Recent Developments in Japanese Robotics Research – Notes of a Japan Tour –

Uwe R. Zimmer[†], Thomas Christaller[†], Christfried Webers[‡]

German National Research Institute
for Information Technology (GMD)
[†]Schloß Birlinghoven, 53754 Sankt Augustin – Germany
[‡]GMD liaison office, 7-5-56 Akasaka, Minato-ku, Tokyo 107 – Japan

Robotics appears to be a very lively and fruitful field of research in Japan. Some of the research topics cannot be found elsewhere at all, and some are significantly advanced. Discussing this impression, a collection of laboratories is introduced with their most outstanding topics. Moreover some background information about research plans, politics, and organisations are given.
This report is based on the notes of a trip through Japanese laboratories in February 1997.

1. Motivation and Criteria

The robotics research scene in Japan is a widespread and lively community. From this scene, research topics and projects that are unique or original will be highlighted. This report is not meant to be a strict scientific discussion of the subjects, but to set a spotlight on recent trends and developments in the Japanese robotics research community and to give links for deeper investigation.

Criteria used for the description of groups and projects include:

- Original and outstanding research topics.
- Basic research issues.
- Disciplines represented in the group, thus the interdisciplinarity of the group – a key issue for most parts of robotics research.
- International exchange (visiting researchers).
- Intended or implemented applications.
- Industrial relationships.
- Participation in research funding programs.
- Organisation or initiation of conferences, workshops, and scientific organisations.
- Special aspects/notes.

The discussed groups and projects are a selection of the laboratories known or have been visited by the authors only. Thus this report focuses on some recent work instead of listing the full range of robotics groups. Up to now, there are more than 150 Japanese research groups concerned in robotics research or closely related topics [73]. And even in this listing the 'classical' control theory oriented stream of robotics, mainly relating to manufacturing manipulators, is not covered completely.

The description of individual laboratories is organized in three sections:

- Biological orientation: The motivation to understand biological creatures and to mimic certain observed aspects is a central issue in these laboratories. Biologically plausible solutions are usually preferred over technologies, exploiting global observers or high speed communications.
- Learning & cognition: Here the understanding and design of artificial creatures is the central aspect. Especially adaptability to current working environments as well as the understanding and modelling of complex interactions between robots themselves and with their habitat is discussed.
- Mechatronics: By studying the complex possibilities of kinematics with many degrees of freedom and understanding high speed feedback systems, a third important aspect of robotics research is addressed.

These categories are anything but rigid. The selection being done here is based on the main motivation of each group. Obviously, solutions originating from investigations in many degrees of freedom kinematics can also be biologically plausible.

The authors are aware of the fact that the selection of 'interesting' topics is to a certain degree related to the research focus and background of themselves. Thus the robotics research activities of the authors should be mentioned briefly by keywords: *Autonomous systems* [10], [64] (especially mobile systems in natural environments), *learning and adaptation* [9], [21], [63] (on all levels of control/cognition), *complete systems* [11] (i.e. 'closed loop' systems), and *complex behaviours* [12], [65] (together with fruitful experimental setups evaluating these behaviours).

2. Biologically Oriented Laboratories

Working with biological creatures (laboratory of *Hirofumi Miura* and *Isao Shimoyama*), mimicing biological systems (*Noboru Ohnishi* laboratory and the laboratory of *Masami Ito*), organizing robotics groups under biologically plausible aspects (the biochemical systems laboratory of *Isao Emura*) or observing human teachers and try to replay and refine recognized actions (*Mitsuo Kawato* laboratory) – these are all aspects of biologically inspired robotics research.

2-1. Miura & Shimoyama Laboratory

University of Tokyo

The laboratory of Hirofumi Miura and Isao Shimoyama at the University of Tokyo handles a range of disciplines under the aspect of some well-defined leading topics. Insect behaviours, biological sensors, µ-robotics, and 'combinations' of biological and mechatronic creatures are some of the topics the laboratory is dedicated to. Strong backgrounds in biology (also in cooperation with the group of Ryohei Kanzaki at the University of Tsukuba), µ-mechanics and µ-electronics, as well as computer science are available. Moreover the team is internationally oriented. Fabrizio Mura for instance (coming from the laboratory of N. Franceschini [16] at the CNRS, Marseille, France) performs research on an insect compound eye design and Raphael Holzer (from Switzerland) experiments with stimulated cockroaches and other setups.

The authors would like to discuss only some aspects out of the research field of the Miura and Shimoyama laboratory briefly: The first aspect is µ-robotics, where ideas from Japanese Origami are joined with sophisticated µ-mechanics, leading to walking machines of 0.7 by 1.5 mm [62]. The energy problem is solved by stimulating oscillations of mechanical parts externally. These mechanical resonances (at 50 and 100 Hz) are used to activate a pushing leg on each side of the vehicle. By using different resonance frequencies on each side, the direction of motion is controlled also. As other sources of energy for the µ-manipulators, structures sensitive to magnetic [25], electrostatic [22], and air pressure changes are presented. All these parts are produced in two sterile rooms owned by the laboratory.

One of the projects including biological components is the usage of a pheromone sensitive antenna extracted from a silk moth for the control of a small mobile robot. It could be shown that this biological sensor can be employed successfully to follow a track of pheromones by an artificial creature [33]. Recurrent neural networks and genetic algorithms are employed also in the development of motion control structures.

In a further experiment cockroaches are stimulated by electrical pulses and heat at some sensitive areas in order to control their walking behaviour. The complete µ-controller as well as the energy and the I/O for this task are applied on a small 'backpack' for the cockroach. Some potential applications are inspections after an earthquake, where cracks or pipes are often too small or rough to use conventional robots. In another experiment individual cockroach legs are extracted, stimulated electrically and attached to an artificial body. Here the movement control is more explicit (and thus complex) than by stimulating the whole insect to move towards a certain direction.

The other way round, a robot controlled by a (completely intact) silk moth in order to follow a pheromone track is also implemented successfully. Being fixed over a conventional trackball, the moth controls the robot by turning the trackball with its feet.

'Conventional' robots, like a six-legged robot are used also to study the generation of walking patterns. Two walking robot designs (in the 'standard scale' mechanics) were produced in the laboratory for this purpose up to now.

Finally a flying µ-robot is presented, where a magnetic sensitive layer (nickel) is used in conjunction with polyimide to produce a wing-flapping movement, controlled by a magnetic field [46].

2-2. Ohnishi Laboratory

Bio-mimetic Sensory Systems
RIKEN BMC, Nagoya, Aichi

The group of bio-mimetic sensory systems headed by Noboru Ohnishi emphasizes the importance of audition, vision and general learning methods for the understanding of biological information processing. In the area of audition very promising results about sound separation in anechoic and empty rooms are achieved already. The direction of each sound source can be extracted with an accuracy of some degree, where the extraction of features is based on the sound's arrival temporal disparities, detected individually in multiple frequency bands. Jie Huang together with Noboru Ohnishi are performing and conducting the research on audition [23].

Zeng-Fu Wang, Kenneth H.L. Ho, Jun Yang, Toshiharu Mukai, Jae-Moon Chung, Tohru Yagi, and Huang Jie are performing research in the area of vision and robotics, where the final goal is the understanding of sensor fusion of modes like audition, vision, and tactile sensing.

