N92-22712

A COST-EFFECTIVE INTELLIGENT ROBOTIC SYSTEM WITH DUAL-ARM DEXTEROUS COORDINATION AND REAL-TIME VISION

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ABSTRACT

Dexterous coordination of manipulators based on the use of redundant degrees of freedom, multiple sensors, and built-in robot intelligence represents a critical breakthrough in development of advanced manufacturing technology. A cost-effective approach for achieving this new generation of robotics has been made possible by the unprecedented growth of the latest microcomputer and network systems. The resulting flexible automation offers the opportunity to improve the product quality, increase the reliability of the manufacturing process, and augment the production procedures for optimizing the utilization of the robotic system. Moreover, the Advanced Robotic System is modular in design and can be upgraded by closely following technological advancements as they occur in various fields. This approach to manufacturing automation enhances the financial justification and ensures the long-term profitability and most efficient implementation of robotic technology. The new system also addresses a broad spectrum of manufacturing demands and has the potential to address both complex jobs as well as highly labor-intensive tasks.

The Advanced Robotic System prototype employs the Decomposed Optimization Technique in spatial planning. This technique is implemented to the framework of the Sensor-Actuator Network to establish the general-purpose geometric reasoning system. The developed computer system is a multiple microcomputer network system, which provides the architecture for executing the modular network computing algorithms. The knowledge-based approach used in both the robot vision subsystem and the manipulation control subsystems results in the real-time image processing vision-based capability. The vision-based task environment analysis capability and the responsive motion capability are under the command of the local intelligence centers. An array of ultrasonic, proximity and optoelectronic sensors is used for path planning.

The Advanced Robotic System currently has 18 degrees of freedom made up by two articulated arms, one movable robot head and two CCD cameras for producing the stereoscopic views, an articulated cylindrical-type lower body, and an optional mobile base. A functional prototype will be demonstrated.

INTRODUCTION

Robotics is a science that analyzes the motion behavior of multiple correlated entities. Robotic engineering is a new engineering discipline that utilizes the knowledge of robotics to achieve those objectives that were previously unattainable unless performed by trained human beings. A generic robot would integrate the actuation of articulated motion, sensor processing, and machine perception into one system.

The application of robots has virtually no limitation, and the major obstacle of robot implementation today is the lack of proper understanding of robotics. In order to achieve what we need most, the robot applications can be categorized into three different levels: utilizing the robot as a function-specific tool, employing the robot as an

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intelligent machine, or constructing the robot as a self-contained artificial creature. Some examples of each level will be introduced to demonstrate the potential usages of modern robotic systems.

The Robot as a Tool

One major criterion for differentiating robots from conventional electromechanical systems is onboard machine intelligence. Current microcomputer technology makes it possible to embed certain autonomous functions in the articulated mechatronic infrastructure. Although there are many intrinsic limitations, such as memory size, processing speed, and hardware constraints, the resulting robotic systems are generally capable of performing a set of specific functions with superior quality. Typical examples are advanced manufacturing processes, microscale devices fabrication, and precision laboratory automation.

The Vital Component of Flexible Manufacturing Systems (FMS). Current manufacturing systems are experiencing a new challenge when the traditional approach is no longer capable of matching the dynamic environment of market demand. As global competition prevails in every sector of the industrial world, the required manufacturing system has to be cost effective, schedule responsive, quality sensitive and long-term operationally stable. As the availability of information and self-education tools becomes reality, long-hour routine jobs are no longer suitable for human labors. Instead, different robotic tools will gradually fill in this gap to constitute the vital component of the flexible manufacturing systems. It is expected that a completely automated manufacturing system would provide reprogrammability, which is essential to accommodate a wide range of production demands, maximize the utilization rate of the available equipment, and maintain uniform product quality.

Furthermore, the incorporation of robotic tools would make the FMS a feasible production solution for those companies of medium or small size as well. Since those labor-intensive operations are minimized, the frequency of repair and maintenance is substantially reduced, and the supporting manpower is consolidated; consequently, the competitiveness of the manufacturing industry will be increased significantly. Once the technology upgrade procedure is properly established, the modern manufacturing technology realized by various function-specific robotic systems will help our country to regain the leading position in every industrial sector.

Application-Specific Integrated Devices (ASID). Several major sectors of our society are encountering severe difficulty in recruiting human workers, e.g. hospitals, schools, law enforcement in major metropolitan areas, fire department and sanitary operations, etc. This phenomenon is significantly affecting our living conditions, and it does not appear that it will improve automatically. There may be some associated social reasons that should be reckoned with. However, it is conceivable that with the help of modern technology, a series of application-specific integrated devices (ASIDs) may satisfy these pressing needs and reverse the trend of downgrading our living standard. Robotic engineering can serve as the major ingredient for integrating the existing electromechanical components with application-specific functionalities to develop the required ASIDs. For instance, ASIDs for nursing can immediately help patients to perform some basic functions wherever and whenever human nurses are not available; ASIDs for day care can assist babysitters by taking care of some routine jobs when they are occupied. All kinds of ASID products can not only utilize currently available technology well to improve our lives, but also will relieve social tension contributed by social restructuring and prolonged life expectancy.

The Robot as an Intelligent Machine

When robot intelligence has developed enough to become mature in dealing with heterogeneous matters, more responsibility can be assigned to robotic systems. Then robots will behave as intelligent machines that can handle a group of related tasks without human intervention. The principle of robotics implicitly indicates a progressive path along which robots are not only application-specific tools, but also can be intelligent machines. The utilization of information, knowledge, and experience has been well formulated such that the capability of handling a group of related jobs can be downloaded to the robot and constitutes a machine with confined intelligence. Two examples are introduced below to point out some potential near-term objectives in developing the robotic system as an intelligent machine.

