A New Model for Autonomous, Networked Control Systems

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***Abstract*—Existing communication utilities, such as the ISO/OSI model and the associated automation pyramid, have limitations regarding the increased complexity of modern automation systems. The introduction of profiles for fieldbus systems, or field-area networks (FANs), was an important innovation. However, in the foreseeable future the number of FAN nodes in building automation systems is expected to increase drastically. And here the authors see an opportunity to revolutionize the operation of intelligent, autonomous systems based on FANs. The paper introduces a system based on bionic principles to process the information obtained from a large number of diverse sensors. By means of multilevel symbolization, the amount of information to be processed is substantially reduced. A symbolic processing model is introduced that enables the processing of real world information, creates a world representation, and evaluates scenarios that occur in this representation. Two applications involving human actions in a building automation environment are briefly discussed. It is argued that the use of internal symbolization leads to greater flexibility in the case of a large number of sensors, providing the ability to adapt to changing sensor inputs in an intelligent way.**

I. INTRODUCTION AND MOTIVATION

NATIONAL and international standardization organizations such as ISO, IEC, SAE, CEN, CLC, and others [1] have developed standards for automation protocols for the transmission of information from several signal sources through a single communication system. These field-area networks (FAN) efficiently link sensors, actuators, and controllers by means of single communication medium. One of the first organizations to define such a protocol was the Society of Automotive Engineers (SAE) (a technical body of military and industrial members in the U.S.) in 1968 [2]. This protocol was the fieldbus MIL 1553, which was first integrated in the Air Force F-16 and the Apache AH-64A attack helicopter. It is still a communication base in avionic systems.

Such simple two-wired transmission principle played an insignificant role in industry at that time, and was of very little interest to the research community. Only in the late 1980s did industry realize that these bus systems are a very efficient and economical way to collect process data, and to control sensors and actuators. CAN and PROFIBUS were among the first FANs, and are still very successful to this day [3]. These principles were subsequently adopted in the OSI model defined by ISO. Initially, only two or three protocol layers were defined, because at the time no need was seen to define layers three to seven, due to the nature and constraints of the applications.

However, industry soon realized the huge possibility of FANs and defined various other types, with characteristics dependent on the specific application. And in the specific case of building automation it was necessary to define protocols consisting of all seven layers, because the number of sensor nodes is typically very large. At present, buildings with 50 000 or more networked nodes are not uncommon. Obviously, this has lead to a dramatic increase in the complexity of such systems, with the associated difficulty of handling the data in such enormous systems.

Initially, the biggest challenge was to bring together the various industry segments that had previously never really communicated with each other. For example, the industry of heating, ventilation, and air conditioning (HVAC) had previously seen no need to communicate with the industry of sunshade systems, or with plumbers, etc. Additionally, interoperability between devices from different vendors was a major issue, which is discussed in depth in [4]. In response, the user groups of the various FANs defined *profiles*, often referred to as the *eighth level* of the ISO/OSI model.

The number of applications where fieldbus systems form an integral part is constantly increasing. New technologies, requiring the networking of electronic components, are emerging. Nanotechnology is aiding the development of new types of sensors and actuators with totally new characteristics, at a minimal cost.

Technologies such as smart dust, wearable electronics, electronic grains, ubiquitous computing, grid-computing, ambient computing, smart personal objects technology, and body area networks are all new scientific directions based on, or utilizing, fieldbus systems. In the foreseeable future, the number of FAN nodes in building automation systems is expected to increase drastically. It is precisely in this area that the authors see an opportunity to revolutionize the operation of intelligent systems based on FANs.

A compelling question is how to integrate, operate, and maintain such future fieldbus systems consisting of a very large numbers of network nodes. Hence, there is a growing need to model huge fieldbus networks. Fig. 1 depicts symbolically the evolutionary steps from simple RS232 communication, through low-power bus systems such as the I^2C-bus, to fieldbus systems whose communication protocols follow ISO/OSI model, and the subsequent addition of profiles to the ISO/OSI stack.

Initial models focused only on the networking aspects of the units. More recently, models have emerged that integrate parts

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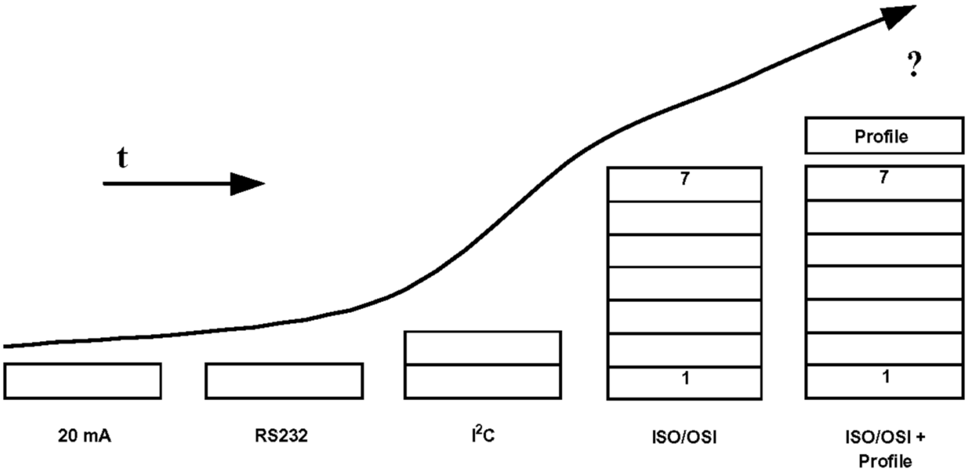

Fig. 1. Important steps in the standardization of two-wired connection of FANs.

of the application as well. This indicates that the next development step should be even more closely linked to the applications, and could even include an entire application. Therefore, if we observe the model from the sensor's point of view at the field level, with special focus on an automation system, this leads us to the notion of an *autonomous, networked system*.