The activities in the Ohnishi laboratory are part of the 'Frontier Research Program' (see section 5 for a description).

2-3. Ito Laboratory

Bio-mimetic Control Systems
RIKEN BMC, Nagoya, Aichi

The analysis of autonomous decentralized systems especially regarding the motor control system, is focused in the group of Masami Ito. Nonlinear dynamical system theory is employed in order to come up with a theoretical framework for the generation of spatio-temporal motor patterns. Beside Masami Ito, Zhi-Wei Luo, Bao-Liang Lu, and others are conducting practical experiments on motorical coordination supporting the theoretical work.

Biological observations are an important source of ideas and a reference frame for the technological systems. For instance the impedance of a human hand performing positioning movements in two degrees of freedom is measured by applying external disturbances while recording stillness, viscosity and inertia [55]. These experiments are closely related to the work performed in the group of Mitsuo Kawato at ATR (see section 2-5). Applying forces in dynamical or unpredictable environments [35] as well as cooperative manipulation of dynamic objects [34] show practical models of biophysiological observations using well founded control theory. Based on the idea of distributed processing and local communication, a visual associative memory system is presented. The system converges to one of the five trained pictures after about one thousand iterations of local filters [26]. There is a lot more to report, but the cited work should stake out the area of research.

The performed work is considered also as part of the 'frontier research' program (see section 5).

2-4. Biochemical Systems Laboratory

RIKEN, Wako, Saitama

The biochemical systems laboratory headed by Isao Endo is based on biological motivations and performs research in the field of distributed autonomous systems using physical mobile robots. A strong background at mechatronic engineering as well as biology supports the practical experiments. As a regular event focusing on the group's topics, the international symposium on Distributed Autonomous Robotic Systems (DARS [4]) is organized by Isao Endo together with Ulrich Rembold and Rüdiger Dillmann from the University of Karlsruhe, Germany. Furthermore the group is well embedded in international collaborations with academic groups (University of Philadelphia or the University of Karlsruhe) as well as industrial partners (VTT Automation, Finland or Necco Co, Ltd., Japan).

Some aspects of distributed mobile robot systems discussed in the group of Isao Endo are introduced briefly: Cooperation is a central idea in many works which are mainly conducted by Hajime Asama and Teruo Fujii. Mobile robots showing more kinematic flexibility through mechanical coupling of multiple robots is presented in form of mobile vehicles that can forklift each other. Thus two such vehicles can overcome a step of almost the height of an individual robot in cooperation [6].

For individual kinematic flexibility of the mobile robots, an omnidirectional drive mechanism was developed based on the idea of free roles on wheels and combined with complete driving mechanics employing only three actuators controlling the three degrees of freedom of the mobile platform directly and a suspension mechanism that supports the practical usage of such platforms significantly [5].

As a suggestion for a locally oriented communication scheme that seems to be much more biologically plausible than radio-links covering the whole workspace, an infrared based communication link is introduced and applied to applications like local dynamic collision avoidance and exchange of small information packets while passing each other [1].

Also locally oriented is a communication scheme that introduces active landmarks which can store information they receive from passing robots and which can furthermore be moved to new locations by the robots. An application of such a communication scheme is for example the setting of specific warning signs in dedicated places. Thus this communication scheme is very flexible, and expandible. There can be even more than one such landmark at the same place, because they can be stacked and be transported as a stack [17].

2-5. Kawato Laboratory

ATR, Kyoto

The group of Mitsuo Kawato as part of the ATR (Advanced Telecommunications Research Institute International) and as part of the ERATO project (see section 5), is dedicated to investigations in the sensor-motor loop of biological as well as artificial creatures. International contacts are intense and many visiting researchers are participating in the research (49 out of 224 researchers at ATR are invited from overseas). In the group of Mitsuo Kawato for example, which is part of the human information processing laboratory, Stefan Schaal – a visiting researcher from Georgia Institute of Technology – is heading the computational learning group in the Kawato Dynamic Brain project (ERATO).

One of the approaches followed is an observing and rehearsal method, where complex sensor-motor tasks like Kendama (a Japanese game), pole balancing and others are performed by human 'tutors' and observed by a stereo camera system. This recorded information is used to initialize a kinematic model that is refined during further process by reinforcement learning methods. Thus the search in the tremendous spatio-temporal state space of a seven degrees of freedom arm (here especially constructed for this experiments using fast hydraulics) is significantly pruned in order to make the learning task efficient. The work could be demonstrated in practical experiments starting from the observation of the human tutor to the learned pole balancing [44]. The theoretical foundation of the 'bi-directional theory' can be found in [39]. Here the central aspect is that the exchange of coordinating control information between higher and lower level components is forced in both ways and that modules are operating in parallel. Details about the reinforcement learning scheme can be found in [13] given by Kenji Doya who is the head of the computational neurobiology group.

In cooperation with Hiroaki Gomi from NTT Basic Research, the human reactions to small disturbances during the movement of a handle in a two dimensional plane are recorded. Measuring the stiffness and other parameters of a human arm during such a movement, the relationship between local reflexive control and overall control by the brain is investigated. Experimental results imply that explicit and continuous control by the brain is playing a more important role than assumed up to now [19], [42]. Another, but closely related research path in the computational psychology group headed by Hiroshi Imamizu is understanding sensory-motor control by means of non-invasive methods, investigating brain activities.

3. Learning & Cognition

The process of adaptation, learning and cognition as understood as situated interactions and modelling of dynamical environments is discussed as: a principle of autonomia in organisms ('Ba' research institute of *Hiroshi Shimizu*), a dynamical system (research conducted by *Jun Tani* at Sony CSL), learning of elementary and complex behaviours with little a-priori knowledge (laboratory of *Minoru Asada*), a process of visual sensing (laboratory of *Yoshiaaki Shirai*), a cooperative system including many types of agents (laboratory of *Toyoaki Nishida*), an interaction of robots and humans in natural environments (real world computing group header by *Nobuyuki Otsu* at ETL), or as imitation and social behaviours (group of *Yasuo Kuniyoshi*).

3-1. 'Ba' Research Institute
Kanazawa Institute of Technology, Tokyo

The group of Hiroshi Shimizu (who is a professor emeritus from the University of Tokyo) is dedicated to the study and modelling of cognitive processes, as seen from the perspective of neuroscience (and its technical models) as well as through philosophical aspects. The Japanese term 'Ba' is a central concept in the philosophy by Nishida, who was also influenced by Heidegger´s phenomenology. Early work considered basic problems of realistic neural models from a cybernetics point of view as, for instance, the self-synchronization of nonlinear oscillations [59]. Holistic vision systems [60] and the control of robust walking machines [52] were investigated as machines employing the ideas of autonomy and decentralization.

Close collaborators in this research are Yoko Yamaguchi from the Tokyo Denki University and Yasufumi Yano from the Tohoku University, who are both deeply involved in the analysis and modelling of neuro-biological systems.

As another related research stream of relevance for robotics, a system for spatial modelling is proposed, which is completely based on biological principles of modelling dynamic neural networks (coupled oscillators) [38].

