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Food for thought paper on "Cognitive Systems"

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Contents

Introduction to Cognitive Systems

By psychology definitions[1] [2], a cognitive process exploits perceptual information, memory, and reasoning to allow problem solving. Cognition is the set of abilities that enable to learn and to react at stimulations from the environment continuously.

A cognitive system is able to implement a deep abstraction that enhance the understanding of the environment through sensing. Another key capability of such a system is the usage or the creation of memories within the perceptual task.

Due to the contextual understanding of a situation, attention could be focused on important perceptions by solving conflicts between different tasks when needed. Moreover, the acquired new knowledge about the environment enhances the perception in the short- or long-term by learning. The learning process is stimulated by feedbacks and shared information.

Similarly to our way of learning a cognitive system should learn from positive or negative feedback, success of failure. An implicit prioritisation of memories is realized by forgetting events that occur less frequently in order to guarantee an easy access to memories corresponding to frequent observations.

The ability to derive potential consequences from an observed situation and their judgement is a key feature enabling a sophisticated decision making. This judgement enables the solution of possible conflicts, finding new opportunities. This kind of intelligence also allows the avoidance of future failures and the generation of strategies that can be applied to certain situations. A situational understanding/awareness and prediction is then achieved, requiring models of the environment for planning efficiently. Also, in uncertain environments where the observations are unknown, a categorization can be applied for extracting known features in order to make a rough behavioural assessment. In this situation, concepts representing the internal idea are applied to a category of

[1] M. W. Eysenck and M. T. Keane, Cognitive Psychology: A Student's Handbook, 6th Edition, Psychology Press, 2013.
[2] D. Reisberg, The Oxford Handbook of Cognitive Psychology, Oxford Library of Psychology, 2013.

unknown observations. The policies of this cognitive sensing capability are also adjusted by 'reflection', 'learning' and 'reasoning'.

Cognition is a broad and complex topic. For technical applications, the intention is to mime this cognitive behaviour already present in nature.

Cognitive Radar Systems

There are examples of working cognitive radars already existing in nature. For example, echolocating mammals like bats or dolphins interact with their environment in a sophisticated way[3] [4]. One manifestation is the ability of bats to change their pulse repetition interval (PRI) and its waveform according to the scenario.

At an early stage of hunting, a long waveform providing good range and velocity resolution is transmitted. While approaching their prey, the PRI and the waveform duration of bats are changed slowly to reduce the unnecessary effort for sensing. Bats are fully adaptive in space and time, being a biological proof of existing cognitive radars[5].

In the frame of the radar discipline, we can state that "cognitive" refers to a system able to dynamically adapt its waveform, its resources and its signal processing algorithms by starting from acquired knowledge about the environment in a dynamic and autonomous way.

A set of performance metrics can be used to define the rules used by a radar system for reacting in terms of response to the sensed environment. According to this definition, three common features underpin any implementation of these types of system:

- intelligent signal processing;
- receiver–transmitter feedback;
- a flexible radar system.

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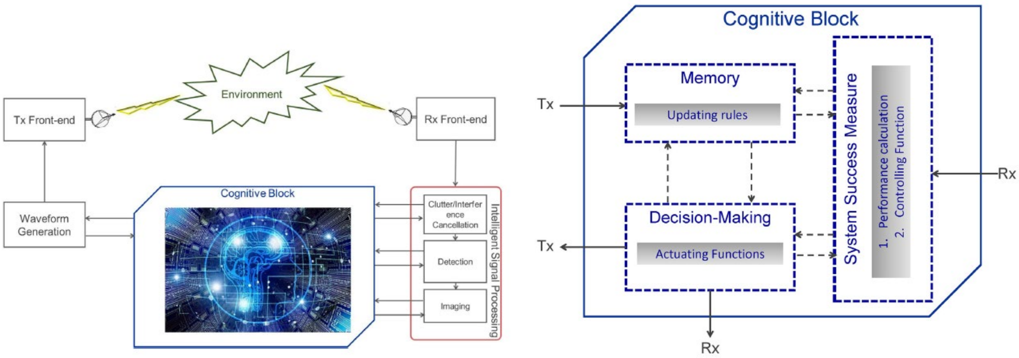
[3] D. N. Lee, J. A. Simmons, P. A. Saillant and F. Bouffard, "Steering by echolocation: a paradigm of ecological acoustics," *Journal of Comparative Physiology A,* no. Volume 176, 1995.
[4] D. v. Helversen, "Object classification by echolocation in nectar feeding bats: size-independent generalization of shape," *Journal of Comparative Physiology A,* no. Volume 190, 2004.
[5] A. Farina, A. D. Maio and S. Haykin, The Impact of Cognition on Radar Technology, London: The Institution of Engineering and Technology, 2017.