A Reliable Means of Optimizing Human Resources. The transfer of low-level work from well-developed countries to developing countries is an apparent trend that is generally accepted by the majority of the world. As this transfer progresses, in the near future there will be a lot of low-level jobs that human workers will no longer be content with. Unless the evolution of human history is reversed, this trend is inevitable. By that time, it would be unquestionable that robots would be the most reliable source for fulfilling the need for low-level work. In particular, labor-intensive, hazardous, repetitive jobs, such as are found in farming, mining, fishing, and security monitoring, are experiencing an urgent need to provide a front-end work force that is highly reliable and yet flexible enough to adapt to variable environments, cost-effective, and also quality sensitive. As long as the threshold of economics is overcome, the employment of robots as the intelligent front-end machines would be commonly acceptable.

An Indispensable Helper for the Physically Challenged. Mobility is one of the major qualities that we in our daily living cannot do without. For physically challenged people, however, maintaining the basic level of mobility can be unthinkably difficult without the assistance of a human companion. Robotic systems have been considered to be the best solution to compensate for disability if the incorporated robotic device is intelligent enough to deal with unknown situations and to communicate directly with the neural system of the host. In examining the latest progress in medical science as well as in robotics, it is apparent that future robotic ASIDs can provide indispensable help for the physically challenged. Moreover, robotic ASIDs for medical applications can not only assist human beings externally, but also can be implanted into the human body to provide critical functions internally.

The Robot as a Man-Made Creature

Once the robotic system can perform intelligent functions with an onboard knowledge base, the next stage will be the development of self-learning capability. In order to build an autonomous system, it is essential that the robot be able to self-adjust both the database and the rule base automatically. In other words, not only could the system variable values be updated and the modeling parameters adjusted, but the rules of formulating the internal representation of the controlled environment could also be modified. With layers of inferencing, a certain self-organizing capacity would then be established to provide a robust decision-making procedure that would be independent of the employed system models. Therefore, the resulting autonomous robot can be regarded as a man-made creature that is self-sufficient for accomplishing the assigned mission. It is expected that as the research and development of autonomous robot intelligence approaches maturity, related biotechnology will also reach the stage where artificially grown biocells can directly communicate with the electronic subsystems. Then, with the merging technology of biorobotics, the issue of self-propagation can be addressed as well. The following two examples are typical cases of utilizing robots as man-made creatures.

Future Explorers of the Unknown Universe. The exploration of the entire universe is considered as the last frontier of human knowledge expansion. However, existing knowledge about human physical systems severely limits the feasibility of space exploration with human presence. Since our imaginative capability and brainpower exceed our physical limitations, it would be more appropriate to send some autonomous robots into the galaxy to help us to explore the unreachable universe before the development of technology for overcoming our physical barriers. It is also likely that the results of autonomous robot explorations will accelerate the growth of human knowledge in terms of better understanding of the three-dimensional physical world.

Settlers in New Territory Unfit for Mankind. The other planets, of which we already have some preliminary knowledge, more often than not indicate a specific physical condition that is not suitable for human living. However, there is plenty of information that needs to be collected and investigated and for which physical contact is necessary. Instead of spending an enormous amount in resources to generate a tiny compartment to accommodate a human's physical limitations, it would be more justifiable to utilize autonomous robots or semiautonomous telerobots as the settlers on those planets as the first stage of exploration. It is believed that the research and development of human space exploration should be preceded by that of space robot exploration.

Robotics as an Application Technology. Within this NASA-funded SBIR project, six technical advancements have been accomplished to demonstrate the developed robotic engineering capability. If robotics is regarded as an application technology, the developed technical advancements are readily available for various industrial implementations.

ROBOTIC-SYSTEM MODULARIZATION

The idea that a reconfigurable, modular robot design can best utilize the advantages of robotics technology as it evolves is a cost-effective one [1,2]. In addition to the analytical development of modular architecture of robotic systems, there are several technical issues that need to be addressed before the successful implementation of modular robot design can take place. First of all, it is essential to incorporate the actuator directly at each active joint; second, the connections between adjacent modules have to be standardized such that the interchange capability can be maintained; also, intelligence localization and distributed control are necessary to maintain the modular functionality [3]. In this program, the modular design of the electromechanical system is capable of decomposing the robotic system into five modules. Each module has distinct functionalities. The corresponding spatial planning, kinematic planning, and motion execution are also considered and designed in a modular fashion, which involves analytical framework development, algorithmic construction, software coding, and system communication protocols. Eventually, a joint-oriented modular mechatronic system will be available to satisfy various demands from simple routine jobs to high-difficulty tasks. A proposed joint-oriented intercoordinate system is shown in Figure 1.

UTILIZING REDUNDANT DEGREES OF FREEDOM WITH AISP

One of the advantages of utilizing the Artificial Intelligence for Spatial Planning (AISP) technique is to carry out the online task planning by systematically maneuvering the multiple degrees of freedom of the redundant robots [4]. Since there are many applications that require the redundant degrees of freedom of the robotic system to perform articulated manipulations, the restriction to a maximum of six or seven degrees of freedom in existing robotic systems substantially constrains the applicability of robots. One of the main reasons for accepting this constraint is the lack of implementable techniques to control redundant robots. The proposed AISP implementation, which utilizes the Decomposed Optimal Transition (DOT) technique for solving the generalized reachability problem [5], presents a major improvement in expanding the domain of robotics technology implementation.

