Cognitive Automation—Survey of Novel Artificial General Intelligence Methods for the Automation of Human Technical Environments

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***Abstract*—Automation, the utilization of control and information technologies for reducing the need for human intervention in the production process is about to meet Cognition—the science concerned with human thinking—and related sciences. More and more processes require analysis and insights that allow controlling them beyond the mere execution of rules and beyond prefitted controllers in order to automatically keep them within the desired conditions. Automatic and flexible decision making based on challenging conditions such as increasing amounts of information, lacking prior knowledge of data, incomplete, missing or contradicting data, becomes the key challenges for future automation technologies.**

In this paper, we present a survey of methods on how to integrate some of a human's capabilities for the use in automation applications. Theories for process modeling, decision making, and hierarchical processing are summarized as well as applications thereof in such areas as Ambient Assisted Living or Robotics given.

***Index Terms*—Ambient assisted living, artificial general intelligence, artificial recognition system, cognitive automation, context awareness, decision making, hierarchical information processing, intelligent perception.**

I. Introduction

THE FOCUS OF research in automation shifts more and more towards systems which need capabilities of complex problem solving and taking ever-increasing amounts of details "into consideration." Already the terms necessary to describe such upcoming problems pose increasing complexity and usage of descriptive language, which gives also a very good impression about the requirements for potential solutions. Speaking in Artificial Intelligence (AI) terms [1], applications of *weak AI* need either to converge towards "stronger" or even *strong AI* applications, as many researchers in weak AI think, or—contrary—researchers need to modify the conceptual framework how human capabilities are modeled (Research in the direction of the original goal of AI, to create intelligent machines that match or exceed human capabilities, is called Strong AI in opposition to application oriented or problem solving tasks that do not need the full range of human cognitive capabilities, which are called Weak AI.). The latter, the assumption of necessary reformulation, is the hypothesis that the authors of this article support. However, complexity is not the only problem. Sensor fusion and (semantic) interpretation of sensor data in general is a closely related field. It rises questions of perception as well as organization of data [2] for memory, and templates and rules for perceptions. Data from different modalities shall be fused to multimodal object representation. But what is an object? Another hot topic is related with action planning, where it is necessary to apply abstract plans to concrete perceptions and situations, factoring in incomplete or wrong information. Additionally, the more flexibility a system is deemed vaccinated necessary, the more the question of dealing with unrestricted environments becomes an issue [3]. Finally, in increasingly complex systems, the topics of security [4]–[6] and safety [7] play also important roles.

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A. Example Areas

The scope of this paper shall be elucidated with the following areas of practical examples in automation. The base for the following examples is the assumption that there is some automation system, which consists of sensors, actuators, communication and processing units. The units are presumably interconnected by some dedicated fieldbus system.

1) Example 1: Data Exchange: Building automation experienced rapid development of protocols, devices, and standards and can be regarded as functionally stable today from a technological point-of-view [8], [9]. However, there is one important issue that hinders further market penetration: The different systems are not able to share their data and use the whole information for additional services (actually there are many attempts to introduce architectures for exchanging data of different source, e.g., [10], but the full potential of multimodal sensor systems is far from being exhausted).

2) Example 2: User as Part of the System: Many examples of applications have been postulated [11] that could be tackled with integrated building automation systems, which take into account knowledge about the user. Many of them are subsumed under Ambient Assisted Living (AAL), the key word for all approaches that help the elderly prolonging independent living within their own four walls (Though, AAL is not only concerned with technologies for the elderly. However, since the development of enabling technologies to overcome particular handicaps is more demanding while targeting much smaller markets, AAL products are mainly only for the elderly and their most common problems.).

3) Example 3: Kitchen Applications: A particular aspect in automating private homes is the realm of the kitchen. The kitchen offers "endless" possibilities for automated services and devices on various degrees of complexity due to the fact that it includes daily common business on the one hand as well as rather seldom, but also predictable activities on the other. Additionally, it is easily possible to define and test use cases for safety-critical situations.

4) Example 4: Robotic Applications: Finally, there is the area of robotics, where mobile, autonomous robots are of highest interest. On the one side are the logical extrapolation of AAL and home automation in the form of a butler, and on the other hand they bridge to industrial automation [12].

B. Top-Down Versus Bottom-Up Approach Towards Human-Like AI

As mentioned above, the authors think that the required strong AI capabilities can only be achieved by rethinking the approach on how such systems are designed by applying a comprehensive top-down approach in interdisciplinary research.