Hiroshi Shimizu is also one of the initators of the Japanese-German 'Ba and Syntopy' symposium, which was held for the first time in December '96 in Tokyo and will have a follow-up symposium in Weimar, Germany, this year. One of the authors is member of the responsible steering committee.

3-2. Sony Computer Science Lab.
Tokyo

The laboratory headed by Mario Tokoro has strong international relations in most fields of computer science. International researchers are regularly invited to the laboratory and support a dynamic and lively group atmosphere. Robotics research is conducted by Jun Tani, in collaboration with Chisato Numaoka (now moved to the Paris dependence of Sony CSL) and Luc Steels from the University of Brussels (VUB), who has visited the laboratory several times. The laboratory is in existence for almost ten years, and has settled on many advanced (basic) research areas.

Involved robotics topics are vision, dynamical systems (implemented in recurrent neural networks), dynamical world modelling, concept formation (symbol generation), and active vision. The first experiments are performed with a mobile robot equipped with a laser range finder. The robot wanders in a maze like environment and detects branches. The sequence of branches, i.e. the time sequences of the data delivered from the laser range finder is used to train a recurrent neural network with internal states, representing the context [54]. The resulting recurrent structure is considered as a dynamical system. A path in the phase state of this system can be regarded as bottom-up generated symbols for the spatio-temporal relations in the environment [53]. In other words, the generated world model has been situated in the current environment. The built up world model can be employed furthermore in planning tasks like general navigation or homing due to its prediction capabilities. The length of the predictable time-series depends strongly on the complexity of the environment (and the dimension of the recurrent neural network, which reflects the complexity of the environment) and the number of learning samples utilized for the training.

The work is currently expanded to more complex concepts of the environment using a vision system on a new mobile robot with some possibilities of interaction, due to a two degrees of freedom arm. Topics like attention mechanisms and active sensing are considered too.

Up to now it could be shown that a spatio-temporal world model can be generated and interpreted as a dynamical system where unbounded series of sensor samples are employed – thus a calibration of the system is not being done by introducing absolute landmarks (or similar information) in advance, but by interpreting the structures in the generated phase-space of the dynamical system.

3-3. Asada Laboratory

Osaka University

The group of Minoru Asada is dedicated to adaptive behaviours and visual sensing. Multiple physical robots are prepared for experiments of cooperation and adaptation of dynamics. One of the considered experimental backgrounds is a soccer playing team, where full kinematic dynamics are handled, and the environment as well as the experimental setup is strictly and consciously defined [57].

Disciplines involved include computer science, vision, and more specifically modelling (and adapting) spatial relationships and interactions. Reinforcement learning [56], [57] and self-organizing [3], [40], [48] strategies are used for adaptation.

Minoru Asada is one of the organizers and initiators of the RoboCup activities trying to establish a common experimental context (or at least a dense discussion about it) for cooperative multi-robot research.

Robots are constructed and built in the laboratory by using toy kits as a mechanical basis and by equipping the mobile platforms with cameras and wireless links to a real-time pipeline video image processor.

Koh Hosoda is performing and conducting research in the field of vision based manipulation as an associate professor of the laboratory.

3-4. Shirai Laboratory

Osaka University

Yoshiaki Shirai is heading a laboratory completely dedicated to vision. Aspects like real-time vision [61], active vision [51], and handling of probabilities of optical features [37] are the main focus of research. Jun Miura (as a research associate) is also involved in most of the research work of the laboratory, especially in the mobile robot work and active vision/planning field.

Work presented include mobile robot applications of active vision (test hypothesis by moving the vehicle (camera) to other positions (perspectives)). Computations are being done off-board, due to low computational capabilities of the employed robots. The employed video processing hardware (multiple digital signal processors) allows for a video rate of 15 images per second, were simultaneous motion analysis of multiple targets is performed [61].

Yoshiaki Shirai has been working in the vision research field for many years [47] and holds a patent on the triangulation principle employed by some laser range finders.

3-5. Nishida Laboratory

NAIST, Ikoma, Nara

The Nara Institute of Science and Technology (NAIST) is one of the youngest Japanese universities being founded in 1991. It is located nearby Nara, the ancient capital of Japan, and a part of the Kansai science city.

Basically the NAIST consists of three graduate schools starting with student enrolment in 1993 in the areas of: biological sciences, information science, and material science. The overall goal of NAIST is to contribute to ‘the development of scientific technology by fostering capable human resources, and thereby actively contributing to international society’ (from the foreword by Hiroshi Sakurai in the ‘96 NAIST guide book). There are several other parts of NAIST, which seem to be very interesting for the organization of modern research facilities, e.g. a digital library and a kind of technology transfer centre which operates internally and externally. There is an educational sub-goal in all units to develop means for an education exploiting new technologies and at the same time providing some of the content for it with regard to the scientific competencies of NAIST.

The school of information science consists of two departments (information processing and information systems) with 19 laboratories covering several subfields of artificial intelligence, computer science, systems theory, and robotics. Of interest in the context of this report are the robotics lab, headed by Takeshi Uno, the image processing lab, headed by Kunihiro Chihara, and the AI lab, headed by Toyoaki Nishida.

In the AI lab, there are two fields of research: One is concerned solely with knowledge processing and its research goal is to contribute to ‘The Knowledgeable Community’ [41]. The other is concerned with developing so-called cooperative environments for real-world agents [49][50], which was the most interesting project for the authors. The scenario used for it can be described as follows.

Given an office room which can be entered by a remotely controlled door, there are different facilities, e.g. racks with books, desks, etc. The room is inhabited by humans and robots, some mobile some stationary. The idea is that the latter tries to cooperate in following some given or implicit tasks. The scientific problem tackled by this project is to ask what kind of ontology these agents must have and share to be successful in cooperating with each another. Creating and maintaining ontologies is an old issue in AI. But of course there are some additional problems to solve if an ontology depends upon different sensori-motor experiences and world perspectives. The approach chosen is to distinguish between different types of ontologies, namely for objects, space, and action.

3-6. Real World Computing at ETL

ETL, Tsukuba, Ibaraki

Ten sections and a total of 60 researchers at ETL are participating in the Real World Computing (RWC) project (described in section 5). This RWC subcommittee is conducted by Nobuyuki Otsu, director of the machine understanding division. Out of the widespread research topics two of the robotics relevant aspects will be highlighted briefly.

For the reduction of the localization uncertainty of a mobile robot in natural environments, two strategies are unified in an office-conversant robot approach [7]. Assuming all underlying stochastic processes to be Markovian, probabilities for the state transitions, the observations, and the plan itself are employed for the spatial reasoning. Still this reasoning is not feasible in complex environments. In order to cut down the search space and the uncertainty of this approach, dialogues with humans in the working environment are considered as a support in the decision processes. Thus the mobile robot is forced to communicate in natural language for getting hints supporting its spatial reasoning. This approach is supported by a speech recognition module developed at ETL [27]. The physical mobile system is fully implemented and was presented in the office environment of ETL by Hideki Asoh from the mathematical informatics section (headed by Shinji Umeyama) and Toshihiro Matsui from the robotics research group (directed by Shigeoki Hirai and Tsukasa Ogasawara). Furthermore Yoichi Motomura and Shotaro Akaho also from the mathematical informatics section as well as Isao Hara (autonomous systems section headed by Shigeyuki Sakane) and Satoru Hayamizu (speech processing section directed by Kazuyo Tanaka) participated in this project.