In a three-dimensional computer graphics simulation, the Advanced Robotic System had an assignment to reach two designated locations, one with specified position and the other with specified orientation. The initial scenario is shown in Fig. 2(a), where the two triangles stand for the given targets. The final scenario is presented in Fig. 2(b), with the top view in Fig. 2(c). With the help of AISP, the robot would be able to reach the assigned target locations without touching the cylindrical obstacle between the robot and the targets.

STEREOSCOPIC REAL-TIME ROBOT VISION

The development of a novel robot vision system falls under the category of advanced sensor technology. The lower level of the image processing produces the edge representation of two asynchronous views as the result of a stereoscopic arrangement of two CCD cameras. The arrangement is shown in Fig. 3. The medium level of image processing performs the basic logic for scene analysis. Both the object identification and the motion analysis are addressed. The results from a relational database are then used for processing at a higher level. By communicating with the corresponding knowledge base, some fundamental geometric reasoning capability can be established to extract the necessary environmental information to support various tasks of robot manipulation. The functional diagram of the developed robot vision system is shown in Fig. 4, and the details can be found in [6].

RESPONSIVE CONTROL IN THE SENSOR-ACTUATOR NETWORK

The sensor-actuator network (SANE) represents the first layer of robot behavior. In order to react to some critical situations as soon as they are sensed, a set of responsive control rules is needed that has the highest priority and will react to the unexpected causes and minimize the potential system damage. Responsive control would be able to override the standard actuation sequence and execute the appropriate emergency action. The sensor-driven interrupts would be terminated only when the alarming situation no longer existed or the related subsystem was (or subsystems were) shut down. The responsive control not only is the intricate part of the system's contingency plan, but also acts as the basic machine intelligence to prevent the user-specified program from making some trivial errors. The development of the responsive control system for the SANE of the Advanced Robotic System demonstrates the fundamental concept of this approach. The incorporation of a neuro-fuzzy data fusion process will be the next step to be pursued in the future research and development of autonomous robots and intelligent telerobotic systems.

THE DYNAMIC KNOWLEDGE EVOLUTION PROCESS

The dynamic knowledge evolution (DKE) process is an innovative approach in developing knowledge systems. For robot intelligence development, the DKE process is utilized to establish the basic geometric reasoning and the modeling and analysis of the environment encountered. In addition to having the common perception of expert systems, the knowledge systems with the DKE process would accept online knowledge base updates, modify rule-based inferencing to optimize the processing speed, and generate consistency rectification with analogy learning and probabilistic reasoning (in particular, Bayesian inferencing [7]). Due to the associated dynamic behavior, the theoretical foundation of DKE has a close relationship with the neural network theory explained in [8]. The resulting FULOSONN (FUzzy LOgic and Self-Organized Neural Network) technique is a new technique in knowledge engineering. Figure 5 shows the functional diagram of the developed control system, and the intelligence flow is depicted in Fig. 6.

MuMicS ARCHITECTURE FOR MACHINE AUTONOMY

The advantage of integrating multiple microprocessors has gradually been appreciated for various applications, such as image processing, fault-tolerant systems, or large-scale real-time computations. Instead of closely coupled microprocessors, a new architecture incorporating multiple microcomputers is introduced. The advantages of MuMicS are the high reconfigurability (which is especially suitable for modular system design), the fault tolerance capability, and multiple asynchronous (or synchronous) tasking. Due to the rapid growth of computer technology, the MuMicS architecture design not only is functionally desirable but also provides a cost-effective solution for numerous applications. The Advanced Robotic System utilizes five microcomputer systems to constitute the control, command, communication and intelligence (C3I) system. One of them is the global intelligence center (GIC), which acts as the brain of the Advanced Robotic System. The remaining four are local intelligence centers (LIC): one LIC controls the right arm, one LIC controls the left arm, one LIC controls the mobile head with vision subsystem, and the last LIC controls the lower body. The functionality of the GIC is shown in Fig. 7. Each center has different functionalities and is connected through a local area network (LAN) system. The completion of the Advanced Robotic System protoflight demonstrates the feasibility of using the proposed MuMicS architecture to develop advanced autonomous robots.

CONCLUSION

Emphasizing robotics as an application technology has been the major guideline for constructing the Advanced Robotic System. Due to the limited resources available, this program has been constrained in its attempts in research and prototyping a systematic approach to developing implementable robotics technology. Advances along six technology thrusts critical to the growth of robotic engineering as a new discipline have been accomplished. The prototype Advanced Robotic System developed in this effort and shown in Fig. 8 can be used as the basis of future robotic engineering development. It is firmly believed that the continuation of all six thrusts in the technological development is necessary to maintain the vital competitiveness of robotic engineering in the United States. It is sincerely hoped that our effort in this program will eventually cause others to regard robotics as a vital technology that can impact our progress and competitiveness.

ACKNOWLEDGMENTS

The research described in this paper was partially carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was funded by a NASA/SBIR contract from the Jet Propulsion Laboratory.

REFERENCES

1. Tourasis, V.D., and Ang, M.H., Jr., "A modular architecture for inverse robot kinematics," *IEEE Trans. Robotics and Automation*, Vol. 5, No. 5, pp. 555-568, October 1989.

2. Schmitz, D., Hoffman, R., and Khosla, P.K., "CHIMERA: A real-time programming environment for manipulator control," Technical Report CMU-RI-88, The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania, September 1988.

3. Chen, A.Y.K., and Chen, E.Y.S., "Intelligent manipulation technique for multi-branch robotic system—quarterly report," SRA Report No. R90-900077-3, Scientific Research Associates, Inc., Glastonbury, Connecticut, September 1990.

4. Chen, A.Y.K., "AISP—A robot intelligence system in spatial manipulation," *Proceedings of ROBEXS '89, The Annual Workshop on Robotics and Expert Systems*, Palo Alto, California, August 2–4, 1989.

