

Cognitive Systems Research in Europe

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1. Introduction

Animals know how to deal with an uncertain world. Everything around them is largely unknown for them, but still they manage to cope. How? They perceive their environment and learn from experience; they adapt to changing circumstances, anticipate the outcome of events and act to achieve their goals. In other words, they are cognitive, because that's Nature's way for dealing with uncertainty.

We want our artificial systems to be just like that. That's why **robotics must become cognitive**. We want industrial robots to be safer, more effective and faster to deploy in the **factories of the future**. And we expect humanoid robots to **step out of the lab**, cope with the real world and **interact with humans** in a safe and helpful manner. Cognitive systems are the only systems that will actually achieve that. Both the future industrial hand robot and tomorrow's robot for therapy will be cognitive systems.

Many scientific disciplines ranging from engineering to philosophy, share the mission of understanding and building cognitive systems. But every research activity works on parts of the whole solution. Cognitive Systems Research (CSR) integrates all this research. It is **Europe's approach** to building the artificial systems of the future, an ambitious research program that is defining the way forward to build intelligent adaptive systems that can serve society in a variety of ways.

2. Resources

2.1. Interactive Community Map

<http://www.eucognition.org/index.php?page=impact-cognitive-systems-research>

2.2. Timeline of Cognitive Systems Research projects funded by the European Commission

<http://www.eucognition.org/index.php?page=impact-cognitive-systems-research>

3. Europe is Big on Cognitive Systems

Today's Europe's vibrant and respected Cognitive Systems Research community is due in no small part to the European Commission foresight and leadership. 10 years of funding by the European Commission have enabled an ambitious research program that could not be developed in a more conservative funding framework. That's because designing artificial cognitive systems requires bringing together wide

spectrum of disciplines like neuroscience, developmental psychology and Artificial Intelligence in order to provide solutions when other approaches fail. Dozens of labs and university departments have had the opportunity to think big, develop basic research, explore various approaches to develop artificial cognitive systems and find some very promising ones. In this decade the community has been bridging the gap from theory to application and now is ready to sit with industry and offer novel solutions in various fields.

4. Robotics must become cognitive

The cognitive systems community has been pushing this message since its very beginning. And now even robotics industry major players are agreeing on this. There is only so much you can achieve with old school robotics and that's not only true for socially interacting robots, industrial applications also must have cognitive capabilities. Because outside the safety yellow cages where industrial robots now operate information is scarce and unreliable, conditions are not so well defined, objects behave in an awkward way and unexpected things can happen. The real world is all about uncertainty and only cognitive systems can cope with it; no pre-programmed system will be able to anticipate, adapt and learn in an unknown environment.

Cognitive systems research goal is to deepen our understanding of issues like learning, memory, prospection, knowledge, autonomy or development in both natural and artificial systems. But we must not think that these are only to be applied to humanoid robots interacting in social environments. Cognition is also important for industrial robots because it is the way forward to make these devices more safe, more effective and faster to deploy in the "factory of the future". Every concept researched in cognitive systems is essential to design the industrial robot controller of the future.

And when we factor interaction with people into the requirements of the systems, cognition then becomes even more important. Why? Because people are cognitive and they behave in a cognitive manner. Any agent that interacts with human needs to be cognitive to some degree for the interaction to be useful and helpful. People have their own needs and goals and we would like our artificial agent to anticipate these. That's the job of cognition.

4.1. The robot hand of the future

The Cognitive Systems Research community is leader in grasping and manipulation research. There are 10 labs dealing with manipulation and several EU projects has tackled the issue from different perspectives (PACO+ STIFF, VACTORS, THE , PACMAN, GeRT, GRASP, CloPeMa, DARWIN) and they all have contributed to the open problem of object grasping and manipulation by robotic arms. Simple 2-finger grippers are out there but industry needs far exceeds the commercial products available. For example mobile phone industries have processes that require a hundred steps that must be performed by a human. A dexterous machine solution would help bring back industries to Europe.

Advances in CSR have led to more powerful, non-trivial grasping and manipulation capabilities, i.e., the handling of “soft” materials such as fabrics, textiles, and garments (with two arms, CloPeMa project) and paper. Grasping consists of sub-problems such as affordance, intention, hand-eye coordination, and compliance, which can be helped by improved vision systems (as used in PACO-PLUS). Another important manipulation task, especially in production lines, is assembly (addressed e.g. by DARWIN).