Another part of the RWC project discusses human interfaces in the mathematical informatics section where a statistical image classification system [32] was designed by Takio Kurita and Nobuyuki Otsu. In this approach the image is scanned and correlated with elementary three times three (binary) filters. The sum of correlations for each type of filter (25 are currently employed) is used as a basic statistical feature discriminating the input image. These features are processed on different resolution levels. In order to produce features that are acceptable for a classifier system, the generated basic describers are clustered using linear discriminant analysis (principal component analysis) or multilayer perceptrons. Both methods seem to be sufficient here. The implemented system is able to discriminate the faces of five different human operators in different perspectives after a teach-in phase of a few seconds each [31]. The system is currently either translation invariant or rotation invariant (by applying a logarithmic and polar coordinate transformation). The learning and the classification can be done on a standard workstation with a classification rate of 25 frames per second at an employed resolution of 80 times 60.

This vision system is applied to a specific application domain, but the principles are general in nature. Thus it could be utilized also for mobile robot applications, where features are not well defined in advance and computational power is strictly limited.

3-7. Kuniyoshi Laboratory

ETL, Tsukuba, Ibaraki

The laboratory of Yasuo Kuniyoshi (currently visiting the MIT AI laboratory, USA), performs research in the field of cooperative behaviours, especially regarding active vision and imitation. Humanoid robotics was introduced recently (partly integrated in the real world computing project). The group itself is internationally oriented, thus four of the seven members are coming from Australia, Finland, USA, and France. From the research topics discussed, cooperating robots and the imitation aspect will be highlighted briefly.

Based on monocular vision sensors, the robots in the laboratory use optical flow methods and zero disparity filtering (which are evaluated off-board with 25 Hz) to generate behaviours like dynamic collision avoidance (collision avoidance with each other while continuous driving), passing each other, and unblocking the paths of other robots by predicting potential collisions. In this complete multi-robot environment the relation between autonomy and social interaction is investigated [30].

As a related stream of research, the principles of imitation are studied considering the example of pick and place operations, where humans take the part of the teacher. The set of detectable actions is given apriori, but they need to be classified based on the observation. Furthermore the research is focused on the adaptation of the learned behaviour in changing operation environments [8]. It is embedded in the ongoing imitation discussions including Gill Hayes and John Demiris [20] or Kerstin Dautenhahn [12]. The results are dedicated for a humanoid robot also, which is currently simulated, but is intended to be implemented physically in the near future.

4. Mechatronics

Mechatronics as a definite bottom-up strategy for robotics research triggers all robotics disciplines by supplying immediate feedback loops as a basic precondition for interaction, or when expressed more generally, by supplying 'bodies' for the 'brains'. Moreover the 'brains' of artificial vehicles are getting more distributed and coupled more closely with the 'body' elements (following biological systems), thus a strict distinction is questionable now.

Mechatronic aspects are considered here by: suggesting a complete frame for modular creatures (the group of *Masahiro Fujita* at Sony), building complex kinematics (laboratory of *Takashi Emura* and the group of *Eiji Nakano*), studying and generating humanoid movements (laboratory of *Hikaru Inooka*), and by investigating in control and µ-mechanics (laboratory of *Toshio Fukuda*).

4-1. Sony Corporation
Tokyo

Robotics research at Sony (outside the Sony computer science laboratory, discussed individually) is performed in the group of Masahiro Fujita at the D21 laboratory, Tokyo. The driving application is entertainment robotics, where all levels of robotics problems are attacked from scratch, meaning almost any hardware and software is designed at Sony. Moreover it is tried to establish a new standard on the new market of entertainment robots (OPENR).

Some cornerstones of this new design should be mentioned briefly: The presented vehicle is a fully autonomous four legged robot showing complex, entertainment behaviours [18]. The robot is approximately 20 cm wide in each dimension. Inside this volume 12 DC motors with gears, touch sensors, an inclinometer, a CCD camera, LED illumination (to be used for proximity measurements in conjunction with the camera), two microphones, two RISC processors and a battery supplying all these components are included, forming a light-weight and in the sense of Rolf Pfeifer [43] well balanced artificial creature.

The actuator modules as well as the sensor modules follow a common interface, that allows these components to be plugged in under power-on conditions and requires a self-identification of each component including its physical (size, weight, etc. pp.) as well as its functional specifications. Therefore a re-configuration of the kinematic-structure is supported significantly. These concepts are also embedded in a software-architecture, supporting the modularity in different configurations including off-board processing of computational expensive modules.

In the presented prototype, all computations are being done on-board, including the video processing, which is based on colour separation. The video camera, as with most other parts of the system, is especially designed for the robot and utilizes a volume of just 4 cm^3. The acoustic interface processes a few tens phonemes.

The group of Masahiro Fujita suggests a rich set of standards for robotic entertainment applications, but most of these features could become a supporting technology in robotics research laboratories also.

4-2. Emura Laboratory
Tohoku University, Sendai, Miyagi

Based on a background of mechanical and electrical engineering, the group of Takashi Emura ('Mechatronics and Precision Engineering') is performing research in design and control of complex kinematics. In particular, walking machines and their control based on internal sensors is a central theme being investigated also by Lei Wang and Yosuke Senta.

Well known elements of mechanical design like non-circular gears are employed for the generation of non-uniform motion, especially in steering mechanisms [2]. The method itself is classical, but the implemention in a non-uniform steering construction is original and shows once again the rich background being offered by the field of mechatronics to mobile robotics research. Furthermore parallel crank-slider mechanisms are used in the construction of a four legged walking machine [45]. Complex kinematics offer finally twelve stably controlled degrees of freedom allowing for a trotting gait movement based on the idea of regarding it as an inverted pendulum using a reaction wheel. The controller design follows classical control theory, but employing a new gyroscope technology, where multiple sensors are combined by a subtraction type of filter resulting in a larger frequency response range [14]. This internal sensor is suitable even for the control of a two legged humanoid walking machine [15].

Another stream of research slightly out of the pure mechatronics area is the design of an autonomous car. Here a small car is controlled in its speed as well as in its steering. The senor system is a single camera mounted inside the vehicle. Despite the standard task of extracting and following some predefined features in the environment, this vehicle is forced to replay a course given by a driving human operator even in slightly changing environments.

4-3. *Nakano Laboratory*

Tohoku University, Sendai, Miyagi

The laboratory of Eiji Nakano is dedicated to mechatronics and presents different and very original solutions for actuators and locomotion. Combination of a legs and wheels on one vehicle together with 'passive' control strategies are proposed. One of the central ideas is to react in unforeseen situation by means of stable kinematics rather than of clever control strategies relying on sophisticated sensor systems. Strategies like jumping robots or omnidirectional drives are investigated in the mechatronics area of the group also.