5. Chen, A.Y.K., "Decomposed optimization technique for two-dimensional N-link serial robot arm," Connecticut State SBIR Program Final Report, January 1989.

6. Chen, A.Y.K., and Chen, E.Y.S, "Intelligent vision process for robot manipulation," SPIE Symp. Intelligent Systems, Boston, Massachusetts, November 1990.

7. Kosko, B., *Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence*, Prentice Hall Publishing Co., Englewood Cliffs, New Jersey, 1991.

8. Box, G.P., and Tiao, G.C., *Bayesian Inference in Statistical Analysis*, Addison-Wesley Publishing Co., Reading, Massachusetts, 1973.

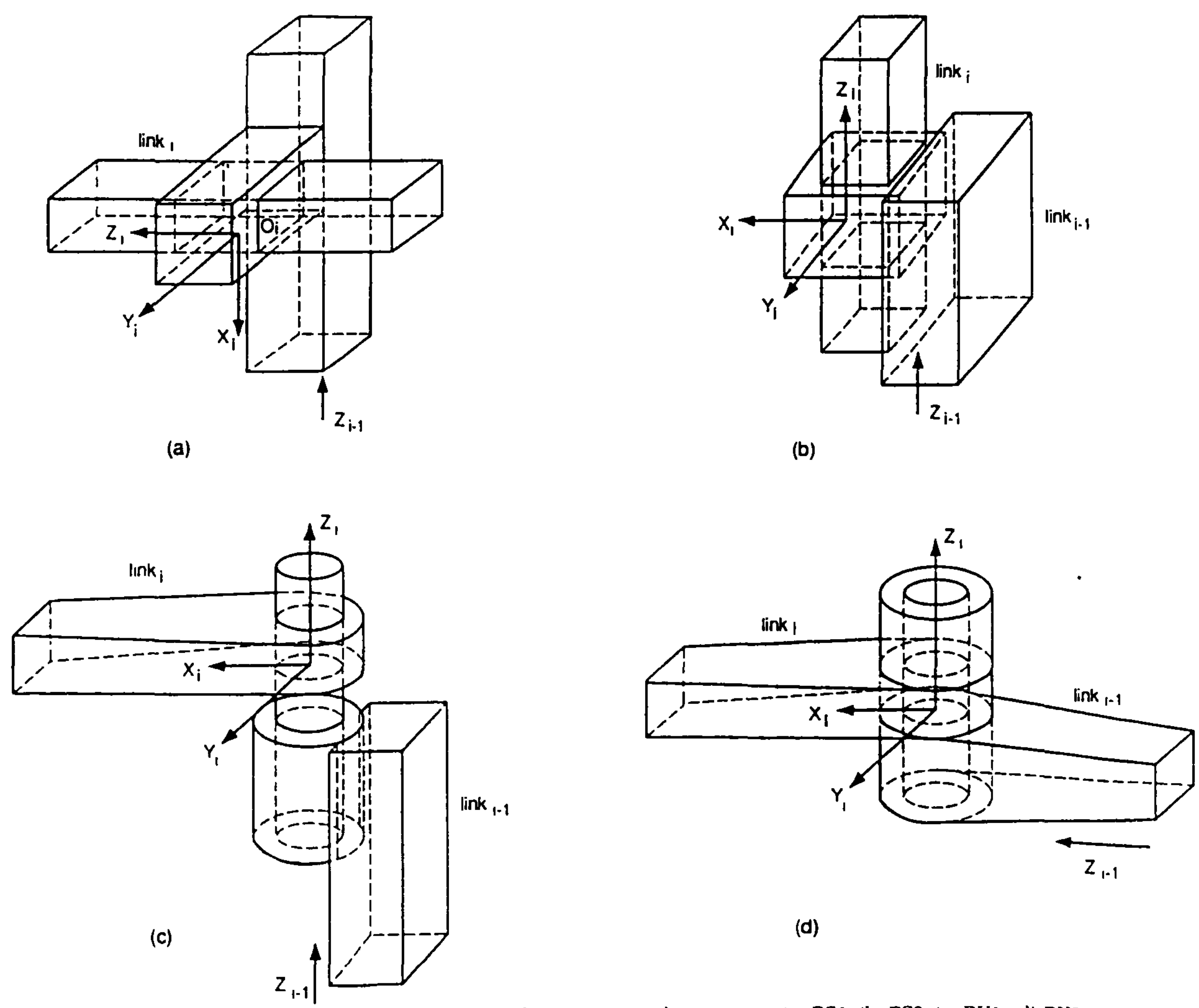

Figure 1. The joint-oriented convention: (a) PS1, (b) PS2, (c) RV1, (d) RV2.