(a) (b)

Figure 1 (a)Example of cognitive imaging radar architecture, (b) Focus on the Cognitive Block. Figure are from [6]

Example of cognitive radar architecture

An example of cognitive radar architecture is shown in Figure 1. Its main components can be described as follows:

I. **The radar transmitter and receiver**: the transmitter acts on the transmitted waveform over time according to the environmental changes to optimising the performance through an "intelligent" signal processing on the receiver. The intelligence in the receiver is built on a learning process through a continuous interaction of the radar with the environment. Such intelligence allows the dynamic adaptation of signal processing and the improvement of overall performances.

II. **The cognitive block**: This block uses the information provided by the signal processing block for enabling the best action to be performed by the transmitter block in order to match the needs of the radar mission (e.g. clutter cancellation, interference mitigation, detection, imaging) according to the desired performances. This process is based on an iterative improvement of the performances as measured through several performance indicators. A measure of the mission success level and a comparison with past actions/results provide the necessary feedback for ensuring that the system can learn from its past actions. Figure 1 (b) shows the main components of this part:

    a. a system success measuring block, linking actions to results. Practically, such a block produces defines the control on the next actions. The controlling functions change according to performance indicators and handle the actuating function to performing adjustments of the system's reconfigurable parameters (e.g. waveform parameters).

[6] E. Giusti, A. L. Saverino, M. Martorella, F. Berizzi, "A Rule-Based Cognitive Radar Design for Target Detection and Imaging," in IEEE Aerospace and Electronic Systems Magazine, vol. 35, no. 6, pp. 34-44, 1 June 2020, doi: 10.1109/MAES.2019.2953433.

b. A memory block embodying the knowledge of the system. It provides the means for learning from past experiences. Memory is dynamic because its contents continually change over time in accordance with the environmental changes. Specifically, if the radar environment changes suddenly or if it is completely unknown, the radar must probe the surrounding for enriching the memory contents by updating the rules that are used to adapt the actuating functions. A feedback-based decision-making block, which identifies the best way for changing the system parameters (e.g. waveform parameters) and the signal processing techniques by correlating information contained in the memory with that produced by the success measure block. This process is feasible through the actuating function, whose role is to inform the system whether the chosen actions are leading to success or failure.

Cognitive Vision Systems

The term cognitive vision system has been recently introduced to define robust, resilient, and adaptable computer vision systems that exploit “cognitive” capabilities. Within the computer vision discipline, the attribute “cognitive” is related to the capability of taking a decision based on the understanding of phenomena sensed by exploiting an EO sensor.

A cognitive vision system should be able to engage in purposive goal-directed behaviour, to adapt robustly to unforeseen changes of the visual environment and to anticipate the occurrence of objects or events [7] [8] [9]. The human biological vision system can be considered as a cognitive system, where the data acquired by the eyes are processed to understanding the neighbour space-time environment. This process is the first responsible of any kind of “reaction”.

In recent years, approaches have been proposed to mimic the human intelligence capabilities by combining prior knowledge and visual information in knowledge vision-based systems, that is a step towards cognitive vision. The capability to anticipate a prospective event requires the ability to operate across time, to extend into the future and to put in place a contextual reaction.

These systems may perform recognition under conditions that pose limitations to computer vision systems, such as the presence of geometrical variation, unideal lighting conditions and occlusion[10] among others. It usually relies on top-down contextual knowledge acquired from visual experiences,

[7] D. Vernon, "The space of cognitive vision", in H.I. Christensen, H.-H. Nagel (Eds.), Cognitive Vision Systems: Sampling the spectrum of Approaches, LNCS (In Press), Springer, Heidelberg. pp. 7–26.
[8] P. Auer, et al., "A Research Roadmap of Cognitive Vision", ECVision: European Network for Research in Cognitive Vision Systems, 2005, http://www.ecvision.org/research_planning/ECVisionRoadmapv5.0.pdf
[9] G.H. Granlund, "Does vision inevitably have to be active? " in Proceedings of the SCIA99, Scandinavian Conference on Image Analysis. 1999
[10] A. Borji, "Negative results in computer vision: A perspective," Image and Vision Computing, no. 69, pp. 1-8, 2018.