It is not to say that bottom-up approaches in principle cannot lead to human-like AI, but their implementation has to be questioned. For example, evolutionary algorithms: The engineer has to design a fitness function that allows the algorithm to increase the performance of its population (through application of mutation, recombination, and best-fit selection). This works very nice for optimization problems where the problem itself can be formulated in form of a function, and the function can be computed or estimated in meaningful time intervals—this statement is in fact true for most applications of weak AI, which are targeted to particular applications. The problem when trying to map those insights to natural evolution (taking nature's solutions as templates for engineering solutions: biomimetics [13]) is its ever-ongoing nature. Natural evolution always takes place with respect to the conditions of the environment. And if one creature adapted its behavior somehow, it posed instantly an adapted environment to all the others that themselves did then undergo further evolutionary developmental steps. In this respect, it can be questioned, if artificial evolutionary strategies for finding the human brain's neural structure or for finding the purpose of particular human genes can be researched without creating a situation (including its own appearance) close to the bias point of its particular establishing—or even tracing the whole story. The question always needs to be: *"What was it meant for?"* rather than asking *"How does it work now?"*.

Hence, for the purpose of applying insights about established abilities into another subject area, the correct approach is to perform a functional analysis, rather than modelling bottom-up. Thereby it is not necessary (nor possible) to totally understand the subject of investigation. In particular, in (software) engineering, methods for this purpose have been developed under the term requirements engineering, very often combined with the usage of Ockham's razor [14] on both sides in order to prevent from trying to model everything at once, but to have a tool helping you to select or sharpen the focus. This is the natural way of conducting research and development for engineers, why should it not lead to success also with respect to human capabilities?

One part of the answer can be sought in the "customer" who poses the requirements in this respect, in other words the template science. Another part of the answer lies in the scientific socialization of the proponents of both, the requirements-posing proponents from the humanities (especially particular branches of psychology) and the analyzing proponents, the engineers. The former are not trained in formulating their theories in axioms and functions and the like. This dilemma can only be solved with interdisciplinary cooperation where both parts concentrate on their strengths, i.e., researchers from the humanities try to select the parts of their theories that fit the problem and engineers try to restructure that knowledge in a way that can be incorporated in a contradiction-free, implementable theory. It would be as meaningless for an engineer to select among psychological theories as it would be for a, e.g., psychologist to decide about different embedded systems for implementing.

In the following sections, research results are summarized that have been developed in such interdisciplinary cooperation. Section II summarizes more traditional approaches and architectures for machine perception, whereas Section III concentrates on cognitive architectures and Section IV concentrates on decision making units. Finally, Section V gives a discussion and outlook.

II. Applied Machine Perception Methods

Here, we give an overview about particular areas of machine perception [15], a basic requirement for Cognitive Automation.

A. Sensor Fusion

A field that exists already for rather long time is that of sensor fusion. It is concerned with combining sensory data from various sources in order to gain information that would not be possible when considering the sources individually. The goals for sensor fusion hence are increasing robustness, coverage, confidence, and/or resolution and/or reducing ambiguity and uncertainty. Elmenreich [16] categorizes concepts, models, methods, and applications for sensor fusion, which is also followed here. The *concepts for fusion* are divided into complementary, competitive, and cooperative fusion. Complementary fusion takes incomplete sensor measurements from distinct, independent sources in order to produce a multimodal representation of the observed process. Competitive fusion is mainly used for redundant sensor configurations, whereas cooperative fusion aggregates information from single sensors, typically with the cost of decreased accuracy or reliability. Reviewing *models for sensor fusion*, it has to be noted that they depend to great extent on their area of application which actually prohibits providing an uncommented list, but giving an extensive review thereof is not within the scope of this work. Thus, we shortly summarize established models [16]: the JDL fusion model architecture (introduced by the Joint Directors of Laboratories; a rather abstract, data-centered architecture with five levels of processing with mutual feedback [17]), the Waterfall model (comparable to the JDL model, but using six stages without any feedback [18]), the Boyd loop (a cycle containing the four steps Observe, Orientate, Decide, and Act [19]; it has been used to couple sensor fusion to decision-support systems), the

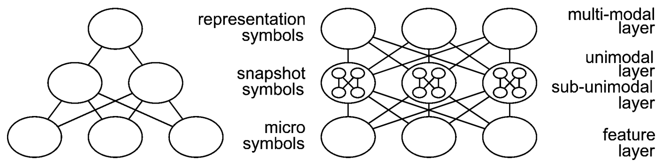

Fig. 1. Hierarchical processing models (left: symbolic approach, right: enhanced neurosymbolic approach).

LAAS architecture (introduced at the Laboratoire d'Analyse et d'Architectures des Systèmes; a hierarchical model comparable to the decision units in Section IV-A that introduces different timings on different levels and provides clear implementation orientation [20]), and the Omnibus model (structured like the Boyd loop, but more sophisticated elaboration on the single processes [21]). Regarding *methods for fusion*, it can be stated that all traditional mathematical models from AI have also found their way into sensor fusion applications. The author of [22] introduces relevant probabilistic methods, and [23] categorizes them into estimation methods, classification methods, inference methods, and artificial intelligence methods. As will be also discussed in detail in Section III-B, it can be noted that those methods typically lack a hierarchical approach and structure that allows for more complex solutions. Finally, since sensor fusion is a very broad field, the same applies to *application areas for fusion*. They range from measurement engineering in general, automation engineering, medical, military, and avionic applications, to bioengineering [15].