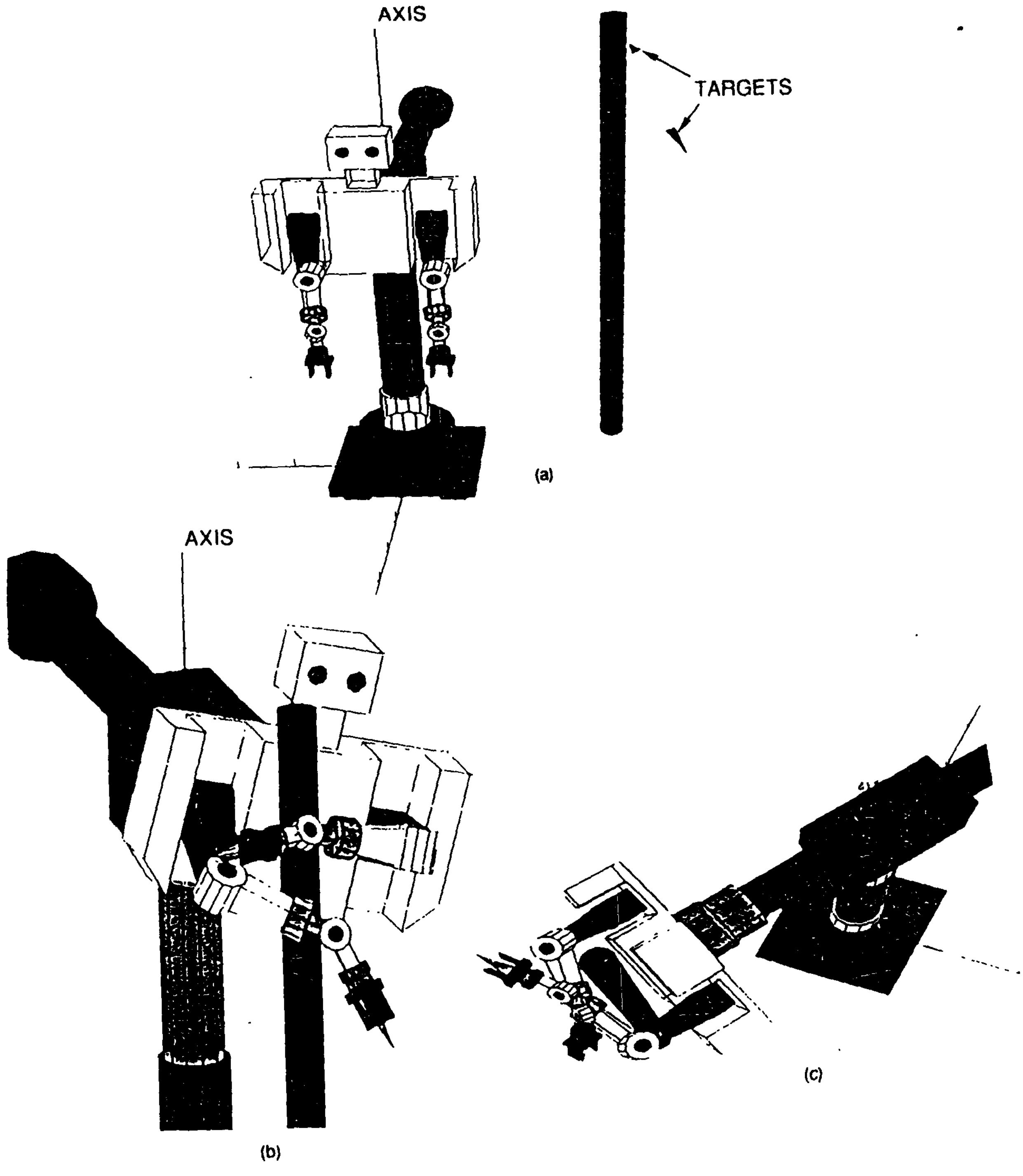

Figure 2. Three views of AISP with collision avoidance: (a) initial scenario, (b) final scenario, (c) top view.

