Proc. of IEEE 2nd International Conference of Development and Learning, MIT, Cambridge, MA, June 12-15, 2002

Dav: A Humanoid Robot Platform for Autonomous Mental Development

J.D. Han, S.Q. Zeng, K.Y. Tham, M. Badgero and J.Y. Weng

Embodied Intelligence Laboratory
Department of Computer Science & Engineering
Michigan State University
East Lansing, MI 48824, USA

Abstract

A humanoid robot, Dav, is developed at MSU as a test-bed for experimental investigations into autonomous mental development. This general-purpose humanoid platform consists of a total of 43 degrees of freedom (DOF), including drive base, torso, arms, hands, neck and head. The body may support a wide array of locomotive and manipulative behaviors. For perception, Dav is equipped with a variety of sensing systems, including visual, auditory and haptic sensors. Its computational resource is totally onboard, including quadruple Pentium III plus PowerPCs, large memory and storage, networks, and long-sustention power supply. We discuss major design issues of a developmental humanoid and the design characteristics of the Dav robot in this paper.

1 Introduction

Industrial robots have been widely and successfully used in controlled industrial settings for a variety of tasks. Great challenges exist for robots to work in general human environments. These are characterized by unknown, unpredictable and changing objects, and tasks that cannot be well specified algorithmically. We call them muddy tasks. Vision, audition and language are at the fore front among cognitive capabilities that are required for muddy tasks. Autonomous mental development seems to give a possible way for machines to handle these muddy tasks [1].

Not until the late 1980's did embodiment receive attention in the artificial intelligent (AI) community, when it was popularized by the behavior-based approach [2][3]. Action generations have been fueled by impressive advances in robot construction, especially in humanoid platforms.

The first humanoid robot is "Elektro the Motorman" at 1939 New York World Fair. It was a legged humanoid robot that "talked," moved its limbs, and played some arithmatic tricks. With the arrival of computers, more impressive humanoid robots have been constructed to demonstrate their specially designed skills. Wabot-2 [4] (1980-1984) was designed and built solely to read music notes and play piano. WABIAN [5] was a humanoid robot capable of walking and dancing. An inspiring engineering achievement in humanoids is the P2 robot from Honda, which is capable of walking and climbing stairs [6]. More recent humanoid systems include H6 [7], ETL-Humanoid [8] and Robonaut [9]. These projects primarily focused on the challenges of mechatronic design and integration of enthropomorphic bodies and programming for generating action sequences.

In this paper, we discuss major issues in designing the body of the Dav developmental robot, and describe the design choices that we made under consideration of other parameters, such as the construction time and cost. In what follows, Section 2 introduces the basic concept of autonomous mental development. The developed robot body, shown as Fig.1, is discussed in Section 3. The conceptual design of Dav, its mechanism, controller and sensors are described in Section 4, 5, 6 and 7, respectively. Section 8 provides concluding remarks.

2 Learning, Perception and World Models

Actions can be programmed in or learned through practice. However, an action is not very useful if the robot does not have a perception capability, not knowing in what environment context to produce an action. Perception is well-known to be very challenging and

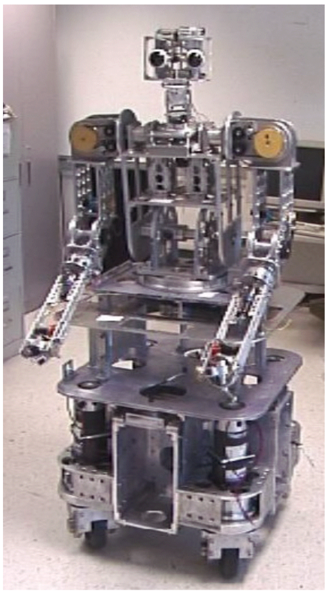


Figure 1: Dav: Mental developmental robot

typically a world model is predesigned. What are the limitation of such a hand-crafted model? Since these issues are closely related to robot construction, we discuss these issues in this section.