In the industrial world control systems face an additional challenge—that of increasing the performance and quality of data processing. Aside of classical approaches this issue is currently being addressed by the discipline of artificial intelligence (AI). During the past 100 years, there has been a concerted effort among neurologists, psychologists, and psychoanalysts to comprehend the complex functional behavior of the human brain, as well as the operation of the peripheral nervous system. And over the last two or three decades remarkable results have been obtained. These insights have paved the way for the exploration of alternatives to current AI models [21], [22]. It is well known that the AI approach to understanding and interpreting the behavior and operation of the human brain is primarily based upon the formulation of formal, mathematical algorithms. The question, however, is whether it is possible to adopt principles from nature to derive more effective solutions that are able to apply principles taken from ongoing research in neuro-psychoanalysis, a discipline, which attempts to close the gap between biological models of the brain and high-level functional description of the human psyche. Applying these models to a technical system description shall yield a bionic system that has the potential of human-like capabilities.

The goal of this paper to introduce a system based on human perceptive principles, that is capable of processing the information obtained from a large number of sensors. By means of symbolization the amount of information to be processed is substantially reduced, and an inner symbolic representation of the real world is created. This approach leads to greater flexibility, providing the ability to adapt to changing sensor inputs in an intelligent way. The paper reflects current research activities jointly undertaken by institutes in Vienna, Austria and Pretoria, South Africa.

In the first part of this paper, we will give a general overview of various aspects and principles of human perceptive awareness. In the second part of the paper, it will be shown how these principles can be applied to two scenarios in the field of building automation and surveillance, leading to an environment with enhanced functionality and superior safety for humans.

The paper is organized as follows. In Section II, a short review of automation systems based on FANs is given. In Section III, modern automation approaches, based on x-by-wire, are briefly discussed. Section IV introduces the relevant biological and psychological principles, with special emphasis on the principle of symbolization of information. In Section V, symbolic processing model introduced, and Section VI gives a short description of two reference applications. In Section VII, two examples of application in a building automation environment are introduced and briefly discussed, and Section VIII explains the results that have bee achieved and gives a short outlook to further work.

II. AUTOMATION

The underlying idea of an automated process is to let the machine do as much as possible. This means that a developer should integrate many autonomous functions into a single control unit. Based on this idea, the two right-hand columns of Fig. 1 depict the current state of automation in terms of the communication aspect of a process. From the perspective of the control system of the entire process, a technical description of a control unit can be modeled as shown in Fig. 2.

The communication unit distinguishes between communication with other systems, and the interface with the sensors and actuators. In larger control units, an operating system is also included, to provide application software with greater independence. In embedded systems, especially in older systems, the application software is sometimes positioned directly "onto" the communication kernel.

Regarding the communication with the sensors and actuators, it was already mentioned in [1] that FANs can be distinguished from local-area networks (LANs) and wide-area networks) by defining a FAN as a bus that provides sensor-actuators communication. From this viewpoint, the 20-mA interface in Fig. 1 also provide such communication means and thus belongs to the family of FANs just like an Ethernet connection (with all

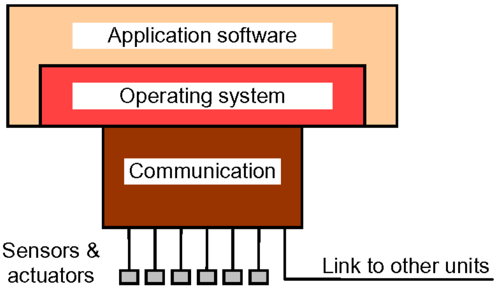

Fig. 2. Model of a control unit.

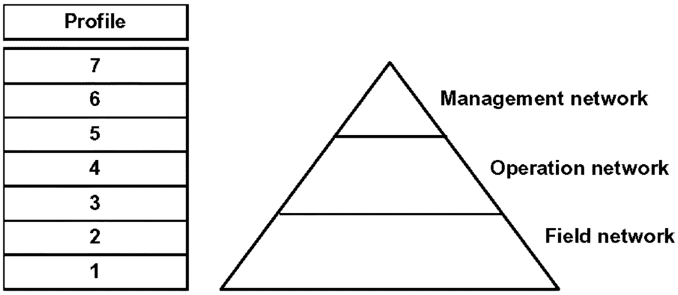

Fig. 3. ISO/OSI model (left) and the automation pyramid (right).

higher-level protocols) that connects sensors and actuators. In this sense, Bluetooth or other wireless bus systems can also be regarded as FANs.

A decisive step in the development of FANs came when parallel buses were replaced by serial buses, on which process and control data share the same medium. This means that process data and control data is transmitted over the same wire, by means of separate protocols. This step paved the way for the OSI/ISO model, as shown in Fig. 3.

In addition to the ISO/OSI model with its profiles above layer 7, the automation pyramid shown in Fig. 3 provides a hierarchical view for automation systems and their communication needs. Standards of this kind can be found in papers of CEN (TC 247 WG4). However, most of these are proprietary developments focused on very specific applications.

The control unit of Fig. 2 is normally implemented by means of a programmable logic circuit (PLC), an industrial (IPC), or sometimes by means of a special embedded system. In most cases, the application software (ASW) forms the largest part of the software; as pointed out earlier, one of the goals of automation today has to be reduction of complexity (and thus the size of software) to be able to keep an overview of design and maintenance of complex systems. Thus, when user groups define additional profiles for the ISO/OSI stack, the goal is to introduce standardization that will lead to an increasingly open software structure.

Fig. 4 depicts an enhanced view of the control unit of Fig. 2. The communication unit is closely linked to the sensors, and resides above the process where all the application functions and sensors are located. At the perimeter, on top of these entities, the human influence and control functions are positioned, linked to the communication unit by application software. Typically, a prime objective of an autonomous system is to reduce the size of the application software.

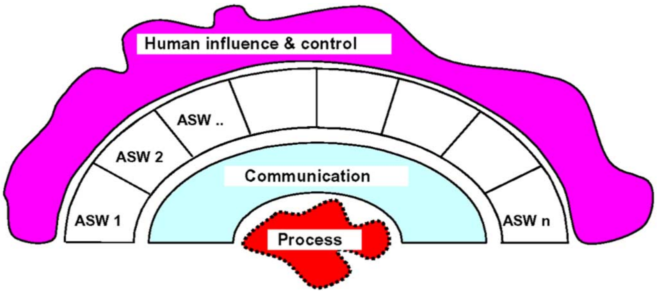

Fig. 4. Process model depicting the ASW.