B. Behavioral and Motion Models

This category of approaches enhances static sensor fusion with respect to time. Recurring patterns (either predefined or learned) are sought within the sensor data in order to recognize scenarios. In order to cope with the huge amount of data and combinations, hierarchical processing is introduced.

1) Processing and Symbolization of Ambient Sensor Data: Representatives of such an approach, e.g., the ones introduced by [24] and [25] propose a layered processing architecture. In the case of this particular approach, it consists of three layers, in which incoming sensor information is processed bottom-up for recognizing scenarios in a building. In the first layer, sensor data is transferred into so-called micro symbols. In all layers, the portions of data are referred to as symbols, based on the idea that humans think in terms of mental symbols (Fig. 1). The second layer is called snapshot symbol layer, the third one representation symbol layer. In the first layer, sensor information is compared to template micro symbols, which are activated in case of an adequate match. The connections to the two above layers are predefined and if the required amount of micro symbols is activated, then a corresponding snapshot symbol and in case of the required snapshot symbols a corresponding representation symbol is activated. Representation symbols can also contain a particular sequence of activations of snapshot symbols. Velik *et al.* [26] enhance the approach by exchanging the predefined connections with Hebbian learning (Fig. 1). The symbols are called neuro-symbols and the layers (from bottom) are called feature symbol layer (layer 1), subunimodal, unimodal (both in layer 2), and multimodal symbol layer (layer 3), as well as scenario symbol layer on top. Their hierarchical structure [27] is based on the structure of the human cortex (which is structured also in three layers [28]). One criticism to such bottom-up approaches is that human perception is also guided through expectation. The mentioned models tackle this with introducing additional functions on the top or even above the top layer of their perceptional models, however, there should be a more elegant solution, where such feedbacks or even distributed processing is incorporated in the model, as it is in case of the decision units presented in Section IV-C.

2) Recognizing Scenarios With Statistical Methods: In opposition to the models described in the last Section, the model introduced by [29], [30] concentrates mainly on temporal patterns in sensor data. The data stream of a single sensor is observed over time and particular moments (e.g., 00:00, midnight) are taken as points for comparison. As long as the courses do not differ, it is said that they measure the same scenario. A number of additional merge strategies is then applied for further comparing nonidentical data streams and finding similarities. Finally, a hidden Markov model [31] is produced that represents prototypical routines, e.g., daily routines of occupancy/vacancy of rooms. Since the model always lasts for particular time spans, it can also be used for forecasting future behavior, if one or several prototypes are selected as possible fits. Hidden Markov models are already widely used, [32], for instance, list speech recognition, econometrics, computational biology, and computer vision. In automation, with the spreading of scenario recognition technology for more and more autonomous devices (see, e.g., [33] and [34]), and with increasing amount of data to be processed on resource-constraint devices [35] their popularity will surely rise further.

III. Cognitive Systems for the Automation Area

In automation, two particular areas are involved in dealing more with humans and human capabilities than other areas: Building Automation (and Smart Homes), since further optimization of processes in buildings can only be achieved when better incorporating the subjective wishes, intentions, and constraints of different users, and Robotics, where humanoid robots are an emerging field—next to the more settled field of industrial robots. Additionally, this section hosts also the introduction to Artificial General Intelligence (AGI), the approach to artificial human-level intelligence not from an application side, but from a theoretical side originated as branch in AI.

A. Ambient Assisted Living

This research area accounts for the fact that people tend to live longer and the implications thereof. It is also true that people tend to advance in years more healthy than in the past, however, increasing health care possibilities and less family care result in almost exponential growth of public expenditures [36]. Aside of medical care, the elderly, as any other target group of the population, demand more services as comfort, security, wellness, social inclusion, technical gadgets and many more, always maintaining also economic implementations thereof (cf. smart grids [37]). Hence, the elderly, or more, aging-related implications, are increasingly not merely seen as a financial burden to society but also as a huge market for many kinds of products. In any case, AAL solutions are specific user-centered solutions. The

EU Support Action *support of a Common Awareness and knowledge Platform for Studying and enabling Independent Living*, CAPSIL is currently developing a European research road map for AAL solutions, mainly targeting independent living, which is only a subset of all demands of the elderly, however, it incorporates most aspects of above mentioned demands (except wellness and gadgets).

The following is a list of topics that are within the focus of AAL technologies and research.

- Entertainment: Memory training, entertaining robots, robotic pets [38], brain training including computer assistance [39], video telephony, senior mobile phones, social networks including accessibility.
- Autonomy: Barrier-free architecture, mobility including driving systems, mobility services, and home mobility [40], domestic robots [41], exoskeletons, personal reminder systems, home security. [42]
- Monitoring Systems: Behavior monitoring [29], [43], physiological monitoring [44], cognitive monitoring, detection of unintended or unwanted situations [45], [46].

