Research on Classification of Intelligent Robotic Architecture

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***Abstract*—It is a hot issue that how to determine the appropriate architecture for building an Intelligent Robot System (IRS). The architecture includes information processing and control system, which ensures reasonable coordination, openness, and scalability of robotic system. Unlike the architecture of computer, the design of a robotic system is so complex that it is difficult to seek systematic analysis methods due to its interdisciplinary nature despite it has built and experimented popularly. The typical reference architecture in the past 30 years are classified and summed up systematically in this paper from the AI robotics and systems analysis perspective. And then the new integrated approaches of conceptual and open physical design model for IRS are presented. In addition, six new common principles for designing architecture of IRS are proposed exploringly on the basis of previous classified research. These methodologies will provide some design guidelines for continuing to refine and improve the existing IRS. Finally, the rationality and feasibility of using these methods is concluded.**

***Index Terms*—IRS, architecture, system analysis, classification, design principles, intelligent**

I. Introduction

The aim of intelligent robotic research is the use of the theory and artificial intelligence technologies for designing, controlling and developing robot. During this research process, how to select and determine the appropriate architecture is the most basic and most critical link for building IRS. Advanced architecture can help to achieve subhuman function including task analysis, perception, planning, reasoning and decision-making, until to realize the design concept of artificial organisms. IRS will be required to become more intelligent for adapting to complex and unknown environment in the future [1]. But if the architecture is designed rationally, the complex behavior, open and scalable platform will be provided accordingly, which determines intelligence of IRS. So it is great challenging that how to combine rationally modules including perception, planning, decision making to form an intelligent system with certain characteristics for a long time. The architecture of IRS is similar to "body" design of living organisms, and with the depth of its research and breakthroughs, people are sure to find a mature methodology gradually to build IRS scientifically.

Bill Gates predicted that the rise of the robot would repeat the path of personal computers, and change completely the lifestyle of this era [2].Whether or not PR (personal Robot) will occur in the future, it is a problem worthy of study. As the father of artificial intelligence robot, Hans.Moravec said that the computer technology had made rapid development surprisingly into the mainstream, but on the contrary, robot technology had brought to its knees, not to achieve its prophecy of the 50s in the 20^{th} century. Indeed, the lack of system analysis methods with reuse approaches leads robotic developers to reinvent the wheel each time a new project starts [3]. Because of the diversity of robotic applications, it is difficult to establish a unified structure as the computer. Therefore, compared with the open architecture of computer, it is necessary to use new thinking to build intelligent robotic systems.

This problem had inspired the people to in-depth study all along. Robin R. Murphy analyzed systematically three main structure paradigm in IRS including reactive, deliberative and hybrid (reactive/deliberative), and

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provided some principles and examples [4].Kolp provided hybrid structure based on multi-agent drawing on organization theory approach [5]. And he concluded that compared to the loop, layers and task trees structure, the S-in-5 and Joint-Venture structure had obvious advantages for build robot system in these areas such as condensability, predictability, failability-tolerence and adaptability. Cai zixing [6] proposed that distributed control is the ideal way to achieve hybrid structure from the perspective of navigation control. Some other scholars [7] had explored in this area also, but few researcher construct IRS using system analysis methods.

With the development of intelligent robot, the application of artificial intelligence (AI) is the inevitable trend for building robotic systems. The same as the brain, the architecture is the platform "body" for realizing intelligent behaviors, so new developments[8] in artificial intelligence can provide some new ideological for designing IRS. Actually, the design of IRS includes both engineering and science. If there is no systematic analysis of the scientific method for guiding robotic engineering, any design methods based on "repeated optimization" and "trial and error" are difficult to achieve intelligent behavior or manufacture robot offline. For example, in order to develop the Roomba robotic vacuum cleaner, a total of 30 prototypes were produced in 12 years [9]. Why is so difficult for design IRS? The reason is that these are very different between computer system and robot system. The robot more like an organism than the computer, and its intelligence and intelligent behaviors improve during the interaction with the environment. Therefore, it is impossible to seek unity as computer architecture. The traditional methods of designing computer system clearly are not suited to designing robot. We must explore other new methods to support the analysis and integration of robotic systems. This problem is considered as the starting point of research in this paper. At first, the reference architectures of IRS are classified and reviewed in last 30 years. And then the common design principles are concluded for designing IRS on the basis of summary. These principles are the foundation of continuing to refine and improve the existing architecture, or design new architecture. Finally, the effectives and rationality of those methodologies are discussed and assessed.