In many FAN working groups, severe practical problems are encountered as a result of earlier definitions and decisions. Initially sensors, actuators, and controllers were defined as profiles. If a smart sensor or a smart actuator would be used, then a further controller would not be necessary. A question to consider is whether these definitions should be changed, or whether the profiles should be redefined.

This problem will have to be addressed in the working groups of various standardization organizations. However, we will consider ways that will lead to an increase in the complexity of the application software (Fig. 4), rather than increasing the human part of the task of controlling the process efficiently. In order to explore this novel approach, the authors have not pursued traditional problem-solving methods, i.e., searching for optimized processes, developing improved mathematical algorithms, or finding efficient structures. The basic aim of this paper is to rethink the entire control unit structure by comparing it with bionic information systems.

Towards this end it is necessary to understand the function of the peripheral nerves (equivalent to fieldbusses) in human beings, which is covered in Section IV. The peripheral nerves are a fundamental part of the human nervous system to obtain perceptive consciousness [12], [13], which is a prerequisite for consciousness. Furthermore, we note that without peripheral nerves a human being cannot achieve consciousness [14], and this prompts us to explore the principal ideas on which our new proposed approach is based.

It also worth noting that in bionic systems the ability to process information is moved to the periphery; instead of central data processing, each sensor is capable of doing data preprocessing; only then os the data further processed in a central unit. Hence, software is rapidly becoming a prime contributor to the total cost of a system. Therefore, one of the key aspects of modern systems is the usage of smart sensors and actuators, leading to powerful, autonomous, distributed systems. As a result, there is an increase in feedback control systems in the applications, which results in more reliable process control.

III. MODERN AUTOMATION PRINCIPLES

Fieldbusses are standard in most areas of automation, and are also included as interfaces in devices, as well as in ASICs. The question that we are concerned with is, why this would make sense. We are living in an age of information technology, where data is collected from processes and transmitted to various control stations, manipulated, and eventually united in higher abstract-level functions, thereby making it possible to control processes more efficiently and with greater precision. The modern airplane is a prime example.

In the early 1980s the European Airbus industry changed to fly-by-wire systems in civil aviation. This made it possible to move the airplane from a stable to an unstable flight condition. It was found that an airplane that is operating in an unstable condition uses 25% less energy [18]. And this became one of the major factors that contributed to the huge success of the Airbus. The unstable condition causes a swinging of the nose of the Airbus A320 at a frequency of about 10 Hz, which necessitated the replacement of the mechanical connection between the control stick of the pilot and the flaps by a fieldbus (MIL 1553), and surrendering the central control of the airplane to various computer systems. This paved the way to replace mechanically controlled processes by x-by-wire systems, resulting in greater economic efficiency, safer long-term operation, lower maintenance costs, and simplified remote control and maintenance.

Modern cars illustrate another important principle. Mechanical gears present a compromise between the different rotational motions of each of the four wheels, the size of the wheels, the speed, the road surface, etc. Future cars will be fitted with a drive-by-wire system, and engineers are already thinking of independent electrical motors for each wheel. This will lead to a situation similar to that of the locust, described in Section 4. Each wheel will have its own intelligent unit that is connected to other wheel control units by a fieldbus, under control of an efficient algorithm. However, this will only be possible if designers are able to integrate a sufficient number of sensors into the wheels and other relevant components of car, leading to huge and vastly complex system.

This example illustrates various points. Future mechanical interconnections will be increasingly replaced by x-by-wire systems (fieldbus systems). This will lead to very complex systems, requiring a large number of diverse sensors that are connected to embedded systems, able to compute and process the flood of sensor data. It will become necessary to describe processes much more precisely in terms of nonlinear mathematical equations and algorithms, than traditional mechanical systems do, and, in many cases, it will become necessary for a machine to operate autonomously, without any human influence or interaction—possibly because the machine is more reliable, or the process task may be monotonous or dangerous. To control such processes, systems will be needed that have better distributed processing capabilities than what is currently available.

IV. BIOLOGICAL AND PSYCHOLOGICAL THEORY

A comparison between an amoeba, a locust, and the human body shows that the nervous system is the primary basis for the high performance of natural, autonomous life. The amoeba does not have a nervous system, but only an indirect communication system based on chemical substances that are transporting vital information. The locust—viewed as a more complex "process"—has a nervous system that operates as a separate entity, and is therefore more flexible in responding to the affects of nature. However, from an engineering point of view it is important to note that the legs and wings of the locust are not mechanically inter-connected, like the wheels of a car. The interconnection is provided by the nervous system, which may be compared to the fly-by-wire, or drive-by-wire, system of an airplane or a car. Thus, a similarity exists between the function of the peripheral nerves and a fieldbus system (FAN) that is encountered in a car or airplane.

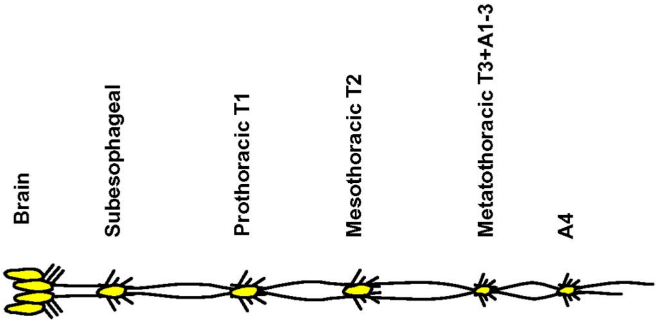

Fig. 5. Model of the nervous system of a locust [5].

Another important observation is that the nervous system of the locust is distributed, and not centralized, as illustrated Fig. 5. It is also interesting to note that the size of the ganglion node in the brain of the locust is comparable in size to the ganglion node of the wing muscles [5].

In a very real sense the "intelligence" of the locust is distributed throughout its entire body. However, compared to the human body, a locust has only a small number of nerves.

