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The Biological Inspired Somatic Neuron Design and its Application in Robot Nervous System

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Abstract – The nervous system is the major controlling, regulatory, and communicating system in human body. One of the basic functions of the nervous system is the sensory, by which one monitors the external and internal environments. Sensory pathways to the cortex usually consist of three sensory neurons termed 1st order, 2nd order, and 3rd order neurons. In this paper, a standard biological inspired neuron was presented, which can be acted as the basis node of robot perceptual systems. The hardware and software has been designed and implemented for modeling, testing and employing sensor networks composing of many identical neuron nodes. Each node are considering ease-of-use and power considerations. Some requirements, such as 'plug-and-play' capability, system integration and dynamic reconfiguration, were described, which is achieved through an 'transducer electronic data sheet' (TEDS) in our networked transducer neuron node. The TEDS contains fields that fully describe the type, operation, and attributes of one or more transducers and its data formats are defined. The paper also specifies a digital interface for connecting neuron to access the TEDS data sheets for reading sensor data and setting actuators. Each neuron can connect more than 8 channel analog signals by 12 bit resolution, two digital channel for SPI and I^{2}C interface sensor, and more than 20 channel I/O for switch signal, it can also offer two channel analog output for controlling purpose. A set of designed neurons can be connected together by different structure to form robot nervous system, not only for sensing, but for controlling too. Example application on robot perception system and future in progress work are discussed in the end.

Index Terms- *End Neuron Inter Neuron Smart networked sensor, TEDS, Robot, Nervous System*

I. INTRODUCTION

To human beings, sense perception is dependent upon sensory receptors. When a receptor is stimulated, it generates nerve impulses that are transmitted to the spinal cord and / or brain, a person is conscious of a sensation when the impulses reach the cerebrum.[1]

As to human skin, there is a huge density of sensor, for example, 250 receptors/cm^2 in human fingertip. Moreover, multimodal sensor like vibration, pressure, shear, tactile, temperature and pain exist. It is impossible for us to design a electronic skin like human, but to robot much more sensing abilities are need. How to connect a maze of complex wiring to a central digital processor like we do today is a big problem especially for biomimetiic robot. The existing method was acceptable as the most complex robot we've built only has 150 sensors. But a cockroach has 30,000 hairs, each of which is a sensor, it is unimaginable to build a biomimetic cockroach by existing technology. [2]

The nervous system is the major controlling, regulatory, and communicating system in human body. The nervous system is based on specialized cells called neurons. The structure of these cells is adapted to transmit signals similar to an on-off switch. Hundreds or thousands of these signals can be integrated together just as the circuitry of a computer can be fashioned into programs to accomplish specific functions. [3]

Once the sensory input (stimulus) has been received by the network of nerve cells the raw data (signals) are added to and integrated with existing information about external and internal conditions. The nervous system is then capable of selecting an appropriate muscle or gland that will produce a suitable response.

There are three types of neurons:[4-6]

- Sensory neurons - designed to detect or receive stimuli
- Interneurons - found mostly in the central nervous system and form vast networks to interpret the senses and control varous effectors.
- Motor neurons - sent impulses to activate muscles or glands.

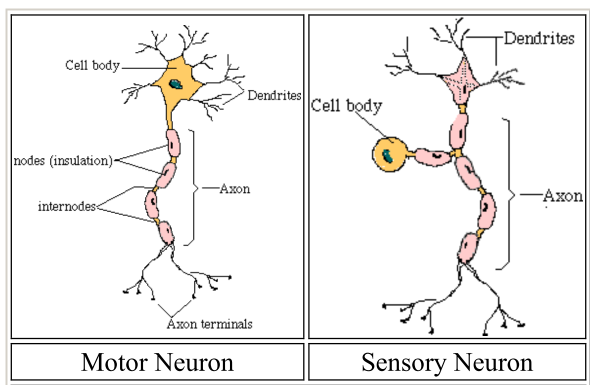

Fig.1 Neuron structure

Inspired by biological sensing mechanism, a standard neuron was presented. The motive of our design is to construct the perceptual systems for biomimetic robot based on the node through needed topology.

In this paper, we introduce the information processing procedure of human somato sensory systems at first. Then the key design points and basic prototype were present. Details of the hardware and software model are given in section 4 and 5 respectively. In the end an example application on robot perception system and in progress work are discussed.