II. Classification of Architecture For IRS

Dean and Wellman thought that architecture is used to describe a series of component parts and their mutual effect [4]. Jiang Xinsong[10] provided that architecture is overall structure including information processing and control system. In short, robot is typical "information" and "complex" system, so it is difficult to achieve consensus for understanding of the architecture. But many research results have shown that appropriate system analysis methods or paradigm can make simpler for solving complex questions like this. The fact recognized by everyone is that the common primitives are perception, planning and implementation for constructing intelligent robot architecture. Corresponding, people use S, P, A to describe IRS. During the research and development process of design IRS, these three primitives(S,P,A) are always the main line. S represents the ability to percept the internal and external state changes, and understands the inner meaning of these changes; P represents the ability to make decisions autonomously based on conditions, status and constraints limit; A represent the basic actions or behaviors of robot. According to this relationship between the three primitives, the structure of IRS is classified three paradigms correspondingly including deliberative ($S \to P \to A$), reactive ($S \to A$) and hybrid (deliberative/reactive).

People had provided much model architecture for IRS from different angles since early 1980's. In addition, the development of distributed artificial intelligence (DAI) had created new conditions for realizing hybrid paradigm. Parallelism, distribution, open and scalability will become new characteristics of IRS. Therefore, we divide previous reference into two categories including traditional and agent-based distributed architecture. This classification helps us to analyze meaning of architecture in all directions from two main lines.

A. The Traditional Architecture

The early architecture of IRS follows the deliberative paradigm ($S \to P \to A$) of hierarchical structure. The classical architecture is shown in Fig.1. It includes hierarchical style (Saridis [11]1979) and vertical chip structure (Shakey [12]1984). And the core of the theory is based on the symbols of the planning, which is from Simon and Newell's physical symbol system hypothesis [13]. These symbolic inference methods express knowledge and problem as a logical process. It can be used to simulate human brain function such as search, reasoning, and learning from the macro. The advantages of this paradigm are strong reasoning ability, the task layer decomposition and clear modular feature. Some scholars also call decomposition structure, because it given the order of S, P and A. And then the robot system design is seen as a one-way flow of the loop, such as Cart [14], NASREM [15] and 4-D/RCS [16]. It had shown that the main bottleneck is slow planning algorithm and difficult to adapt to unknown environment. Although the planning and modeling are enough complex, an experimental platform for realizing AI reasoning mechanism of simulating human's thought such as "introspective" and "deliberative" is provided effectively. Like this, the human brain's higher cognitive functions may be simulated in this platform.

From the perspective of system analysis, the early system analyses of IRS are mainly process-oriented software design methods and the code reuse and portability is not high. Any robotic changes of missions need to re-modeling, planning from the beginning and re-design control programs, which are out of touch with the engineering practices. And one-way circular reasoning processes can not adapt to the environment of uncertainty and unpredictability. As Robin.R.Murphy said that the robot design was considered more as an art than a science.

In the early 1990's, the paradigm of reactive ($S \to A$) based behaviorism was appeared. The central view is that

