by allowing the system to travel along this continuum under a set of contraints given by the robot hardware and by general contraints such as Gestalt principles. This way PACO-PLUS will be able to try out new (contrained) combinations of actions on objects leading to novelty and creativity. Furthermore, a continuous OAC space will allow a more guided exploration of action space to allow for emulation of actions as well as for planning and anticipation of the robots own actions and activities.

In KRA4 we are concerned with interaction and communication. Interaction will be defined in two steps: 1) as action continuation of a recognized action and 2) as complementary action leading to true interaction. Action recognition has become possible through KRA1-KRA3, where we were concerned with self-actions (Sensor-Motor Matching). In KRA4 we are also concerned with the actions of others. Thus, we will perform a similar sensor-motor matching, however, viewing the other here. As a consequence, the system will be able to interpret intentions. Communication will also arise in two steps: 1) As action replacement, where a sign replaces a recognized or planned action and 2) as compositional language where such signs will finally be combined. We note that a sensor-motor repertoire has been developed which is shared between the PACO-PLUS system and its observers (otherwise action recognition would not be possible in the first place). Thus, action replacement will lead to signs that are fundamentally grounded in the shared sensor-motor repertoire of PACO-PLUS and its observer. Combinations of visual or spoken signs form a simple precursor of compositional language.

In KRA5 we will address the theoretical background trying to arrive at results that can directly be used to guide the PACO-PLUS design. We will address different learning and inference techniques and how they can be used to build the anticipatory components of PACO-PLUS. We will derive measures for predictability, complexity and contingency in the context of a closed loop perception action system. And finally we will address the question of a useful system's theoretical approach towards a closed loop perception action systems, where the environment is considered to play an active part, e.g., active through the action of others.

In KRA6 we will address the problem of how to drive an agent to both minimize contingencies and to maximize rewards in the presence of uncertainty. At the low level, we will address the issues of nonlinear estimation and nonlinear control in a time efficient manner in order to be able to close the low level perception-learning-action loop. At a higher level, we will address the development of novel decision making and planning algorithms in the context of OACs for continuous perception and action spaces.

In KRA7 we are concerned with the hardware aspects. Here we address hardware design issues, integration and architecture aspects. This KRA will coordinate the building of the applications. Several highly relevant engineering aspects concerning the problem of haptics, vision and sensor-motor coordination are being addressed. Furthermore, KRA7 will provide a hardware and software architecture that allow the integration of developed methods and algorithms into a cognitive robotic system, possibly including parts that operate concurrently and asynchronously on different sub-tasks, for instance, perception, action, reasoning and communicating.

VII. Scenario and Applications

In the project we will build physically instantiated systems that will be able to (1) recognize, (2) categorize, (3) act, (4) interact, (5) co-operate and (6) communicate with an observer, where every step recursively influences its predecessors. The base-system will be developed as a cognitive agent that is equipped with an active stereo camera head (colour cameras), a human-like dual-arm system with two sophisticated five-finger hands and tactile sensors (haptic and proprioceptive inputs). The system will also be equipped with microphones ("ears") and with a state-of-the-art speech output device for language generation. The system will experience the use of objects it is confronted with by exploration, imitation and creative construction. Based on these methods it will learn to perform complex actions on objects and also to predict the consequences of its actions. This leads to the ability to plan and recognize more complex action sequences. Thus, the agent recognizes and categorizes momentarily existing OACs according to their meaning. This will allow it to select appropriate actions with the goal of continuing an observed action sequence in a meaningful way. We shall demonstrate these abilities by implementing two scenarios:

- Generation of OACs for objects of everyday life, such as cups, bottles and pens will be demonstrated in two complementary ways: the robot can either be the observer or the actor of an OAC. When observing a human performing an action on a specific object, the robot has to be able to understand what the "thing" is (e.g. a cup), what the action currently being performed with it is (e.g. drinking), whether this action is an element of the set of actions that is associated with the observed thing, and whether this action can be mapped on it (the robot) or not. When performing actions on objects, the robot has to demonstrate that it can perceive and understand things (e.g. a bottle), i.e. know the actions that can be performed on it (e.g. a bottle is used for keeping fluids and for directly drinking them or pouring them into other containers for fluids) and execute these actions if possible.
- In the case of human activity, OACs become human object-action complexes and the actions are on the level of body movements that may or may not involve objects. While actions involving objects are covered in the described generation of OACs for everyday objects, here we define two tasks which demonstrate that the robot has the ability to perceive and understand the postures and movements of a human - with and without relating meaning to them. In this scenario the robot has to watch a person performing various movements and to imitate the movements either synchronously (i.e. visual perception has to be performed in real-time) or after a short delay. If the robot recognizes one movement as an action, such as waving, it can choose to perform its stored movement for this action, i.e. imitate a movement in its own style. To demonstrate that the robot has understood the movements of the human not only in terms of his own kinematics but is able to map them to other human-like models as well, he will configure the arms and legs of a human-like doll according to the posture of the observed human at a specific time step.

The system will interact with humans on different levels from the beginning. It will be able to co-operate with other agents and finally derive articulation. First communication skills shall arise from the agent being able to "suggest" a possible action-continuation to the observer, instead of performing the action-continuation by itself. This shall be done by means of action-substitution where a possible action-continuation shall be replaced by a symbolic action ("symbol generation") which the observer can read as a pointer to the intended action-continuation. The base system will operate in a workshop/toolkit scenario. This scenario makes object and action understanding, co-operation and communication and decision making necessary when wanting to construct something. In addition it allows for creativity to occur, because construction may take place without a predefined goal.

VIII. The robot platform of PACO-PLUS

We choose an anthropomorphic system as an experimental platform because - due to their similarities with people - humanoid robots are good at imitation learning and interaction with people. The humanoid robot ARMAR, which was built by UniKarl, will be made available for experiments in the project. The robot has 23 mechanical degreesoffreedom (DOF). From the kinematics control point of view, the robot consists of five subsystems: Head, left arm, right arm, torso and a mobile platform. The upper body of ARMAR has been designed to be modular and lightweight while retaining similar size and proportion as an average person. The head has 2 DOFs arranged as pan and tilt and is equipped with a stereo camera system and a stereo microphone system. Each of the arms has 7 DOFs and is equipped with 6 DOFs force-torque sensors on the wrist. The mobile robot platform of ARMAR consists of a differential wheel pair and two passive supporting wheels and is equipped with front and rear laser scanner. Furthermore, it hosts the power supply and the main part of the computer network.

A new anthropomorphic five-finger hand (see Fig. 1) equipped with an advanced tactile sensing system will be used for manipulation and tactile sensing. In this way we shall provide richer perceptual input and more advanced manipulation capabilities for exploration, learning and interaction. To enable learning of object-action complexes and human-robot interaction, we will first concentrate on the development of an advanced anthropomorphic robot platform and its innate sensory-motor primitives. Since the ability to sense is of greatest importance for learning and interaction, we will pay special attention to the development of a humanoid head for foveated vision. This will be realized by providing each eye with two cameras, one with wide-angle lens for peripheral vision and one with narrow-angle lens for foveal vision (related systems: DB at ATR, Japan, Cog at MIT, USA, Infanoid at CRL, Japan). Since comparable products are not commercially available, we shall develop our own binocular head with foveated vision. The visual system will feature humanlike characteristics in motion and response, that is, the velocity of eye movements and the range of motion will be similar to the velocity and range of human eyes. The head will be designed as part of an anthropomorphic platform that will allow for the integration of motor control and perception.

Fig. 1. Model of the proposed new robot head with two cameras for each eye (left), prototype of the five-finger FZK-hand (middle) and the humanoid robot ARMAR (right), Universität Karlsruhe.

This is essential to get the objects into the fovea, thus enabling explorative head, hand, and body movements for learning of OACs.

IX. Synergies and Exchanges with other IST Cognitive Systems Projects

The project PACO-PLUS is related to a number of other projects funded under the Framework 6 IST Cognitive Systems call, including the IPs COSY, JAST, and RobotCub, and the STREP COSPAL. The closest of these is COSY. The emphasis of COSY is more on high-level faculties, and social interaction and evolution. PACO-PLUS emphasises lower-level neural mechanisms, and can be seen as providing a machine-learning foundation for COSY's assumptions concerning low-level linkage of sensory-motor schemata to interactive language.