II. BIOLOGICAL BASES: NERVOUS SYSTEM AND SOMATIC SENSATIONS

As mentioned former, one of the basic functions of the nervous system is monitoring the external and internal environments. This monitoring requires structures, known as receptors which act as transducers that convert various environmental stimuli into graded signals known as receptor potentials Receptor potentials then initiate action potentials (nerve impulses) which are carried by sensory nerve fibers into the spinal cord and, in some cases, up through the spinal cord to the brain[1].

The nervous system interprets sensory information and determines the appropriate response to a sensory stimulus. Sensory input is carried by pathways to the higher brain, or cerebral cortex. sensory pathways to the cortex usually consist of three sensory neurons termed 1st order, 2nd order, and 3rd order neurons. The whole process of signal can be represented as Fig.2.[7]

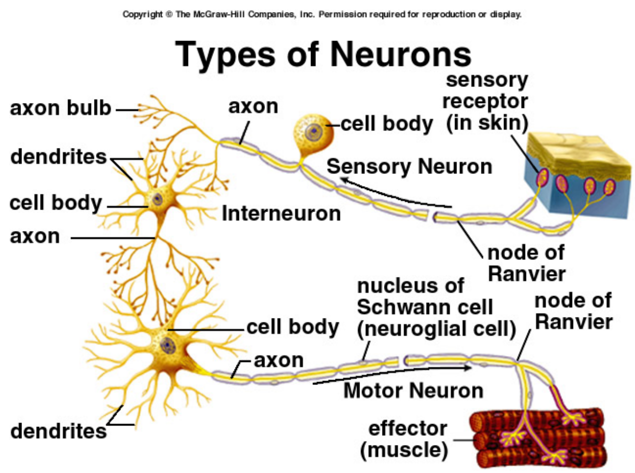

Fig. 2 The somato sensory nervous system

As noted earlier the somatic sensations include touch, pressure, position sense, pain, and the thermal sensations of hot and cold. These sensations are served by receptors located in the skin, subcutaneous tissue, muscles, and the various joint surfaces of the body. A variety of receptors serve the somatic sensations. Some of these receptors are encapsulated and some are functionally distinct free nerve endings. Mechanoreceptors are those activated by mechanical stimuli. The sensation of position comes from joint receptors activated by movements at the joint and from sensory inputs from receptors in the skin and subcutaneous tissue at the joints. The tactile senses of touch and pressure are served by a variety of receptors. In addition to the mechanoreceptors described above, there are receptors for pain and the thermal sensations of hot and cold. These sensations are also served by free nerve endings; remember, however, that some free nerve endings are specialized for some tactile stimuli. All cutaneous receptors and its sensation type, signal and adaptation is as Table1 was shown[1-5].

TABLE 1 Cutaneous Receptors

Receptor	Type	Sensation	Signals	Adaptation
Meissner corpuscle	Encapsulated & layered	Touch: Flutter & Movement	Freq./Velocity & Direction	Rapid
Pacinian corpuscle	Encapsulated & layered	Touch: Vibration	Frequency: 100-300 Hz	Rapid
Ruffini corpuscle	Encapsulated collagen	Touch: Skin Stretch	Direction & Force	Slow
Hair follicle	Unencapsulated	Touch: Movement	Direction & Velocity	Rapid
Merkel complex	Specialized epithelial cell	Touch, Pressure, Form	Location & Magnitude	Slow
Free Nerve Ending	Unencapsulated	Pain, Touch, or Temperature	Tissue damage, Contact, or Temperature change	Depends on information carried

III. THE NEURON DESIGN POINTS AND BASIC PROTOTYPE

The primary motive of our neuron is to realize biological somatosensory function based on efficient topology and as the basis node to form the nervous system for different robot. So it must be able to sense and react to the physical world by a distributed sensor networks. The basis is to achieve sensor network that can preprocess and condense sensory data at the local sensor/actuator level before sending to the higher centralized neuron somewhat like to the way human neurons do. So the basis demand of the designed neuron must be:

- Able to convert the analog signal from force sensor with demanded resolution..
- Able to communicate with each other and upper neuron node with efficient bandwidth.
- Can be react to environments with actuator interface.
- Have interface to existing standard interface sensor like temperature sensor.
- Reconfigurable according to different topology.
- Addressable
- Efficient channels to analog signals and digital signals.
- Plug and Play

In addition, it is designed for ease use of a wide range of digital and analog input/output for different application.