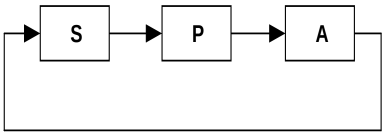

Figure 1. The structure of deliberative paradigm

the robotic intelligence is manifested in the interaction between robot and real environment. Brooks thought that intelligence depended on the perception and action, no knowledge and no reasoning, and the world are the best model. The typical structure is shown in Fig.2.This view consists with the biological nature of reactive behaviors, which emphasize interaction with the environment and firmly convince that the intelligent behaviors are generated from $S \to A$ structure. Therefore, the level of intelligence depends on the adaptability of the environment. The frog-bashing fruit fly experiments done by Humberto.R and Francisoj.verela had proved that some frog's behaviors need not the $S \to P \to A$ process, but achieve the $S \to A$ process through the retina. Then, this behavior-based construction methods became a research hot because of it's more adaptable than deliberative methods. Subsumption (Brooks [17]) and reactive based on motor schema (Akin [18]) are typical structure. This paradigm had broken through the bottleneck of traditional calculation of $S \to P \to A$, and the flexibility and robustness were embodied fully. But the shortcoming is that it is easy to fall into local traps, lack of initiative and lack of guidance and coordination of global. From the perspective of the robot project, this method that the complex behaviors are broken down into basic behavior and let the system operate in accordance with intelligent way, will lead to many exciting cutting-edge research. Because it offers a new approach and direction for people to simulate a simple "organisms" .For example, In Arbib's schema theory [19], schema class may derive three classes: behavior, movement and perception, and they are used to build reactive IRS quickly through object-oriented approach. Proetzsch [20] extended this ideas and provided synthetically approach of IB2C (Integrated Behavior-based control), which are used to analyze a complex network structure of different behavior mechanisms.

The deliberative paradigm lacks of practicality and necessary flexibility and the reactive paradigm lacks of global guidance, so how to make the robot to have ability of planning and reasoning, and do not destroy the success of reaction are attendant problems. With high-performance, low power processors and network communication technologies spread widely, hybrid (deliberative/reactive) paradigm had been developed to overcome these difficulty because this structure enable the robot not only to face the dynamic, complex and unstructured environment, but also have rapid response capability to meet the complex and dynamic mission requirements. Therefore, robotic scholars believe it is the most common paradigm for problem solving.

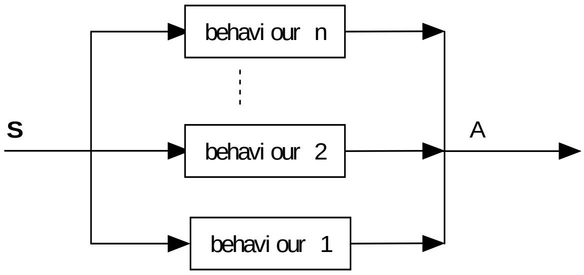

Figure 2. Typical structure of reactive paradigm[17]

Early research about hybrid architecture (Fig.3) focused on solving data exchange between the deliberative and reactive layer. Gat and Bonasso [21] provided three-layer structure including control layer, deliberative layer and coordination layer. The coordination, also named sequence layer, decided what the current behavior should be chosen. Other structures such as SSV[22] and Simmons's Xavie[23] had similar types. Jonathan H. Connell [24] proposed SSS architecture (Servo, Subsumption and Symbolic) to solve information exchange between these three-layers, and it had applied in TJ mobile robot. R.Alami's [25] general structure also consisted of three levels including decision-making, implementation and function layer. The general module is divided into controller and execution unit. The interaction between these two parts was completed by triggering of asynchronous events and two databases (Control and functional database). And the predefined control rules in the form of knowledge in the two database. Pere Ridao[26] provided O^2CA^2 structure which added to control layer between deliberative and reactive layer. Planning behaviors are processed using event-driven in the control layer. From the analysis above, it can be seen that the coordination or control layer are the bottlenecks for restricting system performance.

Good module division is very important for ensuring the portability and reusability of system based on hierarchical thinking. AuRA [27] is the representative structure which includes five subsystems. The subsystem is abstracted as object-oriented class based on schema theory. Relative to these two bottom-up design, a new design strategy is embodied in Saphira structure model-oriented [28] and Task Control Structure (TCA) [29]. The successes of Saphira have shown that the coordination, consensus and communication are three key factors for IRS in an open environment. In TCA, the tasks were decomposed into low-level tasks, and the robot's next behavior states were decided by Markov Decision Process (MDP).