2.1 Actions through action practice

Instead of program action into a robot, another category of efforts aims to train the robot to produce desired behaviors. With redundant degrees of freedom, it is challenging to learn behaviors, especially when training time is limited or when training must be conducted online in real time. Such projects include LWPR on a SARCOS robot by Schaal et al. [10], the simulated model of a 37 degrees of freedom by Mataric et al.[11], and the scheduling degrees of freedom by Grupen et al.[12] motivated the early child motor development.

2.2 Perception-guided actions

In contrast with the above efforts that concentrate on behavior generation without requiring sophisticated perception, a series of efforts deals with perception and perception-guided behaviors. The main challenging perceptual sensing modalities include vision, audition and high-dimensional touch with many touch elements (including range sensing). No matter how complex a behavior (action sequence) is, the behavior is useful only when the robot can produce the behavior in the correct perceptual context and can suppress it in all other contexts.

Studies for perception driven behaviors have had a long history. A well practiced approach is to use human programmer to define features (e.g., edges, colors, tones, etc) or environmental models that are to be used. For example, the recent works on H2 from Honda and Kismet [13] produced impressive perception driven behaviors. Some speech features and visual features are used to establish audio-visual association by an active camera on a robot hand [14].

Programming perceptual capability using human defined features is a quick way to produce results in a controlled setting. A fundamental limitation is that the resulting robot cannot work well in unknown, partially unknown, or changing environments. Weng & Chen [15] explained the inefficiency of human defined features, the insufficiency of hand crafted models, and the difficulty in programming their applicability checker for an unknown environment.

2.3 World-model free approach

The world-model free approach has been studied somewhat independently in two research communities, robotics and computer vision. In the robotics community, they are called behavior-based methods [2][3]. The emphasis is to concentrate on behavior generation directly from range sensor readings or directly from images [16] [17].

The model-free approach in the computer vision community is called appearance-based methods. The appearance-based method started around 1990[18][19] and it appears to be the most popular method in the computer vision community now. Appearance-based methods use statistical tools directly on high-dimensional image vectors, after mean and contract normalization. Thus, an image with m rows and n columns is considered as a d-dimensional vector $v \in R^d$, where $d = mn$. Since high-dimensional statistics tools are directly applied to the vectors in space R^d, this type of methods can take into account not only correlations between nearby pixels, but also faraway pixels. The need to process a high dimensional sensory vector brings out a sharp difference between behavior modeling and perceptual modeling: the effectors of a robot are all known but the sensory space R^d is extremely complex and unknown, and therefore very challenging.

The power of learning directly from entire images has been demonstrated in vision-guided autonomous navigation. They include ALVINN [20] which uses multilayer perceptron (MLP) networks, ROBIN [21] which uses radial basis function networks (RBFN), SHOSLIF [22] and state-based SHOSLIF [23] which uses Fisher's multidimensional discriminant analysis in building a regression tree. As has been shown in the comparison study of SHOSLIF[22] [23], statistics based regression methods perform significantly better than traditional non-statistics based networks such as multi-layer perception and radial base function networks.

Perception-learning based action generation relieves the human programmer from the intractable task of programming perception. However, the above learning process is not fully autonomous in the following sense: (1) Human programmer designs a part of task-specific representation, e.g., features and states. (2) Human programmer has direct control over internal modules during learning, e.g., the coordinates of a moving part not something else are used to control another module. This mode of manual development fundamentally limits the scalability of cognitive and behavioral capabilities.

3 Robot Bodies for Mental Development

The essence of autonomous mental development by machines is the capability of learning directly, interactively, and incrementally from the environment using on-board sensors and effectors[24][25]. A developmental robot should be a real robot that runs a developmental program and is allowed to learn and practice autonomously in the real physical world. Internal representation and some fine architecture are developed autonomously as a result of interaction between the developmental program and the environment[26][27]. Humans, as a part of the environment, interact with such robots only through the robot's sensors and effectors.

The goal of the Dav robot project is to provide a next generation robot platform for research on mental development. Because Dav is meant for mental development, its design requirements are not the same as other humanoid robots. We discuss some major requirements here.

3.1 Mobility

The studies about human newborns raised in a foundling home and in a nursing home by Rene Spitz in the 1940's [28] [29] were the first to provide compelling evidence that normal mental development depends on rich sensory experience and social interactions. Avoiding obvious limitation of experiments on human newborns, Harry and Margaret Harlow chose monkeys as their subject of study in the 1960's. They found that newborn monkeys isolated for 6 - 12 months do not develop their behaviors normally [30].