For this purpose, we designed a prototype of the neuron based on the smart network sensor node designed for network sensor[8]. In the work, we had designed a networked sensor node which integrate a multi-channel analog or digital interface, processor, memory, and a network controller in a single unit. To biomimetic robot, there are too many different kinds of sensors and actuators, the former is for external and internal environment information acquisition , and the latter for movement control and object manipulation. It is a distributed real-time measurement and control system, we choose the smart transducer interface module as our neuron prototype, which is a standard named IEEE1451 for intelligent sensor and actuator. It make the smart sensors easy to interface with network and support wide variety of protocols. Nowadays, it has become a universally accepted transducer interface standard supported by many famous sensor cooperation like AD, TI etc. A simple general model for our neuron can be as Fig.3 was shown.

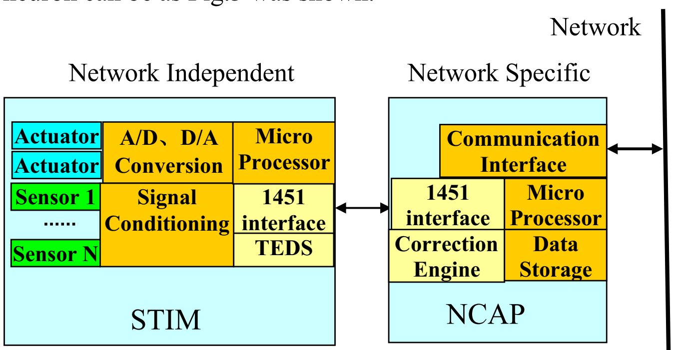

Fig.3 The general model of Neuron

The whole neuron consists of two parts: STIM (Smart Transducer Interface Module) and NCAP (Network Capable Application Processor). The first part is for sensor and actuator interface and local data processing, in which TEDS is used to define the transducer channel, calibration, end user, module itself description etc.. The second part is specified for network, here we identify the upper network communicate with the upper neuron. It is a hardware independent abstraction layer for the sensor interface and defines how the model is mapped through a network abstraction layer to the control network. Here it is a standardized software interface for connecting neuron to upper nervous fiber.

Ⅳ. THE HARDWARE DESIGN

As biology nervous system model from Fig.2, we design our neurons according to its functions in the nervous system. From the general model (Fig.3), we integrate the sensory neuron and motor neuron in the same unit, it is very likely to the working principle of biology. In our designed nervous system, two neurons, named as interneuron and end neuron, were considered.

A. End Neuron

Traditionally, a smart sensor is integrated intelligence closer to the point of measurement and control by a single processor chip. It has some basic computation capability and can communicate with special network in a standardized digital format. Obviously, it doesn't solve the problem of simplify transducer connectivity and have no open properties. This point-to-point connection of process input/output devices to a control system is expensive, both from the installation point of view and from the engineering point of view. The given basic model from IEEE1451 consists of two parts. As we know, CANBus is an universally accepted fieldbus in robot system. We integrated the two parts into a single unit, in which CANbus is embedded as communication network.