Hybrid system architecture has a strong modularity, most of the structures are divided into layers, and layer is divided into modules. In these methods, deliberative module can be designed as stand-alone, high-level components to achieve, and reactive layer can be designed as strong real-time module. Then these two types of modules run in parallel to meet the needs of different performance.

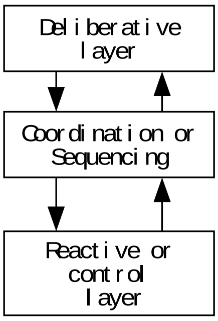

Figure 3.The typical hybrid structure[21-22]

Under the paradigm of combining deliberative and reactive template, the robotic engineering methods of system analysis and integration have space of the application. J.S.GU [30] presented a real-time open control system (ROACS), which processed parallel real-time event and extracted sensing information to finish intelligent decision. He designed a novel robot task language (RTTL) to solve the contradiction between the real-time control and decision. C.Urdiales [31] provided the reaction layer design methods of case-based reasoning (CBR), which stored knowledge in the form of case in database and solved the problems now facing adaptively by the accumulation of past experience. The adaptability and autonomy of IRS were improved during the interaction with the environment. Brooks [32] proposed an open-source component-based software engineering (CBSE) framework designed for mobile robotics. Every component is a stand-lone process and meets the needs of the reactive layer with other components. Hakan Yavun showed us an integrated approach to the conceptual design and development of an intelligent autonomous mobile robot from the perspective of system analysis [33]. It can be seen from review above that hybrid paradigm is still the dominant architecture.

B. Agent-based Distributed Hybrid Architecture

DAI(Distributed Artificial Intelligence) had provided a new way for designing IRS. With the improving and expanding of hybrid paradigm, the non-layer-type structure based on organizational theory and MAS (Multi-agent system) were used to design robotic system successfully, so the large-scale problems were expected to solve by this way. Rosenblatt [34] proposed DAMN structure. The function module voted to produce rational, goal-oriented actions to controller through rules or reactive behaviors, and the arbitration enabled DAMN to have self-organizing ability. Pioggio [35] provided a non-hierarchical architecture named HEIR, which are made of symbolic component(S), diagram component (D) and reactive component (R). These components had no difference of high or low level, and worked independently through the exchange of information each other. But Bryson [36] stressed the advantages of hierarchical organization behavior. In his architecture, each act was abstracted as a module communicated with others. These pioneering studies have provided a new way of thinking for designing modules of IRS.

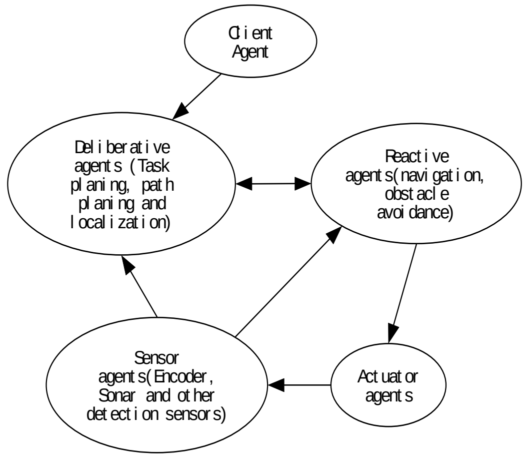

Figure 4. The typical agent-based control architecture[43]

The advantages of MAS have encouraged researchers to replace modules with agents. Generally speaking, agents are independent, autonomous, intelligent and flexible. Parunak [37] defined an agent as “proactive object”. Charles. Antoine Brunet [38] used MAS to design driver model of ARV. This hybrid structure was abstracted as three-layers including control, guidance and navigation which were consisted of different agents. The interaction and sharing data between agents were achieved by blackboard mechanism. In addition, Parunak[37] pointed that agent technology was the most suitable for designing modular, decentralized, changeable, structural malformations and sophisticated applications. Gesu[39] had implemented a distributed architecture in DAISY for autonomous navigation. The system included target discriminator agent, obstacles agent and planer discriminator agent to simplify integration difficulties of robotic system. And D. Busquets[40] also designed five agents(Map management, target tracking, risk management, self-help and communication) to construct navigation system. The agents decided behaviors of next time by voting mechanism.