Does a developmental robot need a body to develop mentally? Does it need its own autonomous behavior in such a developmental process? Richard Held and Alan Hein's study [31] is more detailed and thus shed light on these questions. They designed an apparatus called a "Kitten carousel". Kittens were raised in total darkness until they were old enough to walk. Each pair of them was then put into the kitten carousel. The first kitten in the pair was harness to pull the carousel with a rope so that it could learn how what it sees changes due to its own actions. It can control what it sees through its own actions. The other kitten was carried in the gondola of the carousel where its neck is fixed with the carousel. The kitten sees passively and what it sees is controlled by the pulling kitten instead of itself.

After 42 days of practice, the passive kitten does not develop the cliff avoidance behavior but the active one did. This demonstrated that passive movements are not sufficient for normal mental development. How about human infants? Compos and his colleagues' more recent studies [32] showed that human infants, a week or two after they began to crawl, do not fear of height. Only 40 hours experience careening around in a walker is sufficient for them to develop the fear of height. There have been a lot of studies that showed the importance of autonomous movements in developing humans and animal's sense of the world and their normal behaviors [33] [34].

Therefore, it appears that mobility is a necessary condition for mental development. In order to allow the robot to go to places that a typical human can go, we have decided that Dav will be totally untethered, with all the computational resources on board.

A robot can move on legs or wheels. Due to the stringent requirements on the power of the motors and batteries, we decided that Dav will move on wheels. A wheeled platform makes it easier for the robot to learn how to roam around, compared with biped walking.

3.2 Manipulators

A developmental platform should be equipped with dexterous arms and hands. It is desirable for them to take a human shape so that they can use a wide variety of tools designed for human.

However, the design faces the conflicting conditions:

power and size. We like to have a higher power limb for a larger payload. The higher the power, the larger the motors and other supporting devices. But the size is limited by a typical human size. The electronic boards of each limb must be contained in the same limb. The most challenging of all is to satisfy this self-containment requirement for Dav's hands. We expect that this problem will be better solved if motors are custom designed.

3.3 Sensing

A human has visual, auditory, touch, taste and smell senses. For a developmental robot, the most important ones are vision, audition and touch, in a general setting.

Internal attention effectors are defined for each sensor. Attention is required since the robot cannot learn quickly and generalize without attention. For example, if vision and audition cannot be attended individually, then the robot is not able to recognize a familiar human face if the face is seen while a new piece of music is played, or it is not able to recognize a familiar music if it is heard in a new place. On the other hand, it is not always the case that vision and audition are independent. Lip reading while chatting in a noisy environment is a good example.

Dav has two color cameras as eyes, two microphone as ears, and one speaker as the mouth. All of these are mounted on an 8-DOF head. There are also contact force sensors on the finger-tip, as well as a current and torque sensor for each joint. The touch and torque sensors are important for hand-in-hand teaching i.e., supervised learning. A laser range scanner is mounted at the front of the robot to realize range sensing.

3.4 Computational resource

The developmental program must be able to update its memory for all the sensors within a fraction of a second, e.g., 10ms for sound and 100ms for vision. The control signals of effectors must also be updated at a rate of at least 10Hz.

Currently, hardware implementation is not practical for an algorithm that is expected to change very often through out the research project. Thus, the developmental program is to be implemented by software.

The memory of a developmental robot is expected to be very large. Thanks to the logarithmic time complexity of IHDR[35] [36], it is expected that the refresh rate of the developmental program will not slow down too much when the memory size increases. However, this is still an open question, since we need to test a robot with more extensive learning experiences.

Dav's computer system includes quadruple Pentium III, Flash RAM, Hard Disk Array, and dedicated PowerPCs as its controller.

3.5 Power supply

Unlike other robots, extended training and practice are necessary for mental development. For some complex behaviors, for example, those involving both navigation and manipulations, the training procedure may last several hours every day. Therefore, the battery capacity has to be large enough to support such a daily operation without the need for interrupting operation and changing batteries.