5. EU projects drive Cognitive Systems Research

4 European projects pioneered the research in cognitive systems: COSY, CogX, PACO+ and ROBOTCUB. The research groups involved in these projects transformed the new ideas emerging from cognitive science about how the mind works into actual engineering solutions to make robots faster, more efficient and more autonomous. These 4 projects cover the three different paradigms in which cognitive systems research is built: cognitivism (COSY, CogX), emergent (ROBOTCUB) and hybrid (PACO+). The jury is still out on which of the paradigm is the best, all of them have their strong and weak points. But all of them have advanced the design of autonomous systems and the outcomes of the projects can be traced to today’s research, and more importantly, to today’s technology transfer.

5.1. CogX

CogX developed a technological architecture called CAST that integrated the different aspects we expect cognitive robots to have: mapping, planning, manipulation, vision... CAST has been then included into the ROS repositories and has been extended with grasping and object manipulation solutions from other EU projects (GeRT, PACMAN). Overall CAST has been gradually upping its TRL to 4/5

and is now advanced enough so that a variety of practical demonstrators are being built together with different industry partners:

1. Security patrols for office buildings (STRANDS project, G4S Technology ltd.)
2. Robot companions for patients with dementia in care facilities (STRANDS Project, EEF)
3. Automatic logistic planning (UK company)
4. Object recognition and tracking for police surveillance cameras (UK police)
5. Solution for a safer and cheaper nuclear waste management in the UK (UK company)

5.2. PACO+

PACO+ developed a novel engineering approach for object categorization. It was no longer based on the old paradigm of computer vision (see an object to recognize it) but on the “affordances” concept of cognitive science (objects as opportunities to act in the world). "Object-Action Complexes" (OACs), as the solution is called, are recognized worldwide by the scientific community and new projects are developed in order to extend them and apply them to practical solutions.

1. Robotic companies like KUKA or ABB that now form the Industry part of the robotic PPP are preparing calls to apply the grasping algorithms developed in PACO+ and follow-up projects.
2. KUKA is considering including OAC's in the upcoming Sunrise Operating system.
3. OAC's have been applied in Grasp Learning for Industrial Bin-Picking in the ECHORD experiment LEARNBIP
4. The INTELLACT project is focused on finding applications of OAC's in industrial manufacturing.

5.3. ROBOTCUB

The iCub is one of the main achievements of the “cognitive systems calls”. More than 20 laboratories use it worldwide and its impact in research has crossed the boundaries of the cognitive robotics community, leading to close collaboration with developmental psychology babylabs in USA and Europe and cognitive neuroscience experts. This social impact has been achieved thanks to several projects that have contributed to enhancing the iCub

ITALK was the first follow-up project of ROBOTCUB and its objective was to enhance the iCub with complex behavioural, cognitive, and linguistic skills

through individual and social learning. It contributed to new versions of the iCub but it has also impacted other fields:

- ITALK was the first project where robotics and GPU were used together; the graphics card company nVidia uses iCub/ITALK as an example of the three directions the company sees as worth investing into: (1) robotics, (2) space data analysis, and (3) environmental sustainability.
- ITALK (along with other projects like CHRIS, ROBOSKIN) have made it possible for the iCub to enter psychology labs and develop whole new projects to understand & treat social pathologies (ALTEREGO, DREAM)

ROBOSKIN developed a large-scale robot skin that could be adapted to different robots, one of them was the ICub. ROBOSKIN showed that tactile information originating from the whole robot body provides insights into the cognitive processing that is necessary for robots to be safe and robust in the real-world. Thus ROBOSKIN contributed to the cognitive aspect of the ICub.

But it has also impacted other fields:

- University of Genoa is working on the complete sensorization of commercial and industrial robots with the Italian company THALES dedicated to space robotics and also underwater applications. They have a contract with them.
- IIT is trying to license the patent for non-robotic applications in collaboration with several companies (??)
- Project CLOPEMA is using ROBOSKIN solutions to deal with textile manipulation.