In the case of the human body, the mechanical, mobile parts such as the legs and hands are much more flexible than the comparable body parts of the locust. This indicates that the human body requires a substantially more complex nervous system, with highly efficient algorithms to control and coordinate dynamic activities. Nevertheless, it is important to realize that the human system is essentially the logical extension and further development of a nervous system similar to that of the locust: it is also completely decentralized and distributed, and the basis of control of the muscles are reflex-bows [6], [7]. However, there is one fundamental difference: the main part of the human decentralized nervous system is the brain, which is located for safety reasons in a centralized position in the head, surrounded by protective bones and suspended in a saline fluid.

In recent decades much research in the fields of neurology [7], [8], biology [5], philosophy, and artificial intelligence has been devoted to gain understanding of the brain processes. Also, early experiments with electronic stereo tactile instruments [9] have not really made any substantial contribution towards a better understanding of the complex functioning of the brain. This has indicated that it is futile to try and understand the complex human behavior by investigating the properties of single nerves [10], [11]. Yet, some researchers are still attempting to explain complex human functions, such as consciousness and feeling, in terms of neurons and neural networks [8].

This could be compared to an attempt to explain the operation of a complex computer program in terms of the transistors found in the underlying arithmetic unit. Yet, in the computer literature we would never find books in which the operation of a

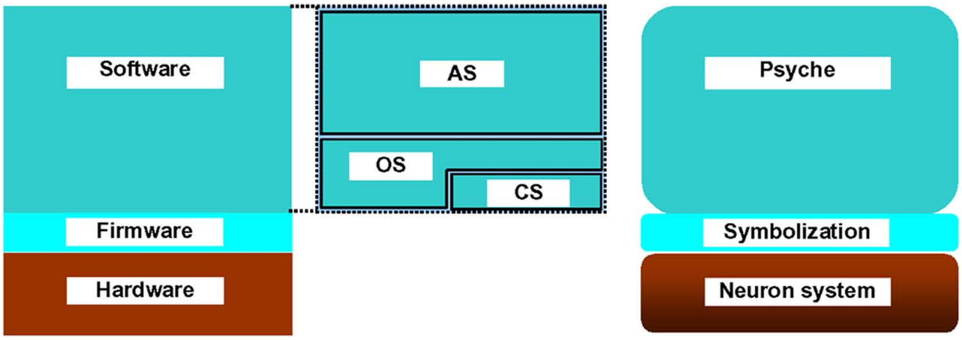

Fig. 6. Comparison of the models of computer science and the PPP viewpoint [15].

word processing program is explained in terms of the underlying hardware.

Freud was one of the first researchers to fully realize the impossibility of this approach, and in response he founded the scientific discipline of psychoanalysis. Today psychology, psychoanalysis and pedagogics (the so-called PPP sciences) are devoted to gain insight and understanding of the workings of the human brain—a task that has kept researchers busy for more than a century. These efforts have been rewarded with substantial progress over the past few decades. However, it seems that in general scientists in the fields of artificial intelligence and computer technology remain oblivious of these scientific findings.

It is our viewpoint that we need a better understanding of brain processes to derive more humanlike intelligence in systems that will enable the development of new solutions for a large number of problems. Therefore, it is imperative to take cognizance of the findings of the PPP scientists. They have already developed models that enable them to explain aspects of human behavior. It is interesting to note that in recent years neurologists and PPP scientists were able to close the gap between the understanding of the functions of neurons and the high-level functions of the brain, such as consciousness and feeling [11], [14]. This should motivate engineers to carefully consider these results to adapt them to the technical world.

In computer technology it is helpful to distinguish between hardware and software. The human body has an analogous model, shown in Fig. 6. The computer hardware corresponds to the human nervous system, and the software to the psychological part. A commonly encountered spontaneous counterargument is that the psychology model is an autonomous system; the hardware/software model is not. However, there is a strong argument in favor of this comparison. If an autonomous system is able to respond to current and past information, we may also view a robot as an autonomous system, but with an "intelligence" that is very rudimentary compared to that of a human being.

In [15], the authors explain the latest PPP results in more detail. And many other books also provide answers to our questions [7], [16], [17]. For example, a human being can be seen as a process that responds to incoming information and past processes, and is required to react immediately, or according to relevant needs and wants [14].

As mentioned above, an important problem is the gap between the "psyche" and "nervous system" of the model in Fig. 7. In the computer world, a *micro-program* (firmware) can be viewed as this "interface". The micro-program activates flip-flops, registers, memories, etc. by means of hardware control lines.

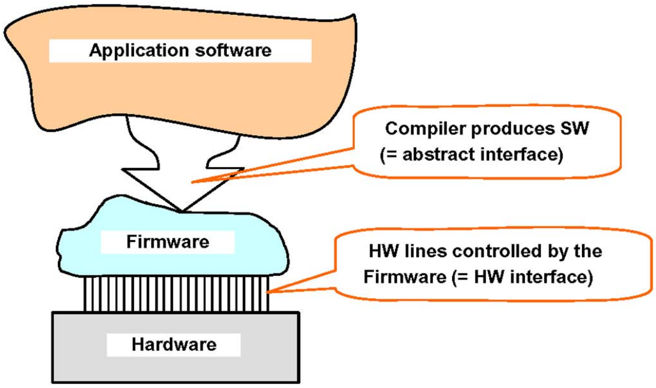

Fig. 7. Micro-program interface between software and hardware.

A. Symbolization by Humans

In the case of the human mind the process of *symbolization* [6], [23] can be seen as the "interface" between the neuron level and the psyche. Symbolization concerns the way in which we visualize real world. The massive amount of data input from the sensors is condensed hierarchically by means of symbolization. A symbol then represents a condensed piece of information that can be processed by the system. This research field was explored and developed by psychologists over the past decade [10], [11], [14], and in [15] these results and findings are explained in more technical terms.

The human brain functions as a modular, hierarchical system. However, Freud was already of the opinion that, as a first step, it is unimportant to link various aspects of human behavior to specific areas of the brain, in order to be able to understand the behavior [14].