Another, related stream of research is conducted by Zhi-Dong Wang and concerned with distributed behaviour-based robotics. A global camera view of the whole scene is employed in order to supply the individual robots with a global task performance measurement. The approach is nevertheless interpreted as decentralized in the way that the global observer is not involved in the calculation of the cooperate dynamics of the robot group. The cooperation emerges from individual behaviours (with a global goal) and from the forces coupled via an object which is pushed by multiple robots simultaneously [58].

Several national 'intelligent robots' contests are initiated by Eiji Nakano regularly, where service applications (cleaning and delivering) and tasks in maze like environments have to be solved.

4-4. *Inooka Laboratory*

Tohoku University, Sendai, Miyagi

The laboratory of intelligent control systems of Hikaru Inooka is based on a strong control theory and engineering background and is concerned with human emulating motions. In particular, mechanical interactions between machines and humans are investigated by practical experiments, and implemented control systems. Thus the work is motivated by the observation of human movements and could have been encountered also in the list of biologically oriented laboratories. For instance a study of human grasping capabilities (with specially built measurement devices detecting force, acceleration and friction) lead to a stable robot grasping hand [29]. Even more complicated, a manipulator arm carrying an object together with a human was constructed. Similar to the grasping hand experiment, the behaviours of two humans cooperating in carrying an object is studied first. Thus the impedance parameters from the different phases during the movements are applied to a robot manipulator and the result was found convincing as a human-friendly mechanical interface for cooperation in transport tasks [24]. In any case the human oriented control strategies are described as significantly better in comparison to self-adapting standard PID controllers. The applications for such human-interfaces are wide spread, as for example building construction, agriculture, or aiding the bedridden or disabled. An active bed compensating for the (front to rear) accelerations of a rushing ambulance car and allowing controlled movements to stabilize the patients condition while monitoring some of his parameters is an example of a medical application implemented here. The mechanical reproduction of human-like movement dynamics could thus be seen as a central motivation for the work of Hikaru Inooka. Even the reproduction of dancer's artistic movements using a small amount of degrees of freedom is investigated.

The group is embedded in international collaborations with Universities in the United Kingdom (University of Manchester, Kings College London, University of Sheffield and others) as well as with the Chinese Chongqing University. Scientific exchange is also supported by the 6th IEEE international workshop on robot and human communication (RO-MAN '97) held at Tohoku University, where Hikaru Inooka is responsible for the general chair.

4-5. *Fukuda Laboratory*

Nagoya University, Nagoya, Aichi

In the laboratory of Toshio Fukuda wide spread mechatronic investigations are performed. Fumihito Arai is currently conducting the μ-manipulation and teleoperation work, where force sensors, μ-grippers and related instruments are developed. Strong industrial relations in the field of manufacturing robotics serves as a continuous source of practical problems that are considered seriously in the group and lead mostly to individual experimental research setups. The robotics laboratory is conducted and organized by Keisuke Morishima, where generations of robots fill the racks of multiple rooms. Robots measuring just 2 cm in each dimension are constructed for investigations of swarm behaviours [36] as well as a 12 degrees of freedom brachiaton robot for research in complex dynamics.

The research is partly integrated in the GASRPA intelligent robot initiative (section 5).

5. *Global Projects*

ERATO, RWC, Frontier Research, GASRPA

Major projects in the field of information technology in Japan are funded among others by the following governmental organizations: Science and Technology Agency (STA), Ministry of Education (MOE), Ministry for International Trade and Industry (MITI) and Ministry for Post and Telecommunication (MPT). An overview of MITI (and partially STA) projects related to information technology can be found in [72].

5-1. ERATO

Exploratory Research for Advanced Technology

The ERATO program (see e.g. [69]) was initiated in 1981 in order to create advanced science and technology while stimulating future interdisciplinary scientific activities and searching for better systems in which to carry out basic research. Traditionally, the Japanese cultural and organizational structure has not enough stimulated scientists' freedom to think along new lines and to participate in groups of researchers from different organizations. Furthermore, young Japanese scientists have been rarely in a position to make important decisions. ERATO was designed to look for new solutions to overcome this obstacles in order to help Japan compete in basic research.

Within the ERATO program the Japan Science and Technology Corporation (JST), a statutory corporation under the Science and Technology Agency, selects innovative, scientifically versed, key individuals as directors for each research project. These directors are responsible for setting up exciting motifs and selecting young and talented researchers participating in the project. The projects must attract both academic and industrial participation. Research themes must be in new emerging or very challenging fields which leads to an elimination of trendy or fashionable themes.

Each project team is comprised of between 15 to 20 scientists usually grouped into 3 sub-teams. Including the supporting staff, attached to each director, most projects involve about 25 persons. All projects are funded at around ¥ 1.7 billion for a five-year project lifetime with no extension. The project teams are employed on a contract basis for two to five years.

All results from a project are the common property of JST and the members of the project team. Any patent right which has resulted from a project is shared by JST (50%) and the members (50%), who are directly responsible for the invention. The portions of the patent right belonging to members can be transferred to their home institutions upon the termination of the project.

5-2. Real World Computing

The Real World Computing (RWC) program (see e.g. [70]) is a research program funded by the Japanese Ministry of International Trade and Industry and aims at the realization of flexible information processing systems for diversified information in the real world by introducing intuition-like processing functions. The program was launched in 1992, and is scheduled for completion in 2002. The research in the first five years has been focusing on five areas:

- *Theoretical Foundations* – Representation of ill-posed information.
- *Novel Functions* – Integration of pattern processing and symbol processing methods.
- *Neural Systems* – Self-learning neural systems.
- *Massively Parallel Systems* – Systems for irregular as well as regular computation.
- *Optical Systems*

After the first five years of research the project is now in a scheduled evaluation phase. The coverage of themes in the first phase has been intentionally very broad in order to explore a wide spectrum of ideas. Also the plan for the next five years must take the rapid development of networking technologies into consideration. For the second part beginning April 1997 RWC will focus on …

- … fundamental technologies to add intelligence to existing information systems (information integration, learning and self-organization).
- … parallel and distributed computing technologies in order to integrate parallel and distributed systems.

Research under the Real World Computing program is conducted by the Electrotechnical Laboratory (ETL) and the Real World Computing Partnership (RWCP), a consortium with 16 Japanese companies and 4 foreign research institutions as its members.

Part of the research is consigned to subcontractors of the partnership, which are mainly public research institutions. While the Electrotechnical Laboratory conducts piloting research, the main part of research is carried out at the distributed laboratories set up at the sites of the partnership members. In addition, the partnership has set up a central laboratory, the Tsukuba Research Centre (TRC), where coordinating and integrating research is pursued.

The ownership of the patents deriving from the program is shared by the Japanese government and the Real World Computing Partnership at 50 percent each. For the patents created by a subcontractor, 50 percent of the ownership of the Partnership, namely 25 percent of the total ownership, is owned by the subcontractor. However, for the patents created by an overseas member from a country where no analogous rule or practice exists, their ownership belongs to the Japanese government completely. These rules apply to patents created by subcontractors also.