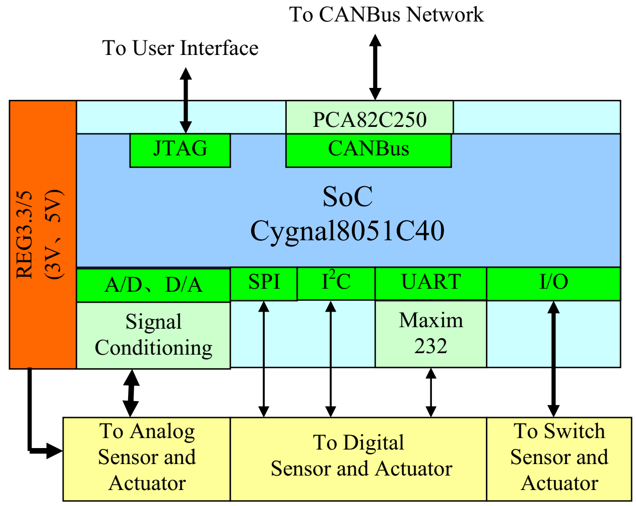

Fig.4 The End Neuron Structure

The processor we choose is Cygnal8051C40**,** Which is a fully integrated mixed-signal System-on-Chip MCU with an integrated CAN 2.0B controller.[9] The designed neuron (As Fig.4 was shown) can offer 8-channel 12-bit 100 ksps ADC and 8-channel 8-bit 500 ksps ADC for analog sensors, output two 12-bit DACs analog signals for actuator control. All analog and digital peripherals are enabled/disabled and configured by user firmware. SPI, SMBus/I2C, and 2 UART serial interfaces implemented in hardware can be used to interface with digital sensors and actuators. The FLASH memory can be reprogrammed even in-circuit, providing non-volatile data storage, and also allowing field upgrades of the 8051 firmware. It is very useful for online program in sensor network usage. The extended interrupt handler provides 20 interrupt sources, allowing the numerous analog and digital peripherals to interrupt the controller. The interrupt driven system requires less intervention by the MCU, giving it more effective throughput. The extra interrupt sources are very useful when building multi-tasking, real-time systems in our design. There are up to seven reset sources for the MCU, it makes the neuron working more robust.

As the designed unit includes analog and digital interface for actuators and sensors, the end neuron can acts as the sensory neuron and motor neuron.

B. Inter Neuron

In our design, the end neuron is not connected to central brain directly. A full-boy sense will help robot to avoid damage in unknown environment and fulfill its tasks as human beings, so a large amount of sensors and actuators are needed, it is inevitable that the end neurons will increase rapidly. The bandwidth would face the same problem as end neuron (too much sensors and actuators). The second reason need interneuron is the function difference. Vision is a good example, it connects with brain directly, it need a special neuron to process its signal. Almost all biology with vision works in this way. End neuron spatial distribution need station to convert local information to central nervous system (main computer).

The inter neuron is the center to process information from parts of end neuron, and it should be able to make simple decision. The data processing ability is the main characteristic. The raw material it got must be digital data or information from local end neuron. The processor we choose for this purpose is LPC2119, which is based on a 16 bit ARM7TDMI-S™ CPU with real-time emulation and embedded trace support, together with 128 kB of embedded high speed flash memory, 4-channel 10-bit ADC, 2 advanced CAN channels, PWM channels and 46 GPIO lines with up to 9 external interrupt pins[10]. With a wide range of additional serial communications interfaces, it is suited for communication gateways and protocol converters as well as many other general-purpose applications. The designed neuron is as Fig.5 was shown.

The A/D in inter neuron can be used for some local necessary sensing, like temperature, pressure. The design will improve the communication efficiency as it is unnecessary to get this information from end neuron. Naturally, the scheme of sensing channels assigned should meets demands.

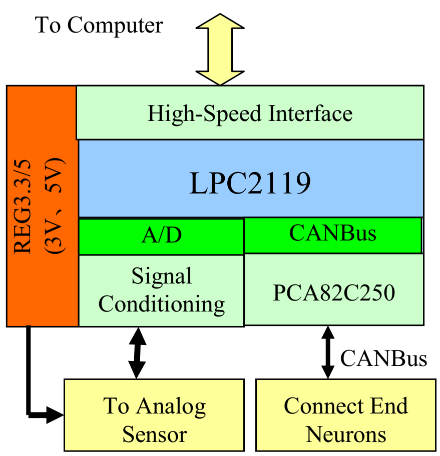

Fig.5 Inter Neuron Structure

C. Power Deign

The power system is a key part in neuron design, as it should offer energy for digital circuit and analog circuit simultaneously. In our design, we also consider offering power for sensors and actuators. The capability should give much attention, the sensors need high-precision power, a little vibration of voltage will influence the measurement precision.

Besides the on-board power, we give a high-precision 5V voltage output for sensors. In practical application, the power assigned to each part needs careful consideration, to avoid the measurement errors. We use REG3.3 and REG5.0 for 3.3V, 5V voltage output.

Ⅴ. THE SOFTWARE

Software management is a critical task in the nervous system administration of large scale networks. The existing tools for software updates in workstations cannot be used with the severely resource constrained neuron nodes.