For example, sorrow, feeling, or the awareness through our consciousness are complex functions that are not located in a specific area of the brain. Rather, these are the result of many functional modules, located in many different areas of the brain, as evidenced by tomographic analysis. Higher functions can only be described by abstract symbolic functions, making it impossible to describe them by means of mathematical algorithms

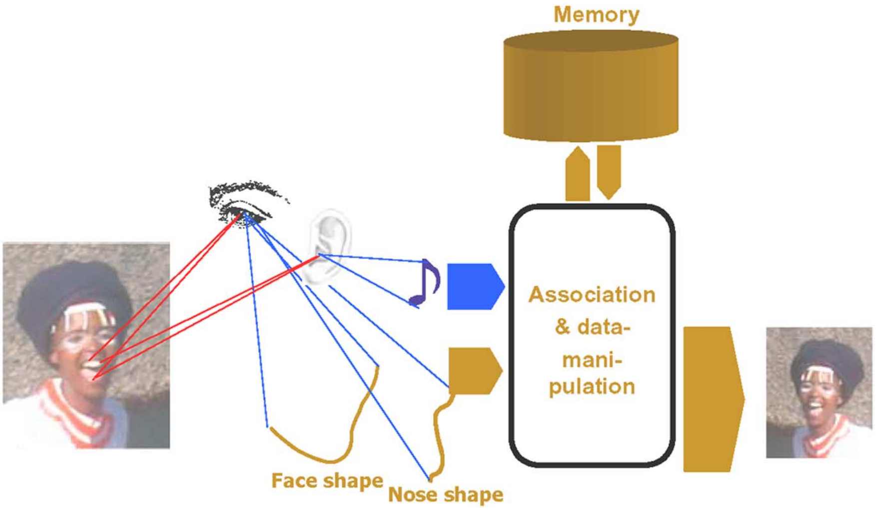

Fig. 8. The outside world is perceived by comparing known images and constructing a representation.

at this point in time (and probably not in the foreseeable future). Hence, we need to consider other models, and it seems plausible to seek for these in the PPP world, where an accumulated body of knowledge of more than a century is readily available.

For the first step in symbolization, two fundamental observations are important:

- how we "see" the world;
- how we adapt and accept this information in our consciousness.

In order to understand these two aspects, it is helpful to introduce the concept of *perception*: *Perception* refers to the processing of all incoming data by the sensors, and associated networked neurons. A child is born with sensors that are not fully developed [20]. But when the child touches its toe with its hands, it feels the toe, sees its hands, and also smells its body and hears its own squealing. These are causal actions that are memorized as an important set of impressions for an infant human being. Many impressions are collected (optical, tactile, smell, taste, and acoustic impressions), and linked to another, so that the child is constantly becoming more able to differentiate between internal and external objects.

It is important to understand that the higher, cognitive layers of the human psyche are not able to process many concepts at the same time: It is impossible to consciously scan the outside world and point out the important objects or activities. Rather, information is processed differently: the sensors, with the neural network behind them, accept only certain characteristics from the outside world. For example, if we see a person, then we see the typical form of the eyes or the nose, and hear typical sounds that we identify as a human voice (Fig. 8). This data is associated with images in our brain, which we see as real images. These images are the *symbols* that are utilized for further processing. We are actually "seeing" virtual images, initiated and stimulated by impulses from the outside world (where "seeing" actually refers to all sensory input, not only visual). Hence, our brain does not need to process complex algorithms to construct an image; it only needs to associate images of symbols by means of a huge database. A current research topic in the PPP field is concerned with the way in which this database is being constructed. The mechanism of perceiving the world as a number of known symbols is the basis for the system concept that is introduced in the next section.

For us as engineers, an important question to consider is how to describe the symbols and scenarios in our brain. And in which way they could be linked in a machine, so that that the machine is able to perceive the internal and external world in a way similar to the human brain.

It should be clear that we need to understand how consciousness works, to enable us to implement such a model. This is an important initial step, in the quest for understanding perceptive consciousness, and how to implement the perceptive part of the model. Perception, which is closely linked to sensory information is followed by a recognition process, which operates solely on higher symbolization level. With this information, a machine would be able to recognize the internal and external world and react more efficiently.

V. SYMBOLIC DATA PROCESSING MODEL

Applying the insights from the domains described above, we proceed to define a model that is able to combine currently available data processing mechanisms with models from neuroscience, psychology, and psychoanalysis sciences. The model consists of two parts: one part is responsible for perception of the environment and creating a world representation, and a second PPP part that operates on the world representation.

A. *Perception and World Representation*

A human being has a complex neural system consisting of millions of neurons. The technical analogy of a neuron is the controller unit of an automation system. The nervous system is completely distributed but the main control function is located in the head, surrounded by a protective shell of bone, and forms the "primary control centre" of a completely distributed system.

Sensors for tactile stimuli as well as the actuators, such as muscles and glands, are connected to the brain by peripheral nerves. Neurologists have defined the structure of the brain in hierarchical terms, and were able to locate special functions by

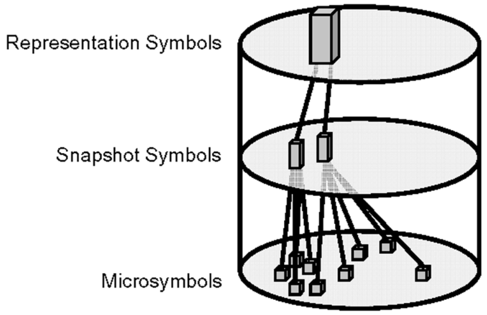

Fig. 9. Symbol creation and information condensing.

observing the effect of injuries to the brain, and also by means of tomography experiments. However, to date, they have not been able to close the gap between the operation of the neural system and higher complex functions, such as consciousness and feeling. Also, they have not been able to explain these functions in terms of neurons. Hence, it is doubtful if such an approach will ever result in new insights into these higher complex functions in the foreseeable future.