B. *Artificial General Intelligence (AGI)*

The community of AGI is rather new, their first publication is the proceedings of the AGI workshop 2006 [47]. AGI is a subset of AI whose proponents support the idea of the creation of a human-level intelligence. As mentioned before, the big difference to mainstream AI work is that there, usually some specialized intelligent solution is sought for a more or less well defined problem. Hence, there are three basic requirements for an AI project to be considered an AGI project.

1) A comprehensive theory of intelligence exists.
2) The theory has to be already implemented or at least an implementation plan exists.
3) Results in the form of publications or implementations exist.

A list of projects can be found on the website of the workshop [48]. Many of those projects share similar architectural components; they are called foundational architecture frameworks [49]–[51]. However, the projects themselves differ in model approaches, application domains, and maturity. The two most cited ones are (Adaptive Control of Thought—Rational (ACT-R) [52] and Soar (originally SOAR: State, Operator And Result [53]; now it is no longer regarded as acronym and no longer spelled in caps), which both are memory-based control architectures. Though they label themselves cognitive architectures, however, from today's point-of-view their central element are their production based memory architecture [54]. Both are among the earliest ones originated. While ACT-R bases on the multi-store concept, SOAR shows a uniform character refusing to define categories of memory types regarding their structure, search control, or memory operations. None of them takes embodiment as mandatory for achieving a cognitive decision unit which strongly disagrees with the point-of-view of other cognitive scientists [55], [56]. From the viewpoint of functional analysis it is more interesting to have a closer look into LIDA (Learning IDA; IDA (predecessor project): Intelligent Distribution Agent) and OpenCog Prime/Novamente [49], [57]. LIDA bases on the CogAff architecture (Cognition and Affect) [58] and a number of theories from neurology, psychology, and cognitive science. At first place LIDA aims at understanding human cognition. Unfortunately, no top level instance is provided giving a coherent model including full interoperability issues among the different theories. In addition to the architecture, an actual AGI implementation needs to follow a cognition cycle consisting of sensing, processing, and acting. LIDA also introduced higher order cognitive processes that require more than one basic cycle for being computed. A basic concept of LIDA is that of dominant and nondominant content. Only one set of information can be dominant at a given time, only the dominant content is taken for computations and learning. For nondominant contents, several methods exist (e.g., forming coalitions) to gain higher probability of becoming dominant. In this way LIDA focuses the attention of the system. In contrast to the common engineering point-of-view, LIDA refuses a clear distinction between functionality and data whose description additionally remains unsolved [59].

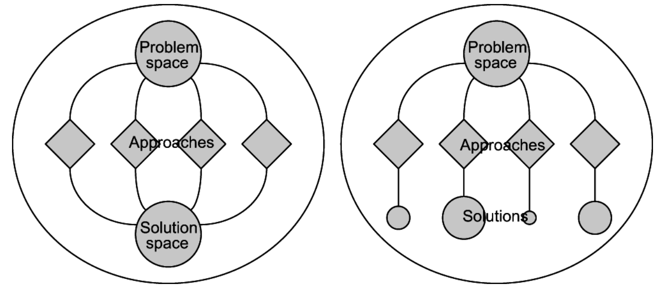

Fig. 2. Comparability of solutions in established areas (left) and in AGI (right). The field is too young and diverse to have produced comparable solutions yet; only the approaches themselves can be compared.

OpenCog Prime/Novamente are two names for basically the same project implementing the PsyNet theory. Their idea is that the mind is made of patterns [60]. These patterns are represented via Atoms interconnected with Hebbian links. Basically, the idea is an extension of traditional artificial neural networks, introducing a flat structure for Atoms and a processing architecture for how to deal with them. According to Goertzel and Pennachin [61], the architecture of OpenCog Prime can be roughly compared to LIDA. However, all modules in their architecture share the same basic type, the Novamente Machine, including a database called Atom Space and functions called MindAgents. Although their long term goal is implementation of a human-like minded agent their present focus are collaborative learning [62] and gene analysis [63], their different application areas and somewhat different approaches makes them hard to compare. One possibility would be with use cases [64], however, it is still necessary to argue about the gained results. As the area is rather young, different groups developed in different directions (Fig. 2). The efforts to work on comparable solutions is rather little, which leaves only the approach itself for comparison, in opposition to areas where the solutions or the solution space provides means for comparative analysis. In LIDA, ACT-R and OpenCog Prime used concepts are not reviewed regarding their compatibility. SOAR is not addressed by this drawback as it should provide a model for human brain mechanisms based on an engineering implementation. Discussed architectures generally have in common that an apparent research plan exists which describes the way human-like cognition should be reached by the particular approach.

Today, also in industrial applications, the topic of agents starts playing a bigger role [65].