The battery capacity is still an unsolved problem, as with electric cars. Currently, with a consideration of cost and capacity availability, we still think that a reasonable choice is sealed rechargeable batteries. Dav is equipped with 480 AmpH batteries and is expected to work continuously for about 4 hours without recharging.

The quadruple Pentium III consumes hundreds of watts of battery power, and is a major power user. Although the current laptop computer boards are a lot more energy efficient, the peripheral support for the current laptop computers is still limited.

3.6 Wiring

Wiring is a very challenging issue for a humanoids, especially for developmental ones. Due to very large number of sensors and motors in the limbs, the number of wires required between each joint reaches a few hundred if data processing and computation are centralized at a single location.

Such a large number of wires causes at least two major problems. First, the rigidity of the wire bundle interferes with dexterous manipulators. Second, the wire bundles cannot sustain repeatative bendings during extended usage and they will break.

We have adopted a network scheme, similar to that used in Honda humanoids. The fast digital network has only a few wires, and the fast speed allows a high throughput accommodating many signal lines.

Further, mechanical parts, especially joints are designed in such a way so that the wires can go through with minimal bending to increase the reliability of the system and reduce maintenance frequency.

4 Conceptual Design of Dav

The conceptional design for Dav consists of the following major characteristics:

- Modular mechnical structure for the ease of maintenance and modification.
- Enough DOFs and range of motion to support mobility and manipulability, as well as active sensing ability.
- Fully-self-contained-body, including computer system, servo circuits, battery group and its charger.
- Smooth cover to allow direct human-humanoid interaction.
- Hollow shaft structures to route all wires through the inside.
- On-board quadruple Pentium III computer system for mental developmental algorithms, and standard PCI as open-ended architecture for expansion.
- Wireless ethernet connection for remote control.
- In-house designed and boilt modular servo control boards distributed through the body for integration with actuators and to reduce the number of wires.
- Control Area Network (CAN) Bus for communication with distributed servo modules and sensors.
- Torque and current sensors for compliant control, safe execution, and proprioceptor sensors.
- Contact sensor in each finger-tip.
- Utilizes standard parts as much as possible to reduce the construction time and costs.

5 Mechanism

Fig.1 shows the body of Dav robot. It is contained in a volume of 750(l) x 750 (w) x 1700(h) (mm) in default posture, composed of four-wheel non-holonomic drive-base, 2-DOF torso, two 7-DOF arms, two 8-DOF hands and 8-DOF head. The mechanisms for some major parts are illustrated in Fig. 2, and the DOF distribution and the installed sensors are summarized in Table 1. The mechanical body contains over 320 types with a total of 1010 custom-made parts.

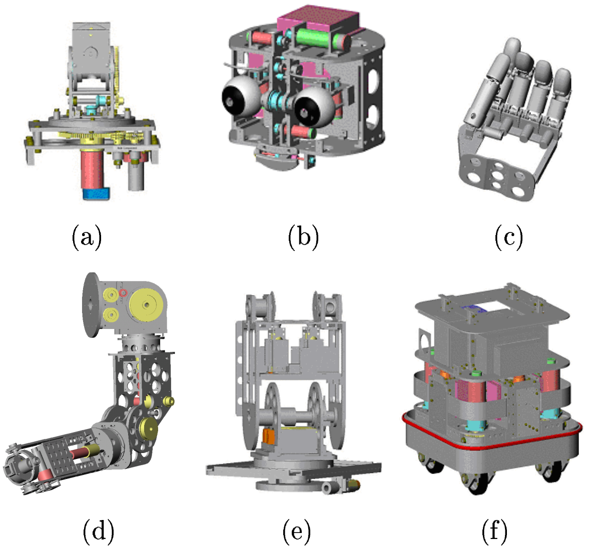


Figure 2: Mechanism of each body part. (a) Neck. (b) Head. (c) Hand. (d) Arm. (e) Torso. (f) Base.

5.1 Drive-base

In order to realize omni-directional as well as both indoor and out-door navigation, two DC-motors are used in each wheel, for driving and steering separately. Totally four wheels are integrated in the base. Installed inside the mobile body are: on-board quadruple PIII computer system, 24V-480 AmpH battery group and its charger, power supplying (DC/DC converter) and monitoring module, servo units for the 8 DC motors integrated with encoders. A bumper with multi-section touch sensors is placed around the bottom of the body for collision protection and sensing.