In order to implement complex control strategies, more and more researchers use agent paradigm to design IRS. Kolp[5] presented a multi-agent architecture for mobile robot control and compared to other classical structures such as control-loop, layered and task-trees. The results had shown that the Structure-in-5 and Joint-venture based on MAS had obvious advantages. Pooya Farahvash[41] designed a multi-agent architecture for control of AGVs, and provided reactive agent with data-driven state change integrated in automated manufacturing environments to control certain tasks. Carmine Grelle [42] used the agent paradigm to design very complex control strategy through multi-objective, fuzzy c-means, and genetic algorithms optimization. The traditional control model was extended in this architecture. Bianca Innocenti [43]had proved that the integration of both approaches including multi-agent and collaborative control were very effective for mobile robot control architecture(Fig.4), and had tested successfully in the Pioneer 2DX mobile robot. J.L.Posadas[44] proposed SC-Agent mechanism to solve interaction and communication under a multi-level and hybrid architecture. The approach of neural network based on evolutionary and reinforcement to design agent were presented in [45] (Stanislav 2010), and the results had shown Q learning algorithm was more adaptative for agent. All these methods of designing IRS had encouraged us to research deeply, and indicated a new direction in the same time. Additionally related software engineering methods had developed. For example, the DOA(Distributed Object Architecture),CBA (Component-based architecture), SOA (Service-oriented architecture) [46] had applied in designing robotic system. Although they are not the same as computer which has unified software structure, these thoughts have provided new methods for robotic system integration.

C. Summary of System Analysis methods

It can be seen from previous classified analysis that the basis of system analysis of IRS is how to select the right architecture. Different areas of application need different reference architecture, but the overall conceptual design model can be concluded further. According to the result of classification analysis, the conceptual model of IRS are abstracted as two layers (deliberative and reactive) and four elements (S,P,A,L) in Fig.5 . Though Learning(L) is considered the primitive for building IRS are still controversy, but the recent machine learning research have proved that it is essential for designing intelligent system.

From the perspective of system analysis, the architecture includes information process and control system. The computing models of IRS have developed from process-oriented, object-oriented, and component-oriented to Agent-oriented. Corresponding, the system also has transferred from centralized system to distributed intelligent system. Based on the analysis of this aspect, it is easy to see that agent-based distributed hybrid architecture has certain advantages.

From an implementation standpoint, we conclude open physical model as Fig.6 to finish mapping from the conceptual model to "robotic body". The computer's open and modularity are worthy of learning and inheritance, so we use general-purpose computer (PC, DSP, ARM or MCU) to construct modules or agents represented S, P, A and L. The Rcp, Pcp, Scp and Acp represent the Remote control, Planing, Sensor and Actuator computer platform respectively, and N represents the number of division for agents or modules.