C. Robotics

Control units for humanoid robots are the most natural continuation of cognitive research in any engineering discipline. With their humanoid body and desired humanoid capabilities in using that body, humanoid robots shall be used in a broad range of general-purpose applications [66]. Hence, a research field called cognitive robotics has emerged in the last years [67]. It is seen as an interdisciplinary field, including among others robotics, AI, cybernetics, biology, and psychology. Current research focuses on perception, locomotion and manipulation, learning, decision making, planning and navigation. Various architectures have been developed (e.g., [68], [69]) following similar paths than that of AGI, however, sometimes emphasizing more the requirements imposed by embodiment. As within other cognitive-inspired architectures it can be observed in cognitive robotics, that the term "cognitive" itself it often used as an eye-catcher without serious argumentation. See, e.g., [70], an example for a path planning algorithm, where the term "cognitive" is used for labeling the aspect that the algorithm considers alternative routes in case the originally planned route turns out to be blocked—as the authors claim: as a human would in this situation. Certainly, human cognitive abilities are more than only being able to find an alternative route in case the desired one is blocked.

IV. Intelligent Perception and Decision Units

In this paper, the term Intelligent Perception implies a selection of significant sensor data and their fusion to semantic symbols which are used for the selection of upcoming actions. For that, symbols must have a meaning for the system which allows to set them into a context. How to assign meaning to symbols, as well as their processing are questions that are widely discussed within the AI community.

A. Hierarchical Perception

When dealing with perception, one must deal with the question of the source of sensor data as well as the way it is combined and interpreted. The first issue is a central topic of embodied AI and emotional machines. Embodied AI representatives [55], [71] claim that a body is essential as physical interaction with the environment forms the foundation for developing intelligent behavior and giving a meaning to sensor input. Emotional AI rejects reducing this interaction to an external process. An extension by internal evaluation processes of the system state is foreseen. This demand is supported by neuroscientists like Damasio [72] who sees emotions as a result of these processes and a prerequisite for reasoning. Though this claim is controversially discussed [73], it is propagated within AI [74].

As a second step, internally and externally perceived sensor data must be interpreted. The fusion and interpretation of nerve-impulses is a task that is solved by any mammalian brain but remains an unsolved challenge in engineering—though, continuous progress is identified. Hence, biological mechanisms are tried to be modeled and applied to systems. This is attempted in flat topologies where decision making is based on a pure sensorimotor coupling [75] or by modeling the human brain on a neural level (see Section IV-C about Decision Units). There the sensor fusion is afflicted by a lack of essential knowledge about brain structures and mechanisms. Realization of simple use cases is possible [76] but more challenging reasoning and planning tasks remain unsolved. Neuropsychoanalytic concepts hold an alternative and possible solution (see Section II-B1 about symbolic approaches). Hence, hierarchical perception concepts are propagated in [24]–[26]. Up to the so called multimodal symbol layer, neuroscientific knowledge is adapted, while psychoanalytic concepts are introduced for the decision making processes. The advantage is a model of perception that is formed by the use of a consistent theoretical basis. Sensor data is not merged in one step but through hierarchical layers. First, data, which are generally locally associated, of the same sensor modality are merged, afterwards the result is combined with other modalities to multi modal symbols. Significant sensor data is filtered by a trained neurosymbolic network (Section II-B1). The upper most decision layer associates the resulting symbols by their attributes and temporal coincidence [54]. Thereby, situations and scenarios are identified that are the foundation for the upcoming decision making process.

B. Hierarchical Information Processing

The mechanisms for data fusion and filtering differ to those for planning and decision making. Hence, a hierarchical perception model requires various types of information processes that are adapted to the different layers. It must be clearly differentiated between information flow and control flow, as well as data storage and data management. By adapting findings from non-engineering areas, scientists sometimes leave this path. A common example is the use of the psychologically inspired multistore memory model. Though this theory has its validity in neurology and psychology, it misses above mentioned principles as it gives a behavioral but not functional description. This characteristic "forces" engineers to provide functionalities on their own and intermix the model with additional specifications that close gaps which remain uncovered by the theory. A drawback that addresses a number of cognitive architectures like ACT-R or LIDA (Section III-B). Not every description of biological mechanisms is feasible for an engineering use nor are they compatible with each other. Dietrich *et al.* [74] introduce a new approach of hierarchical information processing which bases on neurosymbolic processing and provides a clear distinction between merging of symbols and decision making procedures. While the former must be optimized for scenario and situation identification, the latter must handle logic and temporal relations. AI technologies like spreading activation or knowledge reasoning are used for implementing the concept of context-aware decision making in the A.R.S. system.

C. Context-Aware Decision Making

According to [77] building models for intelligent decision units is one of the main tasks in the field of cognitive science. The models which will be listed in this section do overlap with AGI architectures in Section III-B, however, the latter are a specialization and categorization will be done with a different point-of-view.