We anticipate many synergies with the COSY project. PACO-PLUS offers a formalisation for the notion of affordance assumed in COSY. Members of the PACO-PLUS consortium took part in the COSY-sponsored workshop on Representation and Learning in Robots and Animals, held as a tutorial at IJCAI 2005, and gave an invited presentation on the language-grounding aspects of the PACO-PLUS project. Many synergies were apparent.

Considerable synergy is also to be anticipated with JAST, which has a strong emphasis on dialog and assembly of relatively complex structured objects, makes similarly strong assumptions about preexisting communicative and sensory-motor structures of the kind that PACO-PLUS seeks to provide. A dialog group in the linguistics department at the University of Edinburgh is involved in JAST and there are strong links between PACO-PLUS and JAST language groups -in fact, EDIN is named as a possible collaborator in JAST under WP7.

RobotCub is a project with a similar view of the insights to be gained from neuroscientific data, but with a greater emphasis on the developmental emergence of cognitive skills through manipulation, imitation, gestural communication and without the link to language and communication that is proposed in PACO-PLUS. Members of the PACO-PLUS consortium (UniKarl) took part in RobotCub meetings and were invited to the First RobotCub open day. Synergies in building of bodies that can be used as a tool to study cognition are apparent. COSPAL is more specialized towards neural network computation of sensory motor schemata, again without the inclusion of the language element. The PACO-PLUS consortium is deeply interested in the results of these rather different approaches, and will seek to exploit their results, but at present the projects seem complementary.

We see similar synergies with the ESF funded project of Luc Steels and colleagues, and other projects discussed in the body of the project. Communication between these projects will be facilitated by the euCognition Network for the Advancement of Artificial Cognitive Systems Coordination project, which PACO-PLUS expects to join.

X. The Role of IRI in PACO-PLUS

Researchers from IRI will lead the Key Research Activity 6: Decision making, planning and evaluation. To this end, they will work closely with colleagues from BCCN and UniKarl. The core goal is to arrive at a module for decision making and planning.

Furthermore, IRI also colaborates in other Key Research Activities within the project. Specifically, in KRA5 with new categorization mechanisms in reinforcement learning; and in KRA7, with neural network models for the computation of robot inverse kinematics.

A. Scientific key issues we will address in KRA6

- How to decouple perception from action uncertainties?
- How to design low level control laws from uncertain estimation of OACs?
- How to keep an ever increasing representation of OACs tractable?
- How to supersede low level drives? How to naturally establish high level exploration goals?
- How to apply decision making techniques in the context of the OACs?
- How to measure goal reach?

B. Specific tasks related to this key research activity

- Planning I. The task is to show that motor planning capability can be induced from physically learned OAC schemata together with the simplest kind of limited-horizon forward-chaining reactive planners, exploiting the state of the world and the knowledge of others as resources.
- Plan Recognition. Reactive planning will be characterised by search in a limited space of possible situations generated by the affordances of the objects and agents available in the current state or context.
- Planning II. Assessment and improvement of the above Planning I phase.
- OAC Dynamics: Devise and test nonlinear functions for each of the feature dynamics, paying special attention to the temporally invariant features that are best used for OAC categorization.
- Stochastic decoupling of perception and action. Nonlinearly propagate OAC probabilities. Develop novel algorithms to decouple uncertainty between perception and actions within OACs.
- Decision Making: Develop new algorithms for planning in continuous state spaces generalizing the standard Markov decision process framework.

C. Measuring Success

By month 12 we will be able to demonstrate the stochastic decoupling of perception and action in the mobile robot.

By month 24 we will have designed an incremental mapping of OACs into a tractable space-time representation. This is an algorithmic data structure. These scientific findings should lead to two scientific journal publications: a) dealing with the augmented OAC space-time representation, and b) with the coupled nonlinear estimation and control OAC algorithms.

By month 36 the continuation of this work and the foreseen deliverable beyond month 18 will lead to a module for iterative and concurrent low-level estimation and control with OACs.

At the end of the project we expect to have arrived at a decision making module on top (and compatible with) the low-level estimation-control module from months 12 and 24.

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