Self-reconfiguration is the basis to fit the design points, which make it possible to disconnected and reconnected automatically in different arrangement to form a new nervous system for different biomimetic robot. The hardware offers a standard module for the possibility to form the backbone of a practical system. Software architecture must be adaptable to fit the demands of self-reconfigurable robot, i.e. high modularity, deeply embedded and large scale[12]. The hardware neuron modularity requires software modularity to take the advantages of modularity to its extreme. Farther more, the control software needs to embedded on board with the modules to achieve the autonomy of the system*(local autonomy is very important for the end neuron to achieve sensor-motor function)*, and the neuron modules need to be scalable from 100's to 1000's to meet the requirements of different biomimetic robot nervous system. Now, we face a problem from our hardware: how to communicate , coordinate, process and react to the copious amount of sensory data [13].

A. Operation System

The software on end neuron and inter neuron are different, as the former is based on system-on-chip with 8051 core, the later is on ARM. Less work on inter neuron was done, we will use an existing OS for it. To end neuron, TinyOS is a choice, which is a popular event-driven OS for embedded node system. We haven't use it directly, but the event-driven concept. The designed OS is used to manage processor startup, memory, access to hardware peripherals and system service, communication with neighboring neuron or upper neuron, service process.

B. Network soft Architecture

The architecture we designed enables the programming of complex tasks in the highly distributed reconfiguring system. This idea is coming from Y. Zhang[11] making transparent the locality of where process run, by simplifying the synchronization of multiple concurrently changing data, by protecting that shared data and by using a simple unified interface for communication.

To end neuron, we adopt a multi-master/multi-slave structure with four layers of communication. The lowest layer is the physical. It is responsible for data link on the physical media and specifics the behavior of the sensors and actuators. The second layer provides a data fusion in neuron module. The third layer is for data fusion in higher-level between neurons. The fourth layer provides communication services directly to the user application, some local services like higher level of control and management of network happen in this part. The inter neuron communication protocol is like this to some extent, the difference is it should act as management part and pay more action on data exchange between inter neurons and with central computer. More details about the soft architectures will present in another paper.

We use CANBus for neuron communication, however, CAN is for low level compared with interneuron, directly linked to physical media (to inter neuron). For most applications, a higher-level protocol is necessary, not only for inter neuron, but also to end neuron to some extent. In general, the higher-level protocol finish following services:

- Communication buffer: ingress and egress queues.

- Communication configuration: master/slave, point-to-point, broadcast, group communications.
- Communication patterns: block/nonblock read/write, confirmation or handshaking, subscribe/publish structure, etc.
- Fragmentation and reassembly of large message.
- High level data fusion and information feature extraction

C. *TEDS Format and Function*

As a standardized sensor and actuator interface, we use TEDS to realize its functions, such as addressing, data transportation, global status, global control and interrupt etc. To each type channel, it should have the necessary function such as channel identification, transducer data, status and control. To some application, other optional functions as calibration, self-test are need. All those functions are realized by TEDS representation. Channel TEDS, Meta-TEDS, Calibration TEDS are basic.

We identify all connected analog and digital transducer (receptor and effector) in biomimetic robot as seven channel types as following: sensor, actuator, buffered sensor, data sequence sensor, buffered data sequence sensor, event sequence sensor, general transducer.

To Channel TEDS considers transducer related information as lower range limit, upper range limit, physical unit, unit warm-up time, self test key and data converter related information as channel data model, c

hannel data repetitions, channel update time, channel read setup time, channel write setup time, data clock frequency, channel sampling period, trigger accuracy etc.

To Meta-TEDS, data structure related information and identification related information are considered. The former is about version number, number of implemented channels, future extension key etc..the latter is about manufacturer's identification, model number, serial number, revision number, date code, product description etc.

Calibration TEDS considers data structure related information, calibration related information and data integrity information. For example, calibration TEDS length, last calibration data-time, calibration interval, number of correction input channels and multinomial coefficient

D. *Event/Service Process*

The event-driven service process is defined as the transmitting of event state information ('state') and executable service code ('code'). Each neuron with built-in CANbus have multiple channels for analog and digital sensors (force, pressure, temperature, IR) or actuators (switch on/off, motor control etc.), as well as multiple threads of computation.

Events is the state to identify external or internal parameters, it may be from sensor threshold value or attributes of state. A service is associated with a set of parameters that can be set when the service is called, all services are associated with several basic function like "start", "stop", "reset" and "Initialization". Services include hardware and software routine. The former correspond to the settings of neuron peripherals and the later is threads running for particular task.