5.2 Torso

To imitate human body, and also to enable picking up objects at a lower height, a two-DOF torso is placed on the drive-base. Because all the power-supply wires must go through the torso from the drive-base to arms, hands and head, a pancake-shape bearing and worm gear are used in the rotation joint to support a hollow-shaft with a central-hole as large as 50mm.

5.3 Arm and Hand

For achieving highly dexterious manipulation, 7 degrees-of-freedom are integrated into each arm. All shafts of the arm are hollowed for wires. An 8-DOF 5-finger hand is installed at the end of each arm. The 7-DOF arm is distributed as 3-DOF shoulder, 2-DOF elbow and 2-DOF wrist. The 8-DOF hand has 2 DOFs in each of the thumb, index and middle fingers, and 1

Table 1: Description of Dav Robot

Part Name	DOF	Sensors Installed
Drive Base	3	encoders, laser scanner
Torso	2	strain gages, encoders
Arm	7	strain gages, encoders
Hand	8	current, tactile sensors, encoders
Neck	3	encoders
Head	5	cameras, microphones, speaker, accelerometers, encoders

DOF for the 4th and 5th fingers. All 8 DOFs on the fingers adopt worm gear transmissions for compact design. All the servo units, including power amplifiers and controller boards for the arm, are integrated inside the arm itself, except those for the shoulder which are located conveniently in the torso. All the servo units for the 8 motors in the fingers are inside the palm, where the space is very limited.

5.4 Head and Neck

As a sensor platform, the head is designed to support active sensing, such as vision and audition. This 8-DOF mechanism includes 3-DOF neck, where the rotation joint is actuated by an anti-backlash geared motor. The brows and lips are computer-controlled. The two cameras can independently pan and jointly tilt.

6 Controller

The hardware controller for Dav has two levels: a central computer system and low-level servo modules. Fig.3 illustrates the architecture.

6.1 Central Computer and Peripherals

The computer's processing power is especially important for its mental development, which requires real-time sensing, perception, recognition, and motor signal generation. We adopt a quadruple-CPU mother board as the backbone of computer system. It has up to 4 times the processing power of a normal single CPU board, while keeping the advantages of a PC system, such as standard bus, open-architecture and easy upgrades. Based on this backbone, the computer system is constructed with peripherals such as 4 Pentium III 700MHz processor modules, 2G bytes SDRAM and 72G bytes SCSI harddisk array, wired and wireless Ethernet cards, image capture boards, CAN-Bus interface, as well as interfaces for laser scanner and gyroscope sensors. The CAN-Bus interface is used to communicate with the decentralized low-level servo modules.

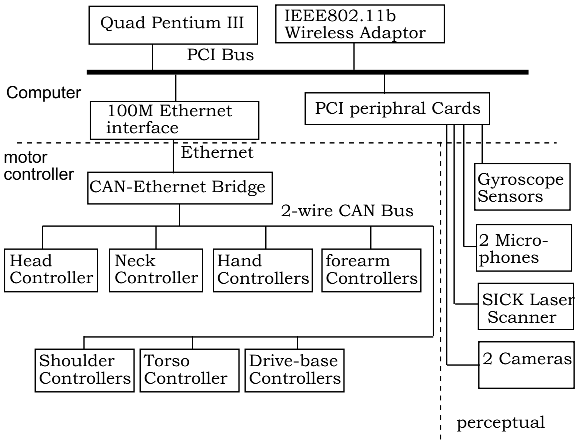


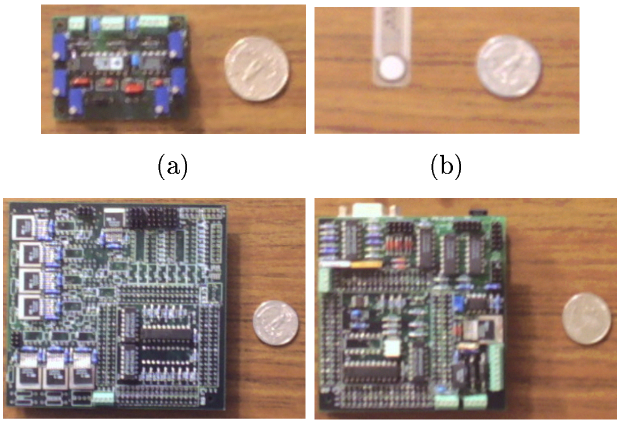
Figure 3: The overall system architecture of Dav.