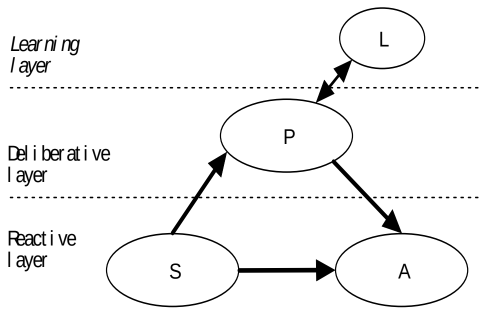

Figure 5. The conceptual model of designing IRS

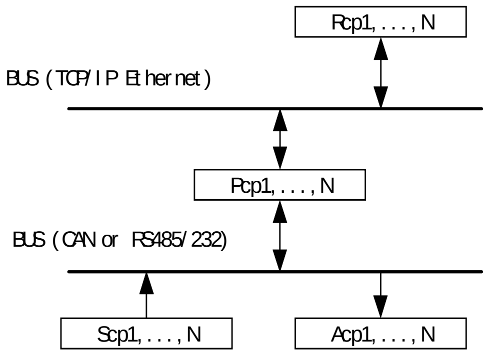

Figure 6. The open physical model of designing IRS

III. Common Design Principles

It is very important that how to construct intelligent robot system scientifically and efficiently. Through classification and summary of past typical architecture, we not only absorb previous experience and lessons, but also induct some common design principles for guiding follow-up study. Therefore, the scientific methodology is expected to get by summarizing previous research robot architecture and application examples. At present, we can foresee that intelligent robots in the future are ubiquitous as today's computer optimistically, but we must face a great challenge from the current trend of view. Compared to computer, the robot is more like an organism, and the aim of robot is not to get result. Robot must be complete certain tasks independently or maintain a particular state in an unknown environment. Although there are very different between both, the platform of constructing robot system is computer-based as Fig.6. Therefore, combining with the characteristics of robot and computer, and absorbing the advantages of computer system, we believe that we can find new ways for designing intelligent robot.

Throughout the study of 30 years in this area, It concludes that designer of early robotic mostly designed specifically for task-specific [21-29].Each type of architecture all reflects the application requirements in specific areas. With the expanding field of application and the system's universality is not enough strong to meet different needs. Recently, more and more researchers [33, 46] are working on the generic architecture for application in different fields or seeking for a common methodology to guiding, so the exploratory study in this breakthrough is worth and promising.

There are two important considered aspects including science and engineering in designing robot system. From the former point of view, robot system is a dynamic system which integrates context-aware, dynamic decision-making, planning, behavior control and implementation. The theory of artificial intelligence is the basis for developing robot. Related theory also includes automation, AI, information system and operational research. Deliberative and reactive paradigms are important and indispensable components of intelligent system, and human or creature all follow these two laws ($S \rightarrow P \rightarrow A$, $S \rightarrow A$) during decision and action. Intelligentization is the main features of modern productivity based on resource "information, energy and material". Traditional structuralism, functionalism and behavioral research methods have penetrated into the theory of designing IRS. The Saphira [28] and Bianca's hybrid architecture [43] are good example for showing spatial distribution patterns of meaning. From the engineering point of view, the architecture is described as a set consisting of modularity. The contents of research include the division of basic modules, relationship between modules, data/control flow to determine, inter-module interface specification and global information resources management. So the abstracted models in Fig 5 and Fig.6 are reasonable for analyzing architecture.

Rolf Pfeifer [48] provided new ideas of embodied cognition. One of his design concepts is "understand intelligent system by constructing" or "Understanding by building". Historical experience have also proved that some new ideas or thought emerge from building a real physical system. This research of bottom-up has given us great inspiration. We must use new perspective to sum up the results of previous studies, if we expect to get general methodology on the basis of previous experiences and views. Therefore, borrowing ideas from Rolf Pfeifer, we have concluded six common design principles for constructing architecture of IRS based on discussion in section Ⅱ.

A. Principles of Modular Division based on S,P,A

The key to design IRS is modularity, and the basis of division depends on the task and application domain. Module's level and scale of division can not be measured quantitatively, but the classification depends on choosing different granularity such as function, behavior and component. No matter how divided modules, the primitive (S,P,A) will not change. From early SPA [12] to Brooks's OCRA [32] and Bianca's architecture based agent [43], they all are expansion and extension of three primitives.

B. Hierarchical Principle of Architecture

It can be seen from the development of hybrid architecture that hierarchical principles are embodied whether in early three-layer structure [21] or later distributed architecture [45]. The content of their research are consistent with understanding intelligent behavior of cognitive scientists. In their view, ability of animal's spatial behavior is divided into reflex-like behaviors, fusion behaviors, learning behaviors and cognition behaviors. The same as the hierarchical structure of intelligent organization of biological systems, robotic intelligence gradually increases from the reaction layer to the deliberative layer. Some soft computing methods such as fuzzy logic, artificial neural networks and evolutionary algorithms are used to design intelligent behaviors in deliberative layer, and achieve a more complex type of cognitive behaviors with the reaction layer.