combined with the bottom-up information constantly collected. For instance, in the human mind the same object can be known, by experience, to exist in a variety of different forms, sizes or shapes. This accumulation of experiences allows human vision to comprehend and classify new images[11] [12]. Therefore, knowledge-based vision systems may integrate the bottom-up data-driven approaches that perform computer vision tasks through machine learning algorithms with the top-down approach offered by prior knowledge into an inference process inspired by biological vision[13].

Common Principles and Proprieties of Cognitive Vision Systems

The aim of computer vision is to provide visual information for a given application[14].

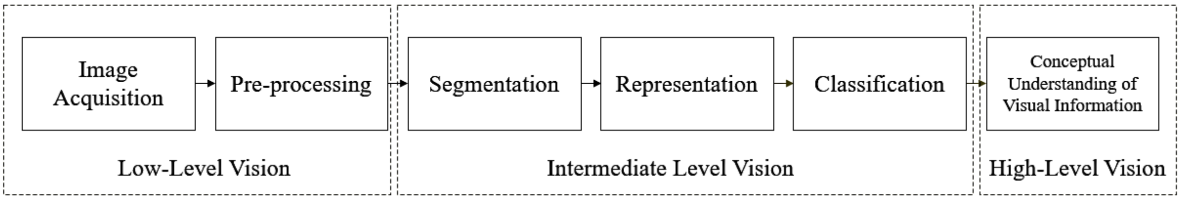


Figure 2 Block diagram of a typical modern computer vision system from [15]

To achieve this, vision systems can comprise different subtasks grouped in three categories:

- **low-level vision**, **intermediate-level vision,** and **high-level vision**. **Low-level vision** tasks include operations such as image acquisition and pre-processing.
- **Intermediate-level** tasks pertain to segmentation, symbolic representation, classification, and recognition.
- **High-level vision** tasks concern with achieving conceptual understanding of the information acquired from lower-level vision modules[15].

[11] P. Meer, "Are we making real progress in computer vision today?" Image and Vision Computing, no. 30, pp. 472-473, 2012.
[12] A. Andreopoulos, J. K. Tsotsos, "50 Years of object recognition: Directions forward," Computer Vision and Image Understanding, vol.117, pp. 827-891, 2013.
[13] Q. Ji, "Combining knowledge with data for efficient and generalizable visual learning," Pattern Recognition Letters, pp. 1-8, 2017.
[14] B. A. Draper, A. R. Hanson and E. M. Riseman, "Knowledge-Directed Vision: Control, Learning and Integration," Proceedings of the IEEE, vol. 84, no. 11, pp. 1625-1637, 1996.
[15] T. Alves, C. Oliveira, C. Sanin, E. Szczerbicki, (2018). From Knowledge based Vision Systems to Cognitive Vision Systems: A Review. Procedia Computer Science. 126. 1855-1864. 10.1016/j.procs.2018.08.077.

A modern computer vision system is the result of the integration of these three levels, including all the tasks required to identify image elements and to establish relationships between themselves or between the elements and the viewer[16] [17]. However, this definition arises from a functional/architectural approach, based on the set of minimal tasks that a system is required to perform in order to be classified as cognitive vision system.

Cognitive computer vision regards the integration and the control of vision systems by using explicit but not necessarily symbolic models of context, situation, and goal-directed behaviour.

Cognitive vision implies functionalities for knowledge representation, learning, reasoning about events & structures, recognition and categorization, goal specification. All these functionalities deal with the semantics of the relationship between the visual agent and its environment[9].

A cognitive vision system must achieve the four levels of a generic functionality of a computer vision system:

1. detection of an object or an event in the visual field;
2. localization of the position and the size of a detected entity;
3. recognition of a localized entity by a labelling process;
4. understanding or comprehension of the role, context, and purpose of a recognized entity.

It can engage in purposive goal-directed behaviour, adapting to unforeseen changes of the visual environment. And it can anticipate the occurrence of objects or events. The system achieves these capabilities by exploiting the knowledge (a-priori knowledge or contextually learned) about the environment, the cognitive system itself and the relationship between the system and its environment.