Moreover, Dav has a current and voltage monitoring module inside the power supply unit, which provides necessary information during normal execution and charging phases, as well as overload protection.

6.2 Servo Controller

The servo control boards and sensor interfaces of Dav are placed as close to actuators/sensors as possible, to reduce the wire distribution through the body. 7 different servo control boards have been designed and fabricated to satisfy the requirements of each group, and are networked by the two-wire CAN-Bus. This structure reduces hundreds of signal wires to only 2, going through the entire body, plus other 6 wires for power supply (See Fig.3 for controller structure).

Fig. 4 shows some examples of house-made servo boards. A quarter coin is shown to indicate the scale.



(a) (b)

(c) (d)

Figure 4: Tactile sensor and samples of 10-types of house-built circuit boards. (a) Strain gage interface. (b)Tactile sensor. (c) Hand servo interface. (d) arm servo interface.

7 Sensors and Perception

To obtain information from its environment and communicate with humans, Dav has a variety of sensors: vision, auditory, range, accelerometers, tactile, torque as well as joint position sensors.

Active vision system: The vision system consists of two micro color CCD camera heads with diameters of 7mm. They are installed on the eye platform inside the head. Each camera has a separate control box that is located in the torso, providing convenient on screen display, automatic gain control, and automatic electronic shutter setting. Video signal sampling is performed by two frame grabber cards which communicate with processors via PCI interface bus. The current digital cameras available commercially can provide digital signal directly, but they do not have as small a size as desirable. Combining torso rotating, bowing and neck pitching allows Dav to see all of the four edges of its drive base.

Auditory system: Two microphones are mounted on the two sides of Dav's head. To make it easy for sound localization, two artificial auricles are added around the microphones. The auditory signals go though preamplifiers and bandpass filters before they are sampled by a commercial sound card attached to the computer.

Accelerometers: To mimic the human's vestibular sensor, two 2-axis custom-built acceleration sensors are orthogonally mounted in Dav's head. Like the human vestibular sensory organ located in the inner ear, these sensors measures the linear acceleration of three orthogonal axis (corresponding to the otolith organs). The sensor readings play a role in coordination of motor responses, eye movement, head posture, and balance of the body. Analog signals from each of these sensors are amplified on a small conditioner board, and digitized by a nearby MPC555 microcontroller.

Torque/armature current sensors: Safe manipulation and compliant motion are especially important for a humanoid robot to directly interact with humans, and torque sensing is necessary for every joint during interaction with the environment. For Dav, torque sensing is necessary to build up its safe manipulating skills. Its torque sensors are made by attaching full-bridge strain gauges on joint shafts with interface boards which include gain-adjustable amplifiers (gain from 10 $\sim$ 1000) and cut-frequency-adjustable low-pass filters. A torque sensor is installed on each joint of the torso and arms. Due to space limits, the figure torque was sensed indirectly by current. A sensitive touch is detected by the tactile sensors on every fingertip. Both the current and the tactile sensor conditioners are integrated into the hand servo module.

Motor position: A quadrature encoder is integrated with every motor on Dav for position sensing, and count numbers are generated by the corresponding servo modules.

All of the above-mentioned sensors are accessible to the central computer, i.e., mental developmental programs via CAN-Bus or local bus. The CAN-Bus and decentralized low-level control modules form an open architecture for possible addition of other sensors.

8 Conclusion

This paper introduced the requirements, the design criteria and the design characteristics for the Dav robot, a humanoid platform for mental development research. It has enough degrees of freedom to support basic actions, such as mobility and dexterous manipulability. It is equipped with major sensors necessary for interacting with environments and human instructor. Its computational resource has a high performance-to-cost ratio by adopting mass market computer hardware. Its CAN-Bus protocol provides an open architecture for sensor extension. Combined with its long-sustention batteries and wireless Ethernet, Dav potentially can be used for research by various research groups.