Ⅵ. APPLICATION IN ROBOT NERVOUS SYSTEM

Here we named the robot sensing and controlling network as nervous system using the same term of human being. This is the goal our research though this work is the initial for it. We establish a simple model for biomimetic robot nervous system, like Fig.6 was shown. The end nodes are for local sensory receptors and acting effectors. It is a combination of sensor neuron and motor neuron. The whole nervous system is divided three layers. The lower layer is end receptors (sensors) and end-effectors (actuator). The mediate layer is connected by CANbus to fulfill field information exchange. The upper layer is high-speed PCI bus for information exchange with computer (brain).

The whole system architecture consisting of three distinct levels: local level, fieldbus level and workstation level. The local level connects the sensors and actuators directly, simple processing and data exchange between nodes happen here, it offers the simple service, like sensor-motor event The fieldbus level connects the smart transducer nodes via a CAN network. It offers the predictable, timely exchange of real-time data. At the workstation level monitoring and configuration activities take place. Emphasis was set on the realization of system functions: sensor testing, calibration and evaluation. High level service is offered in this part.

Fig. 7 is the real picture of designed neuron module, the processor is based on 8051 core. In our design, the transducer on the module we choose include multi-axis wrist force/torques sensor, tactile sensor, distance sensor, acceleration sensor, position sensor and motors, switchs etc. Each sensor is integrated with the networked module according its function and actual application.

Ⅵ. CONCLUSION AND FUTURE WORK

It is a challenge for robot work in an unknown environment, he must interact and evaluate it continuously. The results largely depend on the sufficiency of its sensing. According to the sensing way adopted by most robot nervous system (here named it as we aimed to), it is an open unconstrained problem. The answer must lie in biology, as biological organisms, through thousands of years evolution, have solve the problem quite successfully.

Inspired by the biology nervous system and its information acquiring, processing and transmitting ways, we designed two neurons: sensory-motor neuron and inter-neuron. We hope to use it as the basis node for robot nervous system. This is an initial on the early stages of our work.

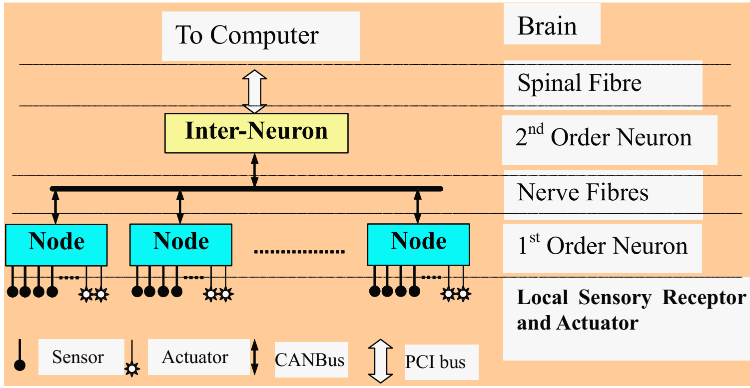

Fig.6 The Neuron model in robotic nervous system

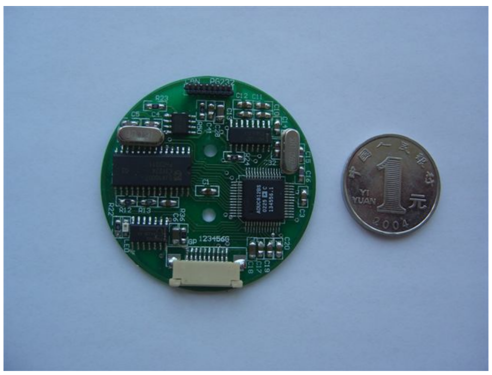

Fig.6 the module for end neuron

The work we had done just offers a biomimetic platform for further research to robot perception system. The nervous system is not like a populous sensor network, it is a tightly coupled distributed system with coordination, real-time constrains and synchronization among tasks over neurons. In addition, each software module typically needs to run in a multi-threaded environment for timely response to multiple sensory inputs and to handle multiple simultaneous actuations. All these are new challenges in software architecture design considering limited computation ability of neuron, limited communication bandwidth, and unstrained environment.

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