Consider, for example, the human visual system. At the sensor level, raw light levels and colors are perceived using an array of light receptors. However, at the cognitive level, the world is seen as consisting of “objects”. Hypercomplex cells, for example, can detect corners, angles and discontinuity [27]. These features represent a compounding of raw visual data into symbolic form. In fact, this symbolic representation is effortlessly utilized and processed by the conscious mind. Humans do not see the world as light levels, but rather as a collection of visual objects. The same applies to the other human senses. We do not sense a specific temperature, but rather are able to distinguish between “hot” and “cold”. We do not hear specific fluctuations of frequency, but rather hear “words”, “notes”, “sounds”, and so on. Our perceptions are automatically translated into high-level symbols. Thus the world is perceived by the conscious mind as a collection of symbols derived from sensory images.

The model that is used in this article comes from the work of neuroscience and psychology, based on [28]. By combining it with hierarchical data processing as known from building automation we get the model shown in Fig. 9. It consists of three layers of symbols: *microsymbols*, *snapshot symbols*, and *representation symbols*. These all exist simultaneously, but on different levels. Symbols can be created, their properties can be updated, and they can be deleted. Symbols are shown as cuboids of different volume in Fig. 9, indicating that their level of sophistication increases at each level. Also, the number of symbols is different at each layer: at the lowest layer occur a large number of microsymbols. At the representation layer there are only a few symbols, where each symbol represents a lot of information of a higher quality.

The three types of symbols shown in Fig. 9 are defined as follows: a microsymbol is formed from the sensory input data. Similar to the many different sensations that the human brain has to process every second, a microsymbol is created from a few single sensor inputs at a specific instant. Microsymbols are created every time the real world changes, and this change causes sensors to trigger. Microsymbols have an event-like character, that exist for an instant. The step from sensor values to microsymbols includes a first processing of the signal in terms of discretization. The ISO/OSI protocol stack up to layer 7, plus profiles are also located below the microsymbol layer. Here, the topology of the network and the transfer of information across the network is defined. Raw sensor and actuator data is collected and passed on to the next level for processing. The interface of this layer is a set of data points that can be processed, regardless of the underlying fieldbus or network technology.

A group of microsymbols is combined to create a snapshot symbol. These symbols represent a part of the world at a certain point of time. The combined snapshot symbols represents how the system perceives the world at a given time instant. The creation of snapshot symbols gives a first layer of associations between the microsymbols.

The next level of symbolization is the representation of the world. Compared to the lower levels of symbols, there are only a few representation symbols, and these are seldom created or destroyed (only their properties are updated regularly). On the representation level, the system has information about the current state of the world, together with the history of recent events. Based on snapshot symbols, the system utilizes all currently available perceptions to create a consistent and continuous representation of the world. Representation symbols are the first level used by an application to obtain information about the world. The snapshot and microsymbol layers below are not used by applications, since the applications represent higher cognitive functions that operate on the resulting set of symbols. It is understood that the mind does not operate on single impressions of the retina, but rather on the perceived symbolic image. Similarly, the applications that operate in the PPP model utilize the representation to obtain scenarios instead of analyzing single snapshots or microsymbols.

Since perception relies on information from sensors which are already employed today, the aim is also to use existing algorithms for the processing this information. The goal of this system is to incorporate existing methods and algorithms (e.g., Kalman filters [29] for position detection or state-of-the-art image processing) and to build a model on top of it.

B. *The PPP Model*

Some neurologists, such as [26], [19], [16], and [14] have realized that the brain can be viewed as a purely functional system. Recent research results indicate that high-level functions cannot be exactly located in the brain. One consequence of this observation is that healing for problems related to higher level functions is only possible by analyzing these functions and finding corresponding remedies, and not by the application of drugs. The psyche should be seen as detached from a specific physical location in the brain. In an attempt to incorporate the research results of Damasio, Solms, Lurija, and Freud, we have introduced the PPP model to enable high-level processing in the system. The PPP model operates on symbols, and introduces the concepts of emotions and drives to evaluate the world representation. The world representation that is created by perception is used to identify scenarios—timed sequences of events in the representation layer. Scenarios have emotions attached to them,

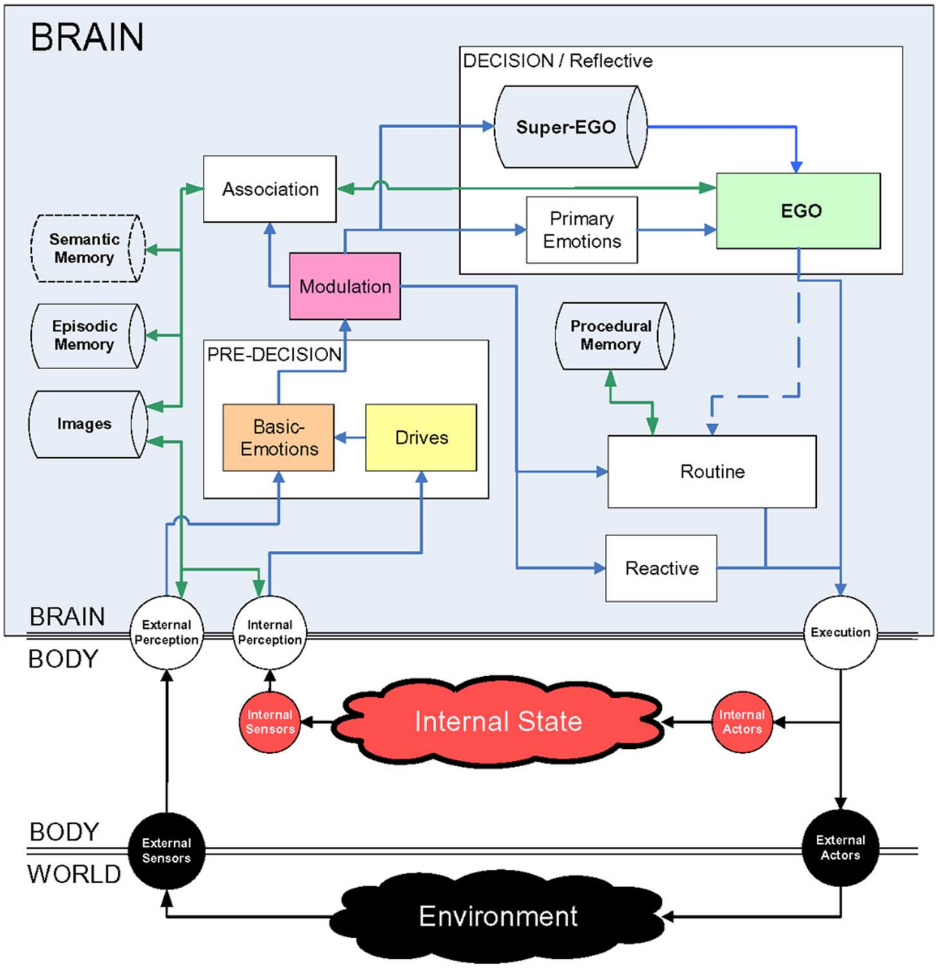

Fig. 10. System model.