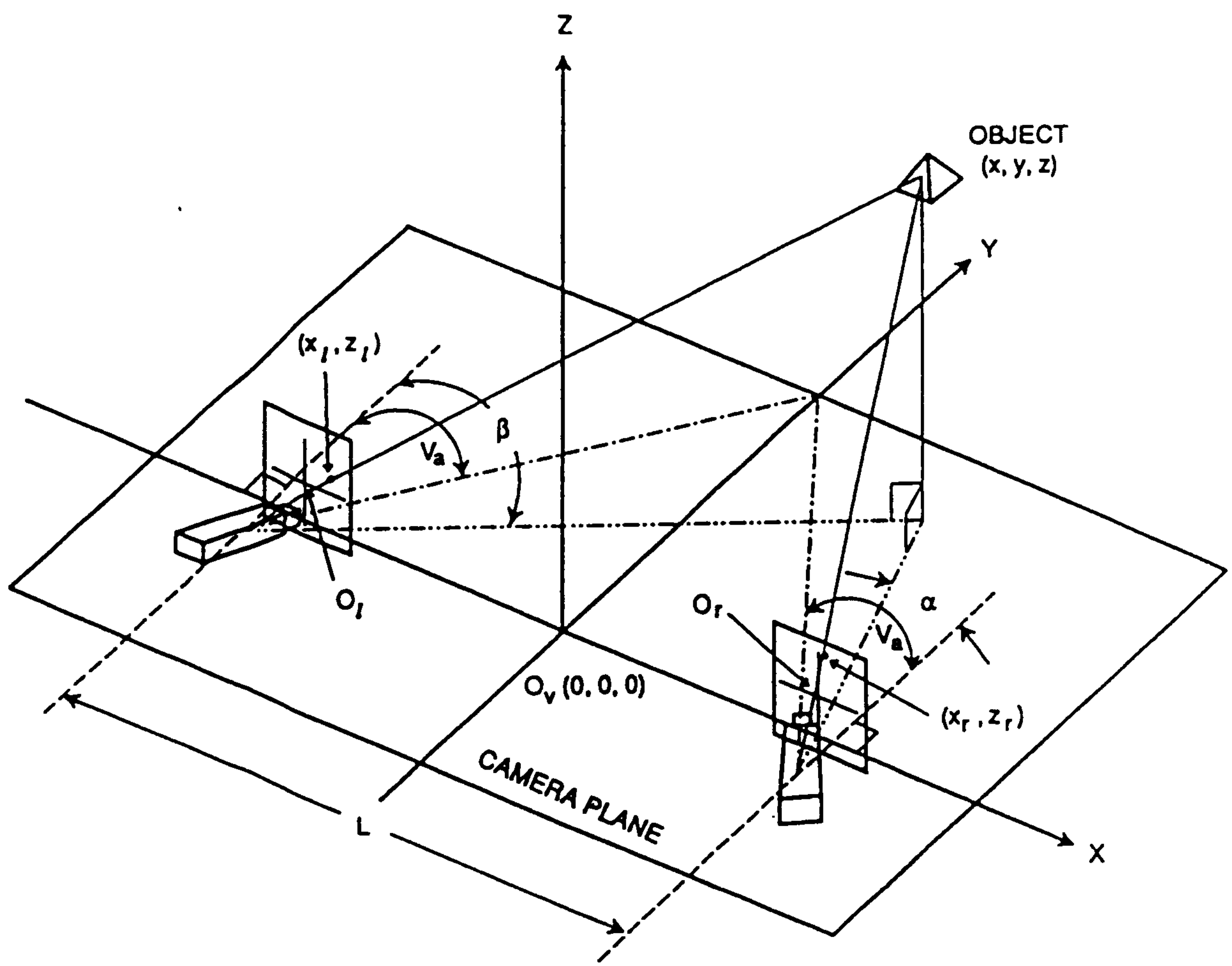

Figure 3. The three-dimensional positioning diagram in the developed stereoscopic viewing system.

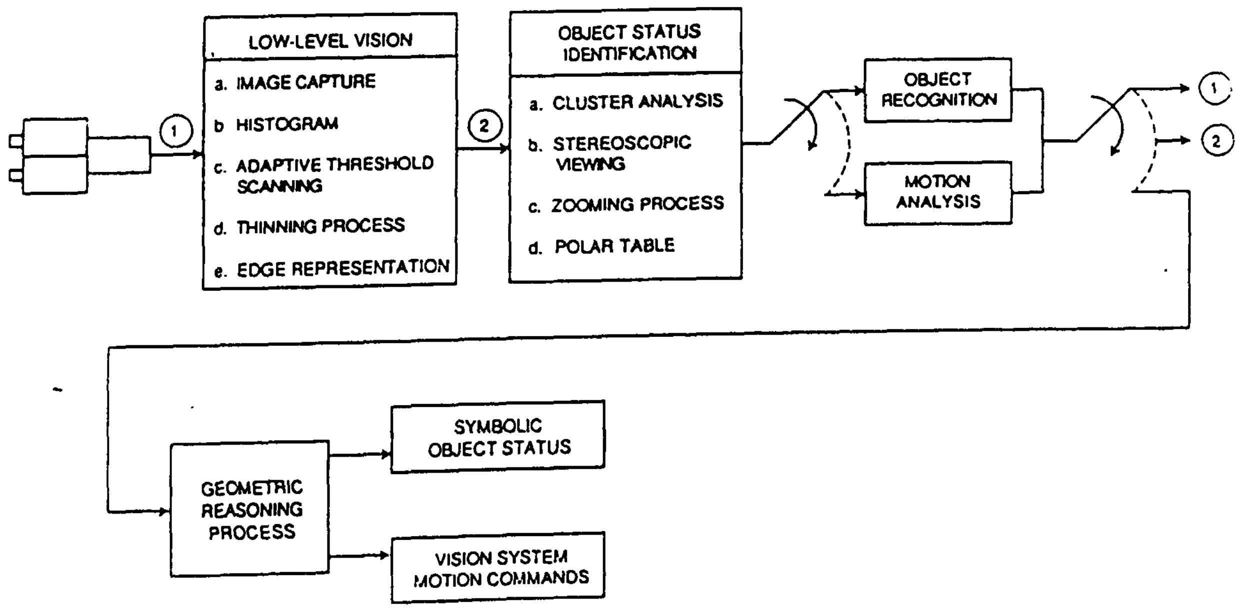

Figure 4. The functional diagram of the new robot vision system.