6. Stepping out of the lab.

To date, no one has designed and implemented a complete cognitive system. But the listed projects and their follow-ups show that cognitive capabilities are being introduced in different applications from humanoid robots to industrial applications. More than that there is an emerging understanding that cognitive systems are the only systems that will actually work in a world that is largely unpredicted, unobserved and uncontrolled. These are some of the projects that are getting their systems out of the lab.

6.1. Search & Rescue Robots

AIROBOTS

The AIRobots project, for instance, developed an inspection system that could both fly and interact physically with the environment. The result is a UAV that can touch

and manipulate, not only fly. In fact the system is the “fly-hand” of the teleoperator, who is not expected to be an expert in piloting, but an expert in the environment to be inspected. All these features are impossible to develop without a cognitive systems approach. Real world situations and non-perfect human interactions call for cognitive solutions.

1. The final system has reached TRL 4/5 and ALSTOM Inspection Robotics is now developing it as a commercial platform.
2. The project SHERPA is a follow-up of the AIRobots project in the sense that extends the architecture to handle search and rescue situations.

NIFTI

Another example is the NIFTi project that developed a comprehensive human-robot-team solution for robot-assisted disaster response. NIFTi is about human-robot cooperation. About teams of robots and humans acting together, interacting together, performing tasks together, trying to reach a shared goal. This is a complex socio-technical system that required a truly cognitive systems view. No ad-hoc solution would have led to a working system. But NIFTI was successfully deployed during disaster response efforts in the aftermath of the earthquakes in Northern Italy, in Summer 2012.

1. The UGV platform developed is now being marketed by BlueBotics (2 patents pending).
2. The ongoing project TRADR aims at developing further the system adding persistence of information and allowing the mixed human-robot team learn from experiences.

6.2. Smart Environments

Cognitive systems algorithms and processes cannot only be applied to embodied systems like robots but to whole environments.

VANAHEIM

The VANAHEIM project for instance enhanced a CCTV surveillance system with cognitive capabilities to provide situational awareness. The development of a novel system of semantic extraction from security cameras led to a surveillance solution that is able to automatically find abnormal human behavior in feeds, detect dangerous events and aggregate behavior over time to find long-term patterns of mass movements. The system has been tested in railways and metro stations. But it also could be ported to airports, shopping malls & home care. There is a broad array of possibilities. The tests have shown that the system is very

advanced, has a high TRL and is ready for deployment. But end users need to be convinced of the real value and interest of the system with long-term evaluation.

SCANDLE

The SCANDLE project also provided solutions for the development of smart environments. It developed a system based on neuromorphic engineering that identifies living beings from inanimate objects just with the use of sound analysis. This can be used in busy road crossings to provide situation awareness, detecting movement in a smoke-filled room where cameras are useless, detection of intentional human movements aimed at harming individuals and recognition of normal/abnormal behavior in a crowd. A cognitive approach was key to extract as much information from the acoustic scene as possible.

6.3. Unconventional Robotics

OCTOPUS

OCTOPUS is an excellent example of the importance of different fields (Biology, Artificial Intelligence, Neuroscience, Engineering) working together. Thanks to FET funding, basic research could be conducted in OCTOPUS that eventually led not only to new insights in biology but also to robotic devices, medical applications of minimally invasive surgery , and that has implications for different industries: microelectronics/shape-memory alloy (SMA) actuators, manipulators in industrial processes, marine inspection. Its outcomes are:

- Real SMA actuator, in collaboration with STMicroelectronics (French-Italian company, largest semiconductor maker in Europe, leader in microelectronic components) and SAES (Italy- based, world leader SMA supplier and manufacturer).
- STIFF-FLOP project creating a soft robotic arm for minimally invasive surgery, directly applying the basic research outcomes and actuation technologies from OCTOPUS.
- PoseiDRONE: applying the research to marine robotics by building soft robots for underwater exploration and intervention. Applications include marine research (e.g., taking samples from coral reefs without damaging the surrounding area) and safety/industry (maintenance in underwater plants).

RoboEarth

RoboEarth is a fast-growing world-wide open-source framework that allows robots to generate, share, and reuse knowledge and data. RoboEarth is effectively a world wide web for robots: a web-based resource that robots can use to exchange

knowledge among each other and benefit from the experience of other robots, customizing that knowledge to suit their own particular circumstances. It is this ability to customize that particularly distinguishes RoboEarth.