Acknowledgements

The work is supported in part by an MSU Strategic Partnership Grant, National Science Foundation under grant No. IIS 9815191, DARPA ETO under contract No. DAAN02-98-C-4025, DARPA ITO under grant No. DABT63-99-1-0014.

References

[1] J. Weng, J. McClelland, A. Pentland, O. Sporns, I. Stockman, M. Sur, and E. Thelen, "Autonomous mental development by robots and animals," *Science*, vol. 291, no. 5504, pp. 599–600, JAN. 2000.

[2] R. A. Brooks, "A robust layered control system for a mobile robot," *IEEE Journal of Robotics and Automation*, vol. 2, no. 1, pp. 14–23, March 1986.

[3] R. C. Arkin, *Behavior-Based Robotics*, The MIT Press, Chambridge, MA, 1998.

[4] S. Shigeki and K. Ichiro, "Wabot-2: Autonomous robot with dexterous finger-arm - finger -arm coordination control in keyboard performance," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 90–97, 1987.

[5] H. Lim, A. Ishii, and A. Takanishi, "Motion pattern generation for emotion expression," in *Proc. 2nd International Conference on Humanoid Robots*, Tokyo, Japan, Oct. 8-9 1999, pp. 36–61.

[6] K. Hirai, M. Hirose, Y. Haikaw, and T. akenak, "The development of honda humanoid robot," *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1321–1326, 1998.

[7] K. Nishiwaki, T. Sugihara, S. Kagami, F. Kanehiro, M. Inaba, and H. Enoue, "Design and development of research platform for perception-action integration in humanoid robot : H6," *Proceedings of IEEE/RSJ International Conference On Intelligent Robots and Systems*, pp. 1559–1564, 2000.

[8] A. Nagakubo, Y. Kuniyoshi, and G. Cheng, "Etl-humanoid - a high-performance full body system for versatile action," *Proceedings of IEEE/RSJ International Conference On Intelligent Robots and Systems*, pp. 1087–1092, 2000.

[9] L. Li, B. Cox, M. Diftler, S. Shelton, and B. Rogers, "Development of a telepresence controlled ambidextrous robot for space applications," *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 58–63, 1996.

[10] S. Vijayahumar and S. Schaal, "Real time learning in humanoids: A challenge for scalability of online algorithms," in *Proc. IEEE International Conference on Humanoid Robots*, Cambridge, MA, Sept. 7-8 2000.

[11] A. Billard and M. Mataric, "Learning human arm movements by imitation: Evaluation of a biologically-inspired connectionist architecture," in *Proc. IEEE International Conference on Humanoid Robots*, Cambridge, MA, Sept. 7-8 2000.

[12] J. Coelho, J. Piater, and R. Grupen, "Developing haptic and visual perceptual categories for reading and grasping with a humanoid robot," in *Proc. 1st IEEE International Conference on Humanoid Robots*, Cambridge, MA, Sept. 7-8 2000.

[13] C. Breazeal, "Social constraints on animate vision," in *Proc. IEEE International Conference on Humanoid Robots*, Cambridge, MA, June 20-25 1990.

[14] D. Roy, B. Schiele, and A. Pentland, "Learning audio-visual associations using mutual information," in *Proc. International Conference on Computer Vision, Workshop on Integrating Speech and Image Understanding*, Corfu, Greece, 1999.

[15] J. Weng and S. Chen, "Visual learning with navigation as an example," *IEEE Intelligent Systems*, vol. 15, pp. 63–71, Sept./Oct. 2000.

[16] M. J. Marjanovic, B. Scassellati, and M. M. Williamson, "Self-taught visually-guided pointing for a humanoid robot," in *From Animals to Animats: Proc. of 1996 Society of Adaptive Behavior*, Cape Cod, MA, 1996, pp. 35–44.

[17] W. Hwang and J. Weng, "Vision-guilded robot manipulator control as learning and recall using SHOSLIF," in *Proc. IEEE Int'l Conf. on Robotics and Automation*, Albuquerque, NM, April 20-25 1997.