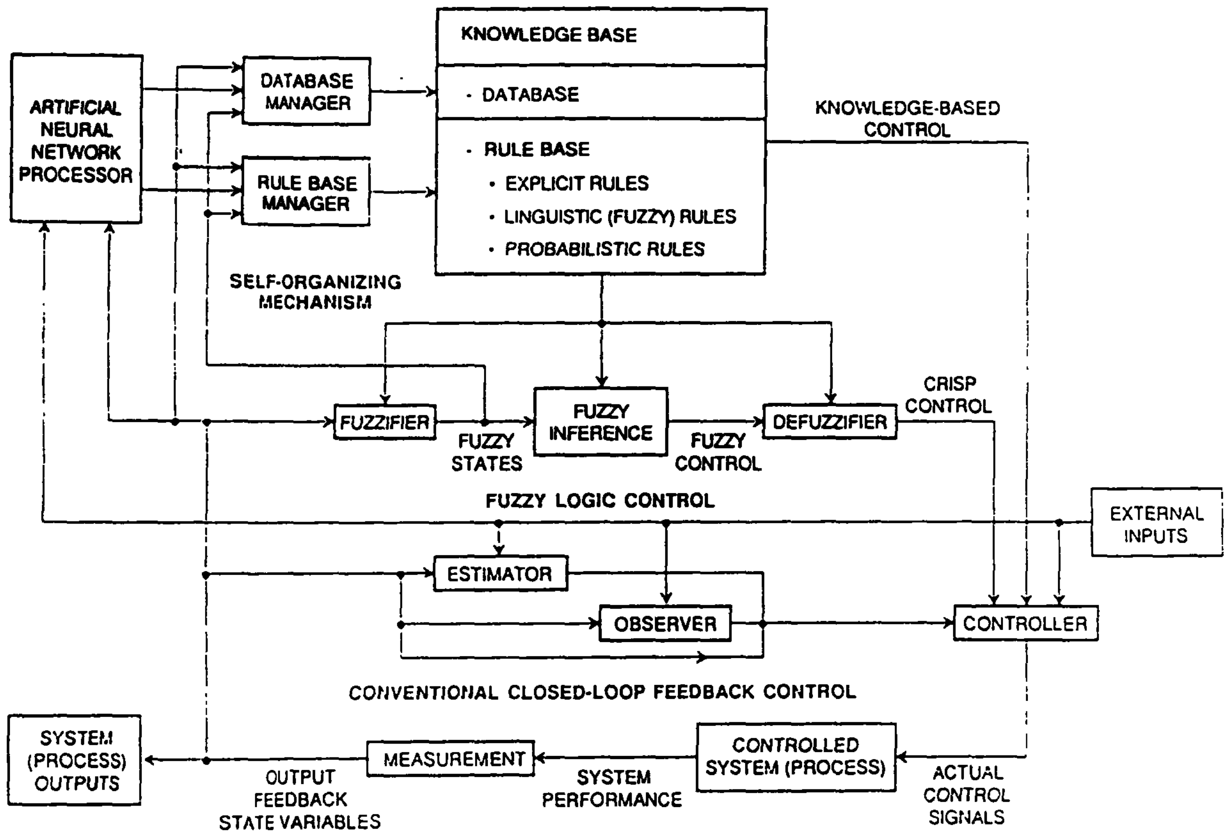

Figure 5 The functional diagram of modern control technology.

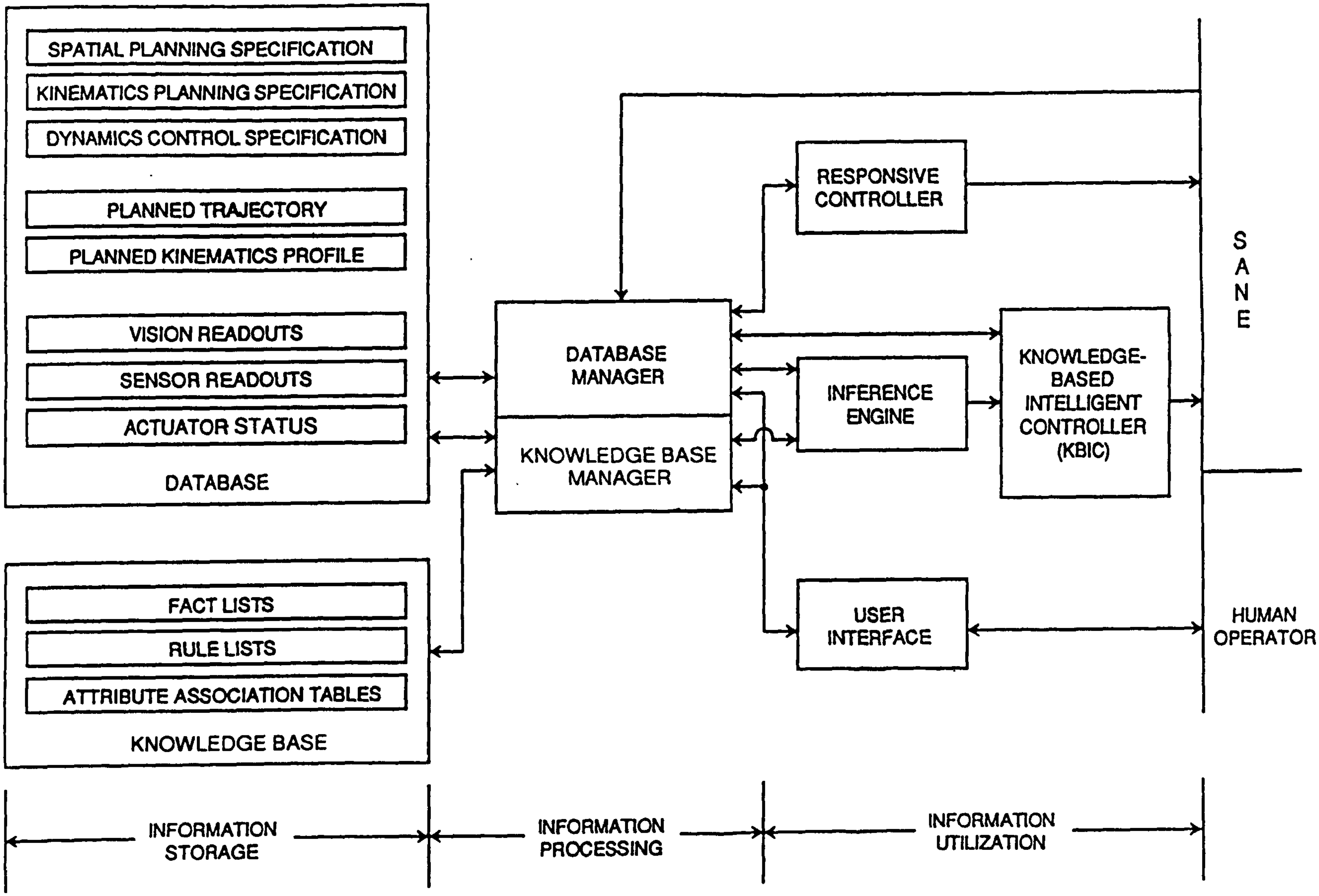

Figure 6. The functional diagram of KBIC with DKE processes.