6.4. Medical, Rehabilitation, Care

CSR has shown that cognitively different people (for example, patients with ASD and other social pathologies) can perform quite well in society when helped by appropriately designed cognitive systems. Mathematical or computational models of the brain and its cognitive processes combined with psychological treatment and robotics approaches led to several programs that use humanoid or animal-like robots to treat autism in children by helping them communicate with other people and learn certain social skills. Developments in clinical cognitive science are essential for new psychological treatments. These are the objectives of European projects like DREAM and ALTEREGO.

Database support systems, knowledge representation models, and expert systems may supplement human expertise and play a significant role in decision making, especially in the medical domain (where IBM's Watson is being deployed, too). Such systems aid in difficult medical diagnosis problems by analyzing clinical data, (semantic) searching in drug databases and/or medical documents for treatment suggestions, and similarity search in medical image databases. As an example for such frameworks, the DebugIT project allows monitoring infectious diseases by extracting microbial case data from clinical information systems.

After surgery, which in some cases is supported by robotic devices such as the "da Vinci" robot, electrical and mechanical engineering approaches lead to applications in physical rehabilitation, e.g., brain-computer interfaced wheelchairs for severely disabled humans, exoskeletons (such as ATLAS), and sports assistants (e.g, playing table tennis). Control learning strategies are important in human motion rehabilitation, and motor control learning is needed in the neurological rehabilitation of people with stroke, Parkinson's, or cerebral palsy.

In general, robots find applications as companions and caregivers by assisting patients who require long-term or even permanent care, such as elder or physically disabled people.

7. Cognitive Systems: Leading Innovation

Cognition is not to be seen as some module in the brain of a person or the software of a robot but as a system-wide process that integrates all of the capabilities of the agent to endow it with this attributes: autonomy, perception, learning, anticipation, action, and adaptation. In much the same way, Cognitive Systems Research is not a “separate” science, but a way of integrating different sciences and providing new methods to come up with flexible solutions to build artificial systems.

Cognitive Systems research, by embracing this integrative approach, is changing the way we understand natural systems and build artificial ones. Concepts like Embodiment and the importance of morphology in cognitive processes; Situatedness and the constant real-time interaction with the environment; or affordances and the fact that objects are opportunities to act in the world; are just three examples of the new paths that Cognitive Systems Research have opened to explore artificial cognition. And these are not just philosophical preferences, the community is building actual engineering solutions based on these new paradigms. Some of these become marketable solutions.

Since the beginning of AI as a research agenda, the process of understanding and building intelligent systems have produced solutions that have found their way into the market. But as soon as the solutions are successful they tend to leave the domain of cognitive systems and become "common" computer science. Most current electronic technologies originated in their embryonic forms as AI research projects, or involve key components that originated in that way. For example, in the field of computer vision, face detection/recognition or activity recognition (e.g. Kinect), ... all originated from decades of cognitive vision research.

Here are the different issues that cognitive systems research address, the European projects that have worked on them and some of the technologies that emerged.

7.1. Learning

All forms of learning help to improve cognitive capabilities and to obtain flexibility and adaptability in real-world scenarios. Several learning methods exist (active learning, reward learning, learning by demonstration, etc.), many of which are based on natural systems. Since (natural) learning is a multimodal process, the interdisciplinarity of CSR approaches can explain how learning actually occurs and at the same time employ or adapt learning methods for applications. Insights include the role of prediction and simulation in learning and cognition, the fact that neuro-structural changes are not necessary for Hebbian learning, and the

importance of mechanisms for autonomous learning for improving the behavior of artificial agents that are integrated in human environments.

CSR has contributed to teaching robots by reinforcement and machine learning (learning controllers from scratch) and imitation learning of motor skills (e.g., CogX, ERC project EXPLORERS). Understanding curiosity-driven learning made robots possible that develop novel skills during their entire “life”, and that can self-calibrate/adapt and recover after failures.

Further applications of learning methods include the adaptive powering of antennae (e.g., mobile phone masts) and handling huge amounts of data (e.g., search machines with spell checkers and translation engines).

7.2. Human-Computer Interaction

An area where CSR has an immediate impact is human-machine/human-computer interaction, i.e., how people relate to machines and how this informs the design of these machines. Example applications include assistive robots for caregiving (see separate section below), artifacts that support communication or cooperation, devices to empower the cognitive capacities of human-machine teams, and the design of consumer electronics informed by psychological models.