Cognitive Systems and Machine Learning

From the previous paragraph we can understand that the main capability of a cognitive system is the ability to learn autonomously from available data, evolving the way in which the system answers by itself to the environment perturbations. Both for Cognitive Radar and for Cognitive Vision systems it is possible to find approaches that mathematically solve relations describing the interaction between the system and the environment by exploiting sensed data and previous knowledge. And it is also possible to enable inside the system a sort of memory that can be used for extending the a-priory

[16] D. Ranasinghe, A. Karunananda, "Using Qualitative and Commonsense knowledge to expand horizons of Cognitive Computer Vision Systems," in Second International Conference on Industrial and Information Systems, ICIIS 2007, Sri Lanka, 2007.

[17] D. Crevier, R. Lepage, "Knowledge-Based Image Understanding Systems: A Survey," Computer Vision and Image Understanding, vol. 67, no. 2, pp. 161-185, 1997.

knowledge. In some cases, the use of machine learning can be the driver for the design of such new systems.

In recent literature we can find some solutions facing the development both of continuous learning and of lifelong learning approaches in machine learning. Recently, a complete overview of the methodologies developed in the last decade has been reported[18]. The author shows the main limitations of the current methodologies, highlighting some possible solutions for identifying the most promising approaches. In this field the main problem is the tendency of neural network models to forget existing knowledge when they learn from observations that are extremely new and unknown[19]. Possible solutions through the adoption of autonomous agents and transfer learning are provided.

Research & technological gaps

Currently, both Radar Sensing and Computer Vision are well-established fields of research. There is a relevant focus on solutions that can be attained by using mathematical descriptions exploiting or not a-priori knowledge. The issue with these approaches is that they often cannot match real-world conditions and they are not able to estimate unknowns.

The ongoing challenge is to develop systems that:

- are robust to deviations from data-driven models;
- do not require the reliance on large training data sets;
- are efficient in terms of computational requirements and memory space;
- are capable to handle degraded data.

Within Computer Vision, these challenges are bringing research activities to find answers especially for the "**high-level vision tasks**" shown in Figure 2.

Potential Defence applications

Application of Cognitive System in defence will cover several applications within the next years.

The development of systems able to adapt themselves to the environment and also contextually "intelligent" enough to learn from experiences in real time is something that is currently under consideration by industries and research institutes when we discuss about new concepts for autonomous system.

[18] G. Parisi, R. Kemker, J. Part, C. Kanan, S. Wermter, (2018). "Continual Lifelong Learning with Neural Networks: A Review." Neural Networks. 10.1016/j.neunet.2019.01.012.
[19] Hassabis, D., Kumaran, D., Summerfield, C., & Botvinick, M. (2017). Neuroscience inspired artificial intelligence. Neuron Review, 95(2), 245–258.

Looking at integrated systems, some examples can be found within unmanned platforms or in the implementation of an autonomous behaviour for unmanned swarm.

Concerning Cognitive Radar and Cognitive Vision, straightforward applications can be explicitly found in the automatic optimization of sensor parameters in case of degraded or unknown sensed environment, detection, recognition, identification and tracking of targets as well as in the analysis of the behaviour of scenario actors and in the automatic targeting of threats.

Final recommendations

Cognitive systems do not generate just answers to numerical predefined problems, but they are able to perform new hypothesis and construct new processes for producing better images.

They refer to a technology able to understand new operative scenarios and to exploit available information, ensuring the higher performance in the results of imaging formation process.

A Cognitive System continuously learns about the environment through experience gained from interactions with the environment. It continuously updates the imaging formation process with relevant information taken from the environment, adjusting in an effective and robust manner.

The whole system constitutes a dynamic closed feedback loop, where the physical layer (the radiation source, the environment, and the sensor) is only a part of the loop.

At a higher level, a cognitive imaging system can tackle the problem of detecting objects, extracting certain visual characteristics and their subsequent association. It can also use classifiers along with automatic learning techniques for taking decisions and for tagging objects and images.

These issues are closely related to the machine deep learning and to the artificial intelligence realms.

Putting it in a simpler way, **Cognitive Systems are capable to actuate a perception-action cycle, based not only on predetermined processing and decision flows but also learning from experience**.