[18] M. Kirby and L. Sirovich, "Application of the karhunen-loève procedure for the characterization of human faces," *IEEE Trans. Pattern Analysis and Machine Intelligence*, vol. 12, no. 1, pp. 103–108, Jan. 1990.

[19] M. Turk and A. Pentland, "Eigenfaces for recognition," *Journal of Cognitive Neuroscience*, vol. 3, no. 1, pp. 71–86, 1991.

[20] D. A. Pomerleau, "Efficient training of artificial neural networks for autonomous navigation," *Neural Computation*, vol. 3, no. 1, pp. 88–97, 1991.

[21] M. Rosenblum and Larry S. Davis, "An improved radial basis function network for visual autonomous road following," *IEEE Trans. Neural Networks*, vol. 7, no. 5, pp. 1111–1120, 1996.

[22] J. Weng and S. Chen, "Vision-guided navigation using SHOSLIF," *Neural Networks*, vol. 11, pp. 1511–1529, 1998.

[23] S. Chen and J. Weng, "State-based SHOSLIF for indoor visual navigation," *IEEE Trans. Neural Networks*, vol. 11, no. 6, pp. 1300–1314, Nov. 2000.

[24] N. Almassy, G. M. Edelman, and O. Sprons, "Behavioral constraints in the development of neural properties: A cortical model embedded in a real-world device," *Cerebral Cortex*, vol. 8, no. 4, pp. 346–361, June 1998.

[25] M. Sur, A. Angelucci, and J. Sharm, "Rewiring cortex: The role of patterned activity in development and plasticity of neocortical circuits," *Journal of Neurobiology*, vol. 41, pp. 33–43, 1999.

[26] J. Weng, W. S. Hwang, Y. Zhang, and C. Evans, "Developmental robots: Theory, method and experimental results," in *Proc. 2nd Int'l Symposium on Humanoid Robots*, Tokyo, Japan, Oct. 8-9 1999, IEEE Press.

[27] J. Weng, W. S. Hwang, Y. Zhang, C. Yang, and R. Smith, "Developmental humanoids: Humanoids that develop skills automatically," in *Proc. First IEEE Conf. on Humanoid Robots*, MIT, Cambridge, MA, Sept. 7- 8 2000, IEEE Press.

[28] R. A. Spitz, "Hospitalism: An inquiry in to the genesis of psychiatric conditions in early childhood," *Psychoanalytic Study of the Child*, vol. 1, pp. 53–54, 1945.

[29] R. A. Spitz, "Hospitalism: An follow-up report on investigation described in volume 1, 1945," *Psychoanalytic Study of the Child*, vol. 2, pp. 113–117, 1946.

[30] H. F. Harlow, R. O. Dodsworth, and M. K. Harlow, "Total social isolation in monkeys," *Proc. National Acad. Sci. USA*, vol. 54, pp. 90–97, 1965.

[31] R. Held and A. Hein, "Movement-produced stimulation and the development of visually guided behaviors," *Journal of Comparative and Physiological Psychology*, vol. 56, pp. 872–876, 1963.

[32] B. I. Bertenthal, J. J. Campos, and K. C. Barrett, "Self-produced locomotions: An organizer of emotional, cognitive, and social development in infancy," in *Continuities and discontinuities in development*, R. Emde and R. Harmon, Eds. Plenum Press, New York, NY, 1984.

[33] M. Cole and S. R. Cole, *The Development of Children*, Freeman, New York, third edition, 1996.

[34] J. H. Flavell, P. H. Miller, and S. A. Miller, *Cognitive Development*, Prentice Hall, New Jersey, third edition, 1993.

[35] W. S. Hwang and J. Weng, "Hierarchical discriminant regression," *IEEE Trans. Pattern Analysis and Machine Intelligence*, vol. 22, no. 11, pp. 1277–1293, 11 2000.

[36] J. Weng and W. S. Hwang, "An incremental learning algorithm with automatically derived discriminating features," in *Proc. Asian Conference on Computer Vision*, Taipei, Taiwan, Jan. 8-9 2000, pp. 426 – 431.