In natural human-human communication, a multitude of verbal and non-verbal behavior is used, e.g. speech, communicative gestures, nods, gazes etc. The verbal and the non-verbal acts together comprise the information necessary for a learner to understand. If robots are to interact with humans in natural ways in the future, mechanisms accounting for the multi-modal complexity of oral human communication need to be developed.

CSR is needed for robots to interact with humans, especially in unstructured, dynamically changing environments which are usually not a problem for humans but still pose formidable problems to machines. Semiautonomous operation, active or proactive perception strategies are ways to deal with such environments, which exist for example in rescue scenarios, as addressed e.g. by the projects NIFTi, TRADR, and WALK-MAN. Robot navigation and interaction in human environments is also addressed by STRANDS.

Verbal and behavioral communication plays a major role in human-machine interaction too, where projects like HUMAVIPS, ALIZ-E, and JAMES address the issue of learning from human behavior and recognizing/understanding/interacting with people. Issues include recognizing the dynamics of social interaction, predicting humans’ actions, evaluating and generating communicative gestures – in

short, finding the conditions for appropriate cooperation between humans and robots.

A service robot in human habitable environment should be able to respond efficiently to human actions and emotion state. The robot should have the ability to express its state in an appropriate for a human way and to find the best action in respect to its task and the observed human's gestures, emoting state etc.

Further examples of human-machine interactions that benefit from CSR include table-tennis robots that predict the moves of their human opponent, robotic tour guides, and light-weight assembly line robots that are capable of safely operating next to human workers. Safety can be increased by using compliant or soft bodies (Probo, COMAN).

7.3. Knowledge & Representation

CSR is shedding light on the acquisition, management, representation and exploitation of knowledge of the (human) mind and is applying the findings to show that robot knowledge can be learned and need not be manually designed

Search engine technology, particularly more recent iterations, that rely on semantic network-like functionality, or the more human-like representation of information on a massive scale to facilitate more accurate search results

Examples include WordNet, Deep Blue, IBM's Watson (with applications e.g. in medical database support systems), search engines like Google and KartOO, and recommender systems such as the one used by Amazon.

7.4. Language

Understanding the neural basis of language or the acquisition thereof can lead to better natural language processing systems, for example machine translation or speech recognition and generation. CSR has contributed to neurophonetic models for speech processing, and "embodied" approaches have proved that cognitive functions previously assumed to be innate (for example language) can be learned from embodied experience.

Apple's Siri is a prominent application of CSR, as it comprises of speech recognition, context awareness, information collection, question answering, and "artificial consciousness".

7.5. Autonomy

Robotic systems that autonomously navigate in largely unknown, changing environments are gaining importance, a prominent example are "self-driving" vehicles. Some of these systems are not fully autonomous but complement humans in their navigation tasks. An important insight from CSR is that autonomous

behavior may be generated based on much simpler interfaces with sensory and motor systems than previously postulated in the sense-plan-act approach to autonomous robotics

In search and rescue scenarios, long-term autonomy is necessary for artificial cognitive systems to “survive” in real-world environments.

Systems that currently employ autonomous navigation skills to a certain extent include vacuum robots, warehouse robots, driver assistance/navigation devices that keep the car on the track and avoid collisions with other cars or pedestrians, and unmanned aerial vehicles.

7.6. Vision and perception

Vision and perception are hard problems. Incorporating social and cultural aspects in visual cognition may improve robotic vision systems, thus, CSR is needed for vision to become more useful in domains such as navigation (driver assistance), surgery, image/object recognition and classification, scene understanding in mobile robotics, face detection, or object tracking.

A concrete example is the HERMES project which employs cognitive computer vision for surveillance systems in factory automation, security, and many other applications.

Perception is a multimodal concept that includes vision. It links to psychology, where for example the phenomena of change blindness and choice blindness may help in the creation of cognitive models of the human mind. By “borrowing ideas” from how human perception is thought to work, i.e., by coming up with computational models that seem to mimic human perception (such as Bayesian reasoning), massive advances have been made in computer vision, for example in recognizing people in pictures.

Applications of CSR in perception are found in human-machine interaction scenarios (facial expression, aggression detection, intention recognition).

END