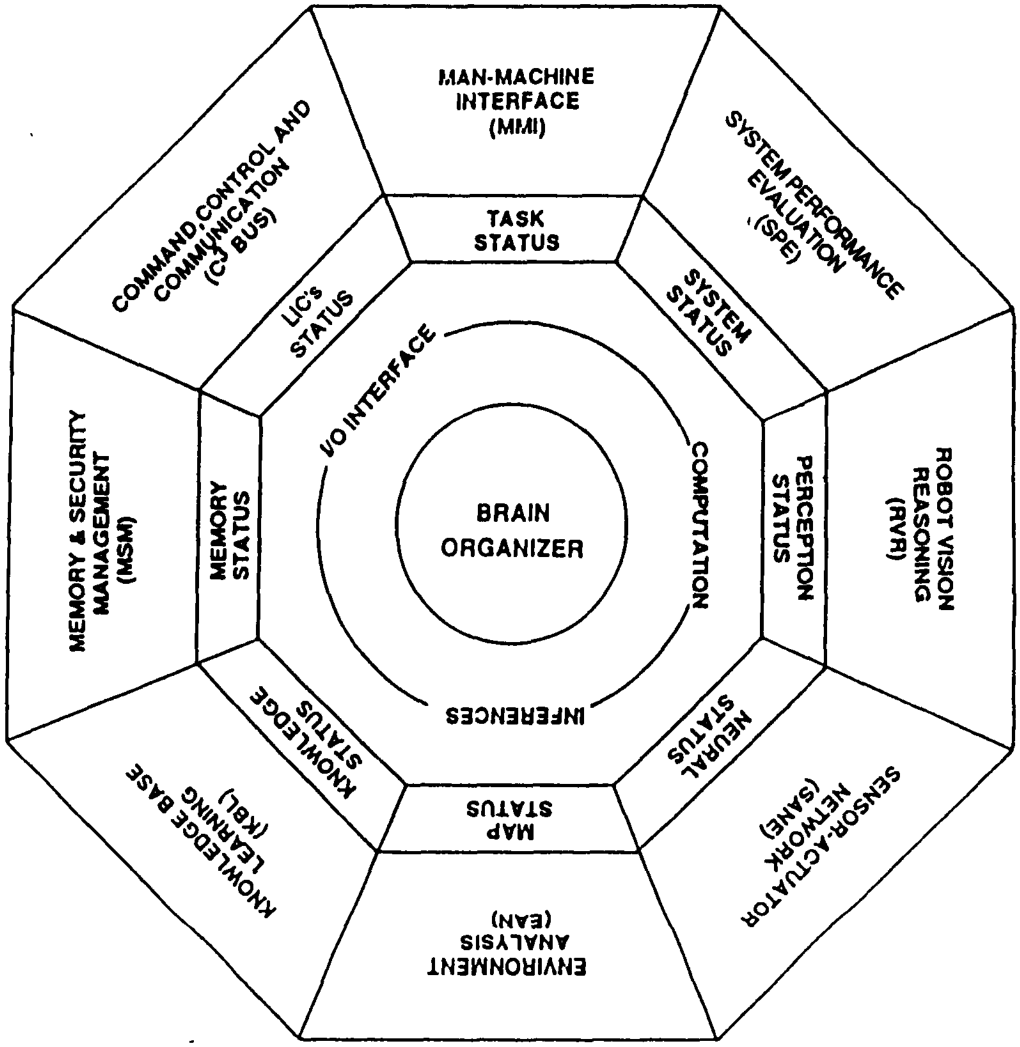

Figure 7. Functional diagram of SRAARS's brain

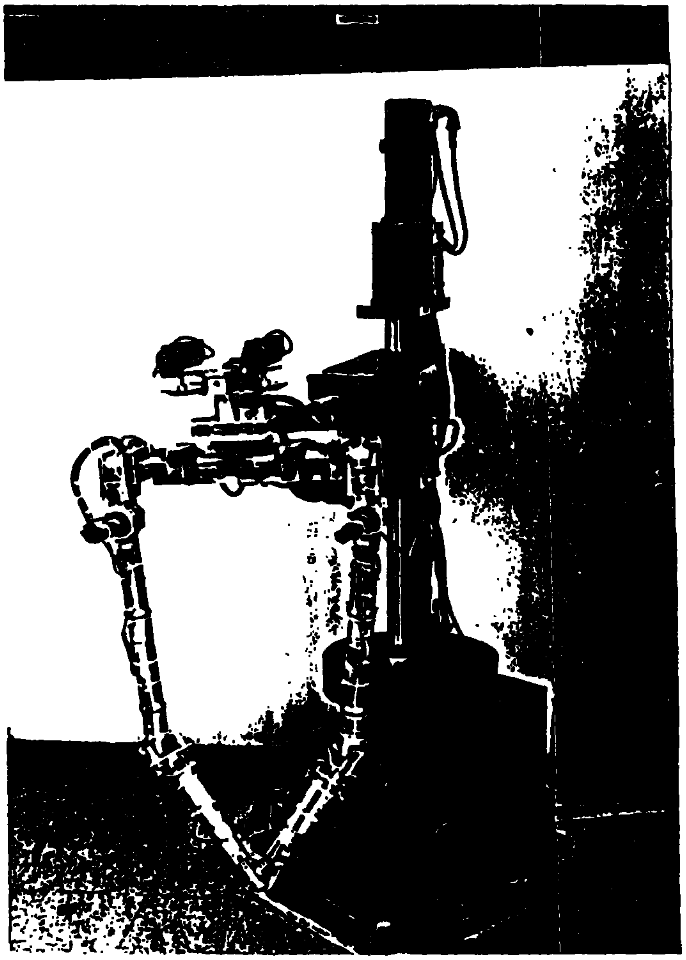

Figure 8. The advanced robotic system prototype.