in order to provide an evaluation of what has been perceived. Updates in the representation alter the emotion levels. Based on emotions, the system makes decisions for appropriate reactions. In order to remain within the scope of this paper, we focus on the observation and perception of the environment; reactions are therefore limited to status information for users.

Drives are intended to prompt the system to achieve a goal. By following its drives the system attempts to fulfill its tasks. Concepts like hunger, fear, fleeing, fighting, etc. are, of course, not applicable to the field of building automation systems, and have to be adapted. The drive "hunger" may be interpreted as the relationship between consumed and available energy. A high "hunger" level would result in the reduction of currently unimportant services, like the heating of unoccupied rooms.

The complete system model as a combination of perception and the PPP model is shown in Fig. 10. The PPP model operates on the world representation and searches for scenarios, to which drives are attached in order to evaluate the perceived world.

The symbolization forms a bridge between the sensors and higher-level modules. It acts as a filter, removes redundancy and "noise" from the raw sensor data, and passes highly condensed symbolic information to higher-level modules.

The perception is able to create successively more abstract levels of representation, by building higher-level symbols from lower-level symbols. Thus, a hierarchy of symbols is formed as shown in Fig. 9 that translates sensor inputs into perceptual symbols. In this way, large quantities of sensor data are condensed to yield a compact set of semantic symbols. The creation of semantic symbols is driven by the ability of the symbols to encode information.

The symbolic representation forms the link to the higher-level models of the psyche. In general, humans consciously perceive only the highest-level symbolic representation of their environment. For high-level models of the psyche, the models and language from the PPP world are adopted. The symbolic representation acts as input to the higher-level PPP-based models. In Predecision, a first evaluation takes place, which feeds the high-level modules Super-Ego and Ego, that are responsible for decisions on how to react on the current state of the real world. As a result, actions can be taken in different form, which is done in the Routine and Reactive modules.

VI. REFERENCE APPLICATIONS OF THE MODEL

We present two cases to illustrate the applicability of the model in a building, such as an office or public building. The applications are part of the PPP model; their task is to perceive high-level scenarios in the world representation and to react to recognized scenarios.

A. Application 1: Human Surveillance System

In the first application we introduce a *human surveillance* system. Making use of light barriers, detectors, pressure sensors in the floor, door contacts, and cameras a system is created that is able to know where a person is in a building. Persons are considered to be anonymous, which means that the system has no specific knowledge about their identity, unless a person is provided with an additional identification mechanism (e.g., authentication at a security door). The system is able to provide information about a person's current and past location, so that the path of a person through a building can be tracked and monitored.

B. Application 2: Theft Protection

The second application supervises sensitive items or objects. In a given room the system monitors a set of objects (e.g., books in a library) that may not be removed. Should a person (intruder) attempt to remove a sensitive object, the system will detect this, raise an alarm, and inform a (human) supervisor.

These two applications share a common scenario: we define a number of rooms on a floor with the same layout for both applications. The sensors that are used are also identical, and mounted in the same position. In this way, the symbolization mechanism shares a common set of symbols (although not all symbols have to be present in both applications).

The system obviously has only a limited understanding of the world it perceives. The fact that cameras are installed does not automatically imply that the system is able to process all the information in a way comparable to that of a human operator that observes and evaluates a camera image. For example, suppose that a dog enters the room. This could possibly be perceived as a "person", since the system has no initial concept of a dog. Hence, the system is bound to make incorrect decisions if it is confronted with facts or images that are outside the scope of its capabilities. This system attribute is intentional, since it does not form part of the task that needs to be fulfilled. If we introduce a new application, which makes it necessary to distinguish animals from persons, the knowledge base of the system will have to be enhanced.

VII. RESULTS

The ongoing research activities have yielded some very interesting results. A prototype implementation of the model, as described above, is used to process sensory information from a real-world, as well as a simulated virtual environment.

A. Prototype Implementation

A prototype implementation of the symbolic processing model operates on data that is gathered by the sensors and the simulated sensor values. The various microsymbols are created using rule-based algorithms or preexisting algorithms to create microsymbols. The rule-based approach uses a set of predefined rules to decide when to create symbols. Although not very flexible, it is the fastest way for symbol creation. Using the tactile floor sensors, microsymbols are generated that indicate motion in the room. Since the model only knows about persons (and not animals or autonomously moving objects), these motions are used for position detection of persons. Only sensor values that fulfill certain temporal and spatial requirements are used to create microsymbols (which are called "footprints"). Depending on the sequence in which sensors are triggered, the system detects either mere footprints or footprints that have a direction of movement.

Motion detectors are mounted to detect motion in the room. Similarly, light barriers detect motion along a line. This information contributes to the positional information of a person. The areas that describe the position of a person are reduced to two-dimensional shapes, approximated by basic shapes such as rectangles, triangles, lines or circles so as to simplify subsequent processing steps.

Cameras are used to detect motion and create microsymbols that contain the size and center of gravity of the moving area. Color histograms of these areas are created to lead to a better identification of persons. A face-detection algorithm, which is part of the OpenCV camera vision library [24] is used for face detection and creates microsymbols that aide in person detection. Again, identification of individual persons is not the goal; the face detection shall rather assist in increasing the reliability of detecting and distinguishing anonymous persons.