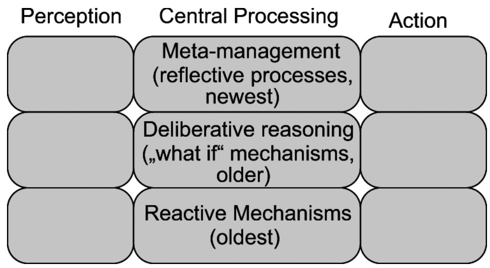

Fig. 3. Top-level view of the three-layered CogAff model. The layers represent reactive mechanisms, deliberative mechanisms, and meta-management.

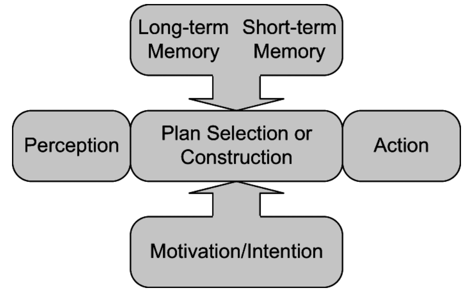

Fig. 4. Top-level view of the Ψ-Theory. It introduces cognitive, motivational, and emotional processes, but lacks a hierarchical structure.

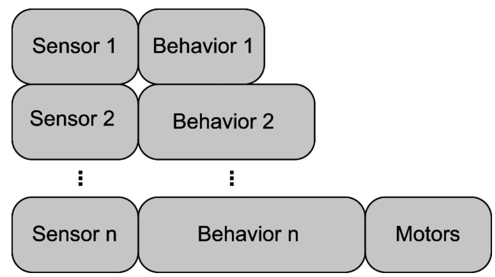

Fig. 5. The subsumption architecture. Each layer represents a behavioral primitive and subsumes the goals of the underlaying ones.

Lang [77] categorized approaches for intelligent decision units into five categories: the *neuroscientific approach*, *affective computing*, the *Ψ-Theory*, *Emotional Machines*, and *Psychoanalytical Models in AI*. The neuroscientific approach is followed, e.g., by the Human Brain Project, and its predecessor, the Blue Brain Project, where a supercomputer shall be used to simulate brain sections, in longer terms the whole brain, on a neural level including synaptic connections in order to test neurologic theories. Due to the huge amount of simulated connections, neurons and activation potentials require massive computational power. According to Markram [78], the Blue Gene/L architecture (22.4 TFlops) is available for the Blue Brain project. Other brain simulation projects are C2 [79], NEUROGRID, IFAT 4G, and BRAINSCALES (the FACETS successor). In the early days of such projects it was sometimes said that a machine with human-like intelligence can be simulated in such way. However, today we can conclude that the results of such projects are impressive in terms of many neuroscientific and hardware architectural insights. But without much deeper knowledge on the structure of the human brain and its phenotypical development, no higher functions of the brain can be simulated and therefore this also left the focus of most projects. What remains is a major issue for brain simulations: increase in computer power (e.g., using multicore architectures [80]), which maybe will experience a big push with the introduction of memristors [81]. This technology already again exalts the imagination towards being the last final missing puzzle piece towards a real capable artificial brain. But, as mentioned before, human-like intelligence is not only a problem of computing power, so that predictions can be doubted.

On a more abstract level the approaches of affective computing can be seen. One of the progenitors of this group is Sloman's CogAff project [58] (see Fig. 3). It introduces a layered architecture for information processing in various differently complex processes (reactive mechanisms, deliberative mechanisms, and meta-management) and is influenced by theories of emotions and cognition. All levels consist of perception, central processing, and action. The term affective comes from affects that are used for evaluation purposes during central processing. Affect, in this respect, is a general term for emotions and feelings of different complexity. Today, the model can be seen as template architecture used to compare other architectures within the nine sections of his architecture. It also serves as discussion base for the question about the minimal requirements for higher complex decision frameworks.

In contrast to that—and at the same time being the biggest drawback—the Ψ-Theory does not make use of a layered architecture, but organizes various processes of different kind in one level (see Fig. 4). The processes are grouped into three main parts: cognitive, motivational, and emotional processes. A second big drawback of this architecture is the fact that all structures and processes are implemented in artificial neural networks. In one publication, the authors claim that it is possible to build a model as exact copy of reality if the model is built molecule by molecule [82]. Taking into consideration Gajski's Y diagram [83] such beliefs need to be discarded from a computer engineering point-of-view [74]. Each level of abstraction in the view of the system has its justification and its own tools for dealing with content in exactly that level of abstraction; they must not be mixed. Thus, it is unnecessary to simulate such a model on the base of molecules, neurons, or anything else below the functional layer, if the function is of concern. Finally, the Ψ-Theory can be compared to Brook's subsumption architecture [71] (regarding the functionality, see Fig. 5). In the bottom-up subsumption architecture, behavior is decomposed into behavioral primitives, where each layer subsumes the goals of the underlying ones, e.g. the lowest layer could be "wander around" followed by "avoid objects" asf.