The funding for the Real World Computing Project from MITI is around ¥ 6 billion per year. In 1996 the number of projects in each research area was:

- Theoretical Foundations 4
- Novel Functions 12
- Neural Systems......................................2
- Massively Parallel Systems.................14
  (including 3 themes which were subcontracted)
- Optical Systems 12

5-3. *Frontier Research Program*

RIKEN, Wako, Saitama

At RIKEN in Saitama near by Tokyo the authors visited not only the group of Isao Endo but also the department which houses the Frontier Research Program (see e.g. [71]). Yoshiro Miki is one of the division directors of this program. Part of it is a large research program called 'The Age of Brain Science'. There is a provisional english draft of the proposed plan for the 'Brain Science Research Advancement Program' [67]. It strives for three important strategic targets:

- Understanding the brain
- Protecting the brain
- Creating the brain

The last one is characterized by: 'The development of brain-style computers: The realization of a robot which can act through an understanding of human intentions, by realizing previously untenable information processing architectures based on uncertainty, fluctuation, fuzziness and associative memory.' As an exemplary goal it is stated to develop humanoid robots that understand human will and intuition.

The entire program will last 20 years and will start with a first 10-year period conducting 47 projects from all three fields mentioned above. There will be a steering committee of the brain science program, consisting of government research funding agencies, representatives from brain sciences and from the humanity and social sciences. All important research institutes and institutions will be gathered as 'Brain Science Stem Institutes'. Furtheron, there will be a central brain science institute to be founded and will consist of two major parts: The instrumentation and information centres and the technology development and support centre. The former will provide all the equipment and infrastructure for conducting the research (machinery and information systems) while the latter will organize the technology transfer process and the running of the facilities.

The aim is to support excellent individuals either for leader-researchers heading a team or as doctorates or post-doctorates. Yoshiro Miki strongly suggests a recruitment of personnel on an international basis, i.e. there is great interest in engaging scientists from abroad as much as possible. This is in contrast to two other research programs, namely the former 'Fifth Generation of Computer Systems' and the 'Real World Computing' programs.

There is an explicit statement that the government secures the needed budgets for this program and is willing to manage them in a flexible and pragmatic way. In the financial year (FY) 1996 a total budget of ¥ 3.7 billion were provided and the plan for FY 1997 is to spend ¥ 15 billion. The research will be reviewed on a regular base: The whole program every 5 years, so-called priority research projects every year. The evaluation process will be made public.

While it is of course too early to make any comment about the research itself, the authors should emphasize the impression that there is a strong attitude for international collaboration and commitment to make this program not only a scientific success but also a social one. New kinds of cooperation between industry and governmental research organisations will be tested and there is a strong emphasis on a flexible management of the whole program.

5-4. *GASRPA*

Grant-in-Aid for Scientific Research on Priority Areas

The Japanese Ministry of Education provides grants directly for researchers or groups of researchers working at universities and institutes (Grant-in-Aid for Scientific Research). The grants are awarded on the basis of the merit of proposals after examination by the specialist committees established within the Research Grants Committee of the Science Council. Recipients of the grants are expected to make important contributions to the progress of science. Grants are supplied through several categories:

Scientific Research on Priority Areas

Fixed-term targeted research in scientifically or socially prior fields such as environmental, earth and space science (including energy science), material science (nuclear materials, chemical materials, new materials), informations science and electronics (include. mathematics), life science (bio-science, oncology, neuroscience), humanities and social science (for each area ¥ 50 - 600 million per year in a period of 3 to 6 years). There are 3008 running projects with ¥ 25 billion funding in 1996. For the 'Intelligent Robot' section of the GASRPA program see e.g. [68].

Specially Promoted Research

Internationally renowned research which is likely to produce outstanding results – for each research ¥ 50 - 3000 million, Period of 3 - 5 years – 48 running projects with ¥ 2.5 billion funding in 1996.

Scientific research

Creative research conducted by university researchers individually or in groups

- Category A: ¥ 10 - 50 million – 3 177 running projects with ¥ 22 billion funding in 1996
- Category B: ¥ 3 - 10 million – 4 857 running projects with ¥ 16 billion funding in 1996
- Category C: less than ¥ 3 million – 11 961 running projects with ¥ 17 billion funding in 1996

Other categories include

- Encouragment of young scientists (37 years or less)
- Scientific Research Promotion
- Grant-In-Aid for Creative Basic Research
- Grant-In-Aid for JSPS fellows (not more than ¥ 1.5 million/year).

The overall funding for the Grant-in-Aid for Scientific Research was ¥ 105 billion in 1996, more then 8% up from the previous year level.

6. General Remarks & Conclusions

Politics, Motivations, Organizations

In his book 'Preparing for the twenty-first century' Paul Kennedy [28] argues that there are two major areas for the industrialized countries which are heavily influenced by science and technology and are decisive in the next decades about prosperation and wealth of the people in these countries and abroad: Agriculture together with biotechnology, and automation together with robotics. Besides the early successes and leadership in the USA today it seems that Japan is leading the overall number of installed robots per country. And obviously Japan is spending a lot of research efforts in terms of money and personnel into designing, constructing, and experimenting with new types of robots. Kennedy analyses the strong and weak points of three countries, and he states that they will have the best chances to be the leading ones by the year 2025, namely, Japan, USA, and Germany.

However, these more strategic questions were not of major interest to the authors during the tour through some 21 laboratories. As mentioned in the introduction a subjective selection was made matching the authors' own research interests. The focus were not so much in mechatronics and robotics for heavy industries but more on biologically inspired designs. Our overall impressions of the many presented systems and the many discussions and talks are the following.

There is an overall tendency to manufacture nearly everything from mechatronics to sensors, chip design, and programming within one environment. This seems to be correlated with the tendency to work on small and µ-robots. They require special components and re-working designs which were successful for larger and more common platforms. The research groups seem to have strong links to local workshops and industries which are able and willing to manufacture even in low numbers the needed components often after some prototype was developed as a feasibility study in the lab itself.

Usually only one or two people, often students or PhD candidates, are designing an experiment and the robot platform most suitable to it. I.e. there are many different and heterogeneous projects going on like a swarm of scouts finding pathways through an unknown jungle. A large and homogeneous project where, for instance, ten or more researchers worked upon, could not be found. Therefore, sometimes it is difficult from the outside and maybe also from inside to understand the general research strategy underlying it and how all these small efforts fit together. But seen from the perspective (which is shared strongly by the authors) that there is not only one successful or correct way to come up with a good robot design, this looks nevertheless very promising. The questions tackled are generally coupled very loosely with an actual application. The authors had the feeling that a kind of humus is generated out of which within the next 5 or 10 years the most successful approaches will be selected and transfered into practice.

The laboratories are often headed by senior scientists who spent some years either in the USA or in Germany often to obtain their Ph.D. and they are very aware of the international scientific community. They are materializing the promise of the Japanese government to repay the international family of nations for what Japan obtained from it in the first place. The authors are appreciating the open-mindedness and willingness to explain what is going on in the laboratories which went far beyond the common kindness of treating a foreign guest. There was never the impression that some information was withheld, of course notwithstanding the usual confidence required for joint ventures with industries.

In Germany one of the authors is working together with an interdisciplinary group of scientists to develop a new framework where the neural sciences, philosophy, cognitive science, and computer science are jointly tackling the phenomena of cognition and intelligence until now only observable in biological systems, namely human beings. The authors were impressed deeply by the force and dedication of the new brain research program described earlier in this report. This is something completely absent in Germany. The US program of deciphering the human genome is more like bringing a man to the moon than understanding man from the inside out.