The output of the microsymbol creation modules is used for the second layer of symbolization, to create snapshot symbols of the current world status, as perceived by the system. In the above example, the various contributions to person detection (footprints, areas of motion, detected faces, etc.) are associated with a snapshot of a person, which is used in the next step to create or update a person's symbol on the representation level. Currently, rule-based algorithms are used that rely on the type of microsymbol information.

At the end of the symbolic processing the system has created a symbolic representation of its environment. In the current prototype implementation this representation consists of persons and objects. This representation forms the basis of the reference applications (Section VI). Using the current representation and the historical data that is available, the applications detect scenarios in the world representation. Scenarios are defined as timed graphs of events that can occur. Graphs operate only on representation level symbols, and can contain multiple paths from one state to another. If an application is able to proceed through an entire graph, it has recognized a scenario. In the current implementation the graph-description of scenarios is done in a proprietary description language. Because the graphs operate on symbolic representation-level data and not on sensor data, the recognized scenarios are not merely state diagrams, but are able to represent complex real-world situations; this is due to the fact that representation level symbols are the result of multi-level symbolic processing.

B. Smart Environment

The model was applied to a real-world installation, in a room that is equipped with a number of different sensors like tactile floor sensors, motion detectors, light barriers, and cameras. The information that is gathered from these sensors is used as the basis for symbolic processing of information. Fig. 11 shows tactile sensors that were mounted on the floor; they produce a binary signal (i.e., no weight information) when triggered by the presence of a person or object.

Fig. 11. Tactile floor sensors in Smart Environment.

The total number of sensors in the Smart Environment includes more than 50 tactile floor sensors, yrn motion detectors with intersecting sensitive areas, 20 activity sensors for equipment (refrigerator, coffee machine, cupboard doors), and height measuring sensors that are mounted in the door to determine the size of a person. Sensor information is always augmented by processing visual data, which is obtained from four cameras in the Smart Environment.

This room is frequently used by a number of different persons and thus provides an ideal test environment for a real-world installation to gather sensor data. Since sensor values are stored in a database, the prototype implementation can be repeatedly run on the same batch of data, thus allowing the refinement of the algorithms.

C. Virtual Environment

The real-world implementation is limited by the number of sensors it can provide, due to cost considerations as well as technological limitations. Therefore, a second source of sensor data was used: a simulation of an office building that allows the implementation of a large number of virtual sensors. It consists of a three-dimensional layout of rooms and halls, in which virtual sensors are mounted and virtual persons can move [25]. The Smart Environment that was described above was implemented as a Virtual Environment, which allows the adjustment of the number of sensors as well as their position. In this way, the system is able investigate the impact of the expected increase in sensors for building automation.

Fig. 12 shows a snapshot of the three-dimensional visualization of the Virtual Environment. The number of tactile floor sensors was increased compared to the real-world Smart Environment, so that the person shown in the figure triggers nine sensors simultaneously. The visualization part of the Virtual Environment is used to create the output of the symbolic processing. By overlaying icons that represent symbols, which the system has created, the user obtains an augmented view of the real-world or virtual environment.

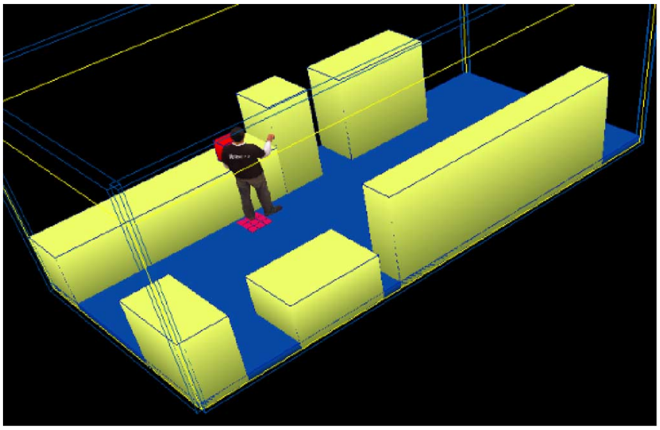

Fig. 12. Virtual environment.

D. Surveillance and Theft Protection

The reference applications (Section VI) are the basic tasks of the prototype implementation. The system evaluates the redundant position information available from the sensors and runs it through the multi-level symbolization. This yields a person symbol on representation level, which contains both the current position and the path of the person through the room. Although the current implementation uses mere rule-based algorithms to determine the position, the next step will implement a combination of fuzzy logic and neural networks for better results. It is planned for the near future to introduce more advanced algorithms for location detection, like the Kalman filter.

The theft protection application is implemented by a simplified object-tracking algorithm taken from a robot soccer implementation. The object of interest is an orange ball, which is easy to track. The application detects the object position and uses the information from the person surveillance application to determine, whether a person currently possesses the object. In case the person leaves the room, while possessing the object, a scenario is recognized, and an alarm is raised.

VIII. CONCLUSION AND OUTLOOK

Automation systems are becoming increasingly autonomous. The basis of such systems in industry, and especially in home building automation systems, are FANs, utilizing the familiar ISO/OSI model. However, it is expected that in the foreseeable future building automation systems with a very large number of sensors will emerge, for which efficient methods will be required to condense and process sensor data.

Inspired by results from the fields of computational neuroscience, cognitive science, psychology and psychoanalysis we propose a hierarchical symbolic processing model. The operation of this model was demonstrated in two prototype installations: a real-world installation and a simulated environment. The simulated environment provides a system that is able to cope with the expected future increase in sensor data, which is currently not possible in the real-world installation.

The model uses a constant stream of input data to develop an internal symbolic representation of the world using a three-layer symbolic processing model. These representations bridge the gap between sensor data and high-level models. Algorithms, which can be implemented in distributed autonomous nodes, are able to automatically condense a large amount of sensor information into representation symbols. This allows the scaling up of building automation systems without dramatically increasing the network load.

With this approach the authors intend to open a wide field for the development of new automation control systems. It is noteworthy that although the content of this paper is focused on the specific area of building application, it is not limited to it. The principles considered in this paper can be readily applied to other related industrial or process applications.

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