The research area of emotional machines has another goal, the improved human computer interaction. This is not to be confused with emotion detection techniques, where it is tried to detect the emotion of a person with different methods. Here, machines are constructed in order to express emotions that a human can read. This does however not mean that the machine itself is capable of experiencing any emotion in a human or, as for that, animal way. As bodies for such robots dog-like [84] and seal-like [85] bodies, human-like heads [86], baby-like bodies [87], or purely artificial creatures like Kismet [88] have been used. Their applications range from purely research to treatment of Alzheimer patients or as pets for people with little social inclusion. Also, avatars with a range of facial and bodily expressions have been designed that act as guide or communication interface in computer games and software.

As a last research area in decision units, interdisciplinary efforts together with psychoanalysis are mentioned. Psychoanalysis is mainly known as a particular form of psychotherapy, but psychoanalysis as a term is actually used for three different purposes: the psychoanalytical method of investigation of mental processes (including the setup with the couch), the psychotherapy that uses the investigation method as an interface tool between therapist and patient, and finally, a set of theories about mental functions. The latter is, what makes psychoanalysis so interesting for engineers who want to create intelligent machines: Theoretical psychoanalysts hold a lot of theories, how our mind works (Only a small number of psychoanalysts conducts research and sees themselves as theorists, the big majority are therapists: users.). It can be discussed, how accessible those theories are for the nonpsychoanalysts (from our experience it is very hard for engineers), how accepted among psychoanalysts large parts of those theories are (fragmented into different schools), and how comprehensive they are (psychoanalysts never claimed to have comprehensive theories—it is sufficient for therapy—hence, many things necessary for synthesis are left blank). However, psychoanalysis is the only science available with that knowledge. For a detailed discussion about that topic including other templates for knowledge transfer like psychology, neuroscience, etc., see [89] and [90]. Advocates of this research alliance are Leuzinger-Bohleber and Pfeifer [90], Turkle [91], Minsky [92], Buller [93], and the research group being the home of the authors of this paper led by Dietrich [89].

Above, five categories of cognitive architectures are discussed on the basis of a selected representative. Modeling the physical brain is a bottom-up approach and often comes with the claim to provide a tool for testing neurologic theories but also emerging intelligence by modeling brain structures. The CogAff project is settled on a higher abstraction level but defines a fully behavioral description of individuals. This comes with the drawback that within complex systems like mammals, mechanisms which lead to a behavior cannot be described by modeling the behavior itself. This would be like modeling the internal mechanisms of a camera by observing the behavior—pulling the release button and getting the photo on the screen [94]. Another concept of modeling complex technical systems is the use of a layered architecture. Though, this concept is generally accepted and proven, it is disregarded at the Ψ-Theory even though it deals with a quite complex system—the human beings cognition processes. Emotional machines are to act emotional. While the aim to increase the human-system interaction is feasible, the use of the term emotion is a kind of misleading. Emotional machines like Kismet [88] actually do not obey of any kind of emotion but trigger emotions in their observers. Hence, they do not incorporate theories and models of emotions or have any kind of evaluation of the system state. Psychoanalytically inspired decision units try to take care for some of the mentioned drawbacks. First, they are based on a functional description of mental processes. Second, psychoanalysis combines an external with an internal evaluation system. Third, in combination with neuropsychoanalysis, psychoanalysis covers the areas starting with perception up to decision making. A drawback is that functional descriptions of scattered mechanisms are unavailable. These gaps require interdisciplinary work between scientists, neuropsychoanalysts and psychoanalysts.

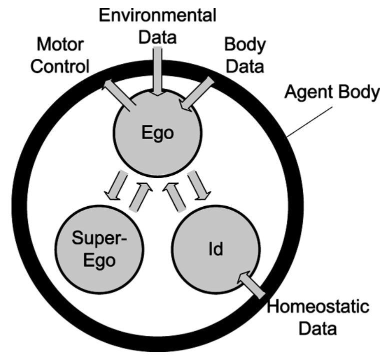

Fig. 6. Top-level view of the A.R.S. model. The components represent the functional units of the Freudian structural model, in which the Ego has to mediate between conflicting demands of the Id (representing the body), the Super-Ego (representing behavioral rules), and from the perceived reality.