7. Acknowledgements

As a central support, Keiko Saito as well as Yoshiko Numata from the GMD Tokyo office organized events very carefully and reliably. A tremendous organizational work was also undertaken by many laboratory members in order to enable a smooth trip and free minds for the scientific discussions. Thus we found a very warm welcome in many laboratories during this trip. Most groups were very well pre-

pared to fill some hours with presentations of ongoing work. Moreover an amazing amount of practical experiments were especially prepared, giving intense impressions of ideas and concepts. Yes, we still know all the names, but unfortunately they are far too many to be listed here individually, without breaking the format of this report. Thus we like to express deep thanks to all the people supporting this trip and we will keep discussions (and travel) in Japan as a very warm remembrance once again.

References

[1] Yoshikazu Arai, Sho'ji Suzuki, Shin'ya Kotosaka, Hajime Asama, Hayato KKaetsu, Isao Endo
Collision avoidance among multiple autonomous mobile robotis using LOCISS (LOcally Communicable Infrared Sensory System)
Proc. of the 1996 IEEE Intern. Conf. on Robotics and Automation, Minneapolis, Minnesota, April 1996

[2] Akira Arakawa, Takashi Emura
Motion and power transmission mechanism for nonuniform motion
Journal of Advanced Automation Technology, Vol. 7, No. 3, 1995

[3] Minoru Asada, Shoichi Noda, Koh Hosoda
Action-based sensor space categorization for robot learning
Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1502-1509, 1996.

[4] H. Asama, T. Fukuda, T. Arai, I. Endo (eds.)
Distributed autonomous robotic systems 2
Springer Tokyo 1996

[5] Hajime Asama, Masatoshi Sato, Luca Bogoni, Hayato Kaetsu, Akihiro Matsumoto, Isao Endo
Development of an omni-directional mobile robot with 3 dof decoupling drive mechanism
Proc. of the 1995 IEEE Intern. Conf. on Robotics and Automation

[6] Hajime Asama, Masatoshi Sato, Nobuyuki Goto, Hayato Kaetsu, Akihiro Matsumoto, Isao Endo
Mutual transportation of cooperative mobile robots using forklift mechanisms
Proc. of the 1996 IEEE Intern. Conf. on Robotics and Automation, Minneapolis, Minnesota, April 1996

[7] H. Asoh, Y. Motomura, I. Hara, S. Akaho, S. Hayamizu, T. Matsui
Combining probabilistic map and dialog for robust life-long office navigation
Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS'96, pp. 807-812

[8] P. Bakker and Y. Kuniyoshi
Robot see, robot do : an overview of robot imitation
AISB Workshop on Learning in Robots and Animals, Brighton, UK, April 1996.

[9] Jörg Bruske, Ewald von Puttkamer, Uwe R. Zimmer
SPIN-NFDS Learning and Preset Knowledge for Surface Fusion - A Neural Fuzzy Decision System
Proc. of the ANZIIS ´93, Perth, Western Australia, December 1-3, 1993

[10] Thomas Christaller, Joachim Hertzberg
LAOKOON: learnable, autonomous, and cooperating robots in sewer systems (in German)
In: Maar, Ch.; Pöppel, E.; Christaller, Th. (eds.): Die Technik auf Weg zur Seele: Forschungen an der Schnittstelle Gehirn / Computer. Reinbek 1996, pp. 358 - 360

[11] Thomas Christaller
Cognitive robotics (in German)
In: Maar, Ch.; Pöppel, E.; Christaller, Th. (eds.) 'Die Technik auf Weg zur Seele: Forschungen an der Schnittstelle Gehirn / Computer' Reinbek 1996, pp. 321 - 326

[12] Kerstin Dautenhahn
Getting to know each other – artificial social intelligence for autonomous robots
Robotics and Autonomous Systems, 16, pp. 333-356

[13] Kenji Doya
Efficient nonlinear control with actor-tutor architecture
Mozer, Jordan, Petsche (eds.) Advances in Neural Information Processing Systems 9, MIT Press, Cambridge, MA, USA, 1997

[14] Takashi Emura, Masaaki Kumagai, Koji Ogawa
Expnsion of the frequence respone using multiple sensors and subtraction type of filters
Technical report, University of Tohoku, Sendai, Japan

[15] Takashi Emura, Noriaki Kasai, Lei Wang
Experimental study of a biped imitating human walk
Proc. of the Intern. Symposium on Microsystems, Intelligent Materials and Robots, Sept. 27-29, 1995, Sendai, Japan

[16] N. Franceschini, J.M. Pichon, C. Blanes
From insect vision to robot vision
Phil. Trans. Royal Socitiety Lond. B. 1992, pp. 283-294

[17] Teruo Fujii, Hajime Asama, Thomas von Numbers, Takanori Fujita, Hayato Kaesu, Isao Endo
Co-evolution of a multiple autonomous robot system and its working environment via intelligent local information storage
Robotics and Autonomous Systems, 19 (1996) 1-13

[18] Masahiro Fujita, Koji Kageyama
An open architecture for robot entertainment
Proc. of the first intern. conf. on Autonomous Agents, Marina del Rey, CA USA, February 1997

[19] H. Gomi, M. Kawato
Equilibrium-point control hypothesis examined by measured arm-stiffness during multi-joint movement
Science, 272, 117-120 (1996).

[20] G. Haye, J. Demiris
A robot controller using learning by imitation
A. Borkowski, J.L. Crowley (eds.), Proc. of the 2nd Intern. Symp. in Intelligent Robotic Systems, pp. 198-204, Grenoble, France

[21] Bärbel Herrnberger, Uwe R. Zimmer
Deriving Baseline Detection Algorithms from Verbal Descriptions
Artificial Neural Networks and Expert Systems '95 November 20-23, 1995, Dunedin, New Zealand

[22] Raphael Holzler, Isao Shimoyama, Hirofumi Miura
Hybrid elctrostatic-magnetic mircoactuators
Proc. of the IEEE Intern. Conf. on Robotics and Automation, pp. 2941-2946, Nagoya, May 1995

[23] J. Huang, N. Ohnishi, N. Sugie
A biomimetic system for localization and separtion of multiple sound sources
IEEE Trns. on Instrumention and Measurement, Vol. 44, No. 3, pp. 733-738 (1995)

[24] Ryojun Ikeura, Hikaru Inooka, Kazuki Mizutani
A control method for a robot cooperating with a human in carrying an object
Proc. of the Japan USA Symposium on Flexible Automation, K. Stelson, F. Oba (eds.), The American Society of Mechanical Engineering, Book No. 10394A - 1996,

[25] Tadaanobu Inoue, Kazuhiro Iwatani, Isao Shimoyama, Hirofumi Miura
Micromanipulation using magnetic field
Proc. of the IEEE Intern. Conf. on Robotics and Automation, pp. 679-684, Nagoya, May 1995