C. Principle of "High cohesion and low coupling"

Whether the modularity depends on function, behavior and agent-based, the principle of "High cohesion and low coupling" is embodied during the design process. Each subsystem completes the global task by collaborating with others. The relationships between modules determine the data flow and control flow, so it is important to devise subsystem reasonably. This design strategy actually reflects the thought of "division and interaction". It not only considers dividing complex problem into sub-problems, but also considers that how to synthesize the various sub-problems for solving the original problem. This strategy is favorable toward integrating software and hardware, and complex distributed problem solving. These benefits are fully reflected in the literature [33].

D. Design Priciple of Redundancy

Redundancy of biological systems, based on robustness, make it easier to adapt to the environment. The methods of copying part in robotic engineering would increase the cost of robot. But the functional redundancy is easier to achieve than part redundancy. For example, some function of vision subsystem and ultrasonic subsystem are overlap in robot navigation. These ideas also are reflected in Brooks's subsumption architecture [17], Akin's reactive architecture and agent-based architecture [18].

E. Coordination Priciple Between Deliberative and Reactive

Most previous studies have shown that deliberation and reaction are essential to construct intelligent robot system with good adaptability to environment. The deliberative ability represents modeling, planning and intelligent decision, and the reactive ability represents real-time responding for overcoming the uncertainty of dynamic changes during the execution. The coordination between deliberative and reactive make robot have strong features and application flexibility. Whatever we design distributed component system or agent-based system, this principle is essential means .The SC-Agent architecture [44] had provided a new idea for solving this problem effectively.

F.Principle of Open-hardware Based Computer Platform

From the development of architecture of IRS in last 30 years, we find that the computer is the main driving force. The intelligent system on the basis of open architecture of the computer has good scalability and portability. Therefore, computer software design method may be extended to the field of robotics. It can be expected that there are robot-specific operating system in the future. Microsoft's Robotics Studio [46], DSS and ROS [46] had shown this trend. The methods of system analysis (DOA,CBA and SOA[46])also have been applied in designing software of robotics.

IV. Conclusion

With the embedded system and the rapid development of new artificial intelligence, a new development opportunities has been brought by them, and it make people see hope that the robot enters every home in the future. We have attempted to provide a coherent framework or system analysis method for designing architecture of IRS in this paper. And the effectiveness of the system analysis methods has been proved in my practice of designing intelligent inspection robot.

From the development of architecture in last 30 years, we find that hybrid paradigms are effective design methods for constructing IRS. And we also find the traditional architecture and agent-based distributed hybrid architecture will exist in the same time because of complexity in designing robotic system. The new integrated approach of conceptual and physical design model in this paper has provided a solution for analyzing complex information system. The discussions in this paper have shown the computer's paradigm of system analysis had changed from process-oriented, object-oriented and component-oriented to agent-oriented. And the agent-oriented distributed hybrid architecture has more obvious advantages such as modularity, integration capability, scalability and openness than traditional architecture. But currently, the both coexist and promote each other. No matter which architecture we use, it needs a systematic methodology during design process. In addition, many scholars lead agent theory into the design to solve the flexibility between modules, but how to join self-learning mechanism to architecture still need further study.

The aim to study architecture of IRS is how to construct intelligent robot scientifically and efficiently. Compared to the computer, the robotic system is a classical "information system" and "complex system", and the work discussing the integrated approach to development IRS is unclear. Therefore, On the basis of summing and assessing a large number of structures over the past 30 years, six general methodologies are proposed in this paper. These common principles would help people to save time and cost for perfecting or designing new architecture.

Although the robot intelligence is so mysterious that people understand it only from a different side, we also explore some general scientific method to construct artificial organism. The thought "understand intelligent system by constructing" has given us a new perspective for design IRS. The principles of modular division based on S,P,A, hierarchy, high cohesion and low coupling, redundancy, coordination between deliberative and reactive, and open-hardware based computer platform will guide us to analyze robotic architecture efficiently, because we believe that more effective, rigorous and clear goal-oriented comprehensive methodology, more effective and scientific methods to design IRS.

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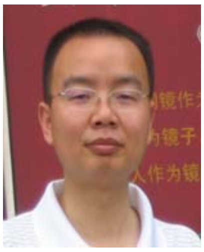

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