As has been introduced above, the A.R.S. model [95] is another attempt to develop a reference architecture for a decision unit for a proactive agent. It should resemble human-like thinking based on psychoanalytical concepts. The developed model (see Fig. 6) represents a reactive feedback loop with two different sources of input and one output. The inputs are received from sensors measuring homeostatic values for later generation of drives and sensors for measuring bodily status and external values for later construction of perception. All input has to pass several stages of processing, the first being neuronal processing, where, e.g., in the eye already basic feature extraction takes place. The second stage is so-called neurosymbolic processing [26]. Here, the gap between neuronal and symbolic processing is bridged. Neuronal information is processed similar to the way in an artificial neural network with modality-dependent amount of layers, but the output is a set of symbols. For humans it is only possible to "think in" symbols (this is the common understanding, however, there exists no proof yet), not in pure sensor information, otherwise the overwhelming amount of information could not be dealt with. Finally, after decision making, the resulting action has to walk through this process the other way round, which is called neuro-desymbolization. Here, motor commands are desymbolized in sets of, e.g., stimuli for muscles or muscle fibers.

Following neurosymbolic processing, information is transferred to the mental realm. The model thereof is based on Freud's second topographical model, also called the structural model. To apply the model to a technical decision unit the main functionalities and interactions between the three identified instances Id, Ego, and Superego had to be identified. The first instance — the Id — generates the drive demands triggered by bodily needs or an imbalance in the internal homeostasis. The second instance — the Ego — is responsible for the reality demand combining knowledge about reality and the possibilities, constraints and subjective consequences of outer perceptions. The third instance builds the demands of the Super-Ego. Those demands are coming from social and cultural rules and believes. These three instances build the first and highest layer

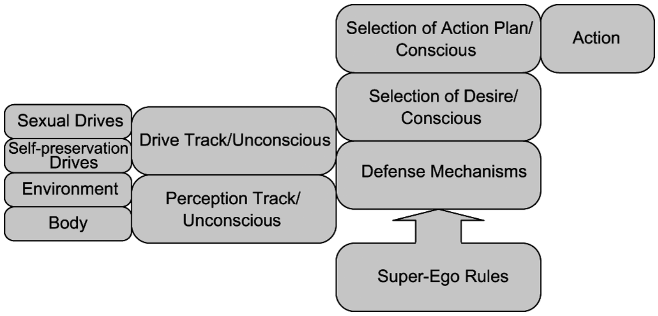

Fig. 7. Second level view of the A.R.S. model. One this level of abstraction it can be compared to the CogAff model (Fig. 3) and the Ψ-Theory (Fig. 4). It provides a more detailed functional decomposition of mental processes, since it is targeted for the control of more complex processes.

of abstraction of the model. In the second layer of the A.R.S. model, which is shown for comparison to the CogAff model and the Ψ-Theory (see Fig. 7), the inputs are differentiated into four types, two sources of drives and two sources of perception, which are then processed unconsciously. The result, an unconscious, subjectively evaluated representation of self and world is filtered in the defense mechanisms according to the learned rules of the Super-Ego. All content that passes the defense can become conscious. Conscious processing takes place in another two steps, first the most important desire according to drives, Super-Ego, and reality is selected, for which's fulfillment in the second stage an appropriate action plan is constructed.

Perception and unconscious processing of drives as well as parts of the unconscious processing of perceptions belongs to the instance Id, the Super-Ego has its own module, the remaining functions belong to the instance Ego, which has unconscious and conscious parts.

V. Discussion and Outlook

This paper presents a survey among different aspects related to Cognitive Automation. Many branches of engineering face similar challenges to overcome, namely, complexity, multimodal perception, navigation and planning, and the like. The almost generally accepted approach is to learn from human capabilities, since we, the humans, seem to be able to cope with all these problems more or less well, but still beyond comparison to machines. Unfortunately, even the answer to the question where to search for descriptions about human capabilities already splits researchers into different groups, not to speak about how to implement those theories or integrate several theories into one framework.

Automation reached a point where we become able to deal with problems ranging in scale from nano to Mega and in area of application from chemistry to medicine or finance. Automation is of concern in almost all businesses since it helps in supporting core interests of companies that are subject to competition and in need of further development. As diverse as the problems faced are also the solution paths followed. What can be viewed as trends in cognitive automation are the following: First, at least on a hardware level, standardization becomes a more and more important issue. For instance, in humanoid robot soccer, the standard platform league—where all participants use identical hardware and even the same drivers—gains popularity. Also, ROS [96] as an open-source meta-operating system for robots becomes available for more systems and can be used to control the platforms on a standardized way. Fieldbus and other communication systems for many different areas of applications have also been standardized. As a second trend, hierarchical processing, in general, becomes more popular as it allows decoupling and solving problems on different levels of abstraction. Maybe we will see a standardized processing architecture one day as it has been introduced for communication systems with the ISO/OSI model. Third, with different approaches, a trend to more humanoid appearances can be observed. There are humanoid robots on the one hand and cognitive architectures on the other. Both research directions imply interdisciplinary cooperation with experts from the humanities. Actually, in a broader sense, we see this as the fourth observable trend: interdisciplinary research.

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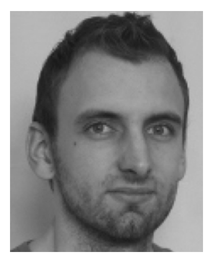

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