[26] Satoshi Ito, Hideo Yuasa, Koji Ito, Masami Ito
A pictorial pattern recognition based on a associative memory by use of the reaction-diffusion equation
Proc. of the second intern. symposium on Autonomous Decentralized Systems, pp. 249-256, Phoenix, 1995

[27] K. Itou, S. Hayamizu, K. Tanaka, H. Tanaka
System design, data collection and evaluation of a speech dialogue system
IEICE Trans. on Information & Systems, E76-D, 121-127, 1993

[28] Paul Kennedy
Preparing for the twenty-first century
Random House, New York, 1993

[29] I. Kim, H. Inooka
Determination of grasp forces for robot hands based on human capabilities
Control Engineering, Practice, Vol. 2, No. 3, pp. 415-420, 1994

[30] Y. Kuniyoshi
Fusing autonomy and sociability in robots
Proc. First Int. Conf. Autonomous Agents (Agents97 Invited talk.), pp.470--471, Marina del Ray, CA, USA, Feb.5-8, 1997

[31] Takio Kurita, Kazuhiro Hotta, Taketoshi Mishima
Scale and rotation invariant recognition using higher-order local autocorrelation features of log-polar image
Technical report, ETL, Information Science Devision, 1-1-4, Umezone, Tsukuba, 305 Japan

[32] T.Kurita, N.Otsu, and T.Sato
A face recognition method using higher order local autocorrelation and multivariate analysis
Proc. of Inter. Conf. on Pattern Recognition, pp.213-216, 1992

[33] Yoshihiko Kuwana, Isao Shimoyama, Hirofumi Miura
Steering control of a mobile robot using insect antenna
Proc. of the IEEE/RSJ Intern. Conf. on Intelligent Robots and Systems (IROS '95), pp. 530-535, Pittsburgh, August 1995

[34] Zhi-Wei Luo, Koji Ito, Masami Ito, Atsuo Kato
On cooperation manipulation of dynamic objects
Advanced Robotics, Vol. 10, No. 6, pp. 621-636, 1996

[35] Zhi-Wei Luo, Masami Ito
Control design of robot for compliant manipulation on dynamic environments
IEEE Trans. on Robotics and Automation, Vol. 9, No. 3, June 1993

[36] Naoki Mitsumoto, Toshio Fukuda, Koji Shimojama, Akio Ogawa
Micro autonomous robotic system and biologically inspired immune swarm strategy as a multi agent robotic system
Proc. of the IEEE Intern. conf. on Robotics and Automation, pp. 2187-2192, 1995

[37] J. Miura and Y. Shirai,
An Uncertainty Model of Stereo Vision and Its Application to Vision-Motion Planning of Robot
Proc. 13th Int. Joint Conf. on Artificial Intelligence, Chambery, France, Aug. 1993

[38] Y. Miyake, Y. Yamaguchi, M. Yano , H. Shimizu
Environment-Dependent Self-Organization of Positional Information in Coupled Non- linear Oscillator System --- A New Principle of Real-time Coordinative Control in Biological Distributed System ---
IEICE Trans. Fund , 1993

[39] Hiroyuki Miyamoto, Stefan Schaal, Francessca Gandolfo, Hiroaki Gomi, Yasuhara Koike, Rieko Osu, Eri Nakano, Yasuhiro Wada, Mitsuo Kawato
A Kendama learning robot based on bi-directional theory
Neural networks, vol. 9, no. 8, pp. 1281-1302, 1996

[40] T. Nakamura, S. Takamura and M. Asada
Behavior-Based Map Representation for a Sonor-Based Mobile Robot by Statistical Methods
Proc. of RSJ/IEEE International Conference on Intelligent Robots and Systems, pp. 276-283, 1996.

[41] Toyoaki Nishida
The knowledgeable community: towards knowledge level communication
In The Seventh International Forum on the Frontier of Telecommunications Technology, Tokyo, Japan, November 29-30, 1995

[42] Elizabeth Pennisi
Tilting against a major theory of movement control
Science, Vol. 272, No. 5258, April 1996

[43] Rolf Pfeifer
Symbols, patterns, and behaviour:
Towards a new understanding of intelligence
Proc. of the
Japanese Conference on Artificial Intelligence, 1996

[44] Stefan Schaal
Learning From Demonstration
In: M.C. Mozer, M. Jordan, and T. Petsche (eds.), Advances in Neural Information Processing Systems 9. Cambridge, MA: MIT Press, 1997

[45] Y.Senta, T.Emura, Y.Noguchi, M.Hiraki, A. Arakawa
Trotting Gait of a Quadruped Robot Using Parallel Crank-Slider Mechanism
Proc. of the Int. Conf. on Advanced Robots (1995) 406

[46] I. Shimoyama, Y. Kubo, T. Kaneda, H. Miura
Simple microflight mechanism on silicon wafer
Proc. of the IEEE MEMS '94, pp. 148-152

[47] Yoshiaki Shirai
Three dimensional computer vision
Springer-Verlag, 1987

[48] Y. Takahashi, M. Asada, S. Noda, K. Hosoda
Sensor Space Segmentation for Mobile Robot Learning
Proceedings of ICMAS'96 Workshop on Learning, Interaction and Organizations in MultiagentEnvironment, 1996

[49] Hideaki Takeda, Kenji Iino, Toyoaki Nishida
Ontology-supported agent communication
In Working notes of 1995 AAAI Spring Symposium on Information Gathering in distributed environments, pages 160-165, 1995

[50] H. Takeda, K. Iwata, M. Takaai, A. Sawaada, T. Nishida
An ontology-based cooperative environment for real-world agents
Technical report, NAIST, Ikoma, Nara 630-01, 1997

[51] H. Takizawa, Y. Shirai and J. Miura
Selective Refinement of 3D Description by Attentive Observation for Mobile Robot
Robotics and Autonomous Systems, Vol. 17, pp.15-23, 1996

[52] G.Taga, Y.Yamaguchi and H.Shimizu
Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment
Biol. Cybern. 65, 147-159, 1991

[53] Jun Tani
Model-based learning for mobile robot navigation from the dynamical systems perspective
IEEE Transactions on Systems, Man, and Cybernetics – Part B: Cybernetics, Vol. 26, No. 3, June 1996

[54] Jun Tani, Naohiro Fukumura
Self-organizing internal representations in learning of navigation:
a physical experiment by the mobile robot Yamabico
Neural Networks, Vol. 10, No. 1, pp. 153-159, 1997

[55] Toshio Tsuji, Pietro G. Morasso, KKazuhiro Goto, Koji Ito
Human hand impedance charcteristics during maintained posture
Biological cybernetics 72, pp. 475-485, 1995

[56] E. Uchibe, M. Asada and K. Hosoda
Behavior Coordination for a Mobile Robot Using Modular Reinforcement Learning
Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.1329-1336, 1996

[57] E. Uchibe, M. Asada, S. Noda, Y. Takahashi, K. Hosoda
Vision-Based Reinforcement Learning for RoboCup : Towards Real Robot Competition
Proc. of IROS 96 Workshop on RoboCup, 1996

[58] Zhi-Dong Wang, Eiji Nakano, Takuji Matsukawa
A New Approach to Multiple Robots' Behavior Design for Cooperative Object Manipulation
3rd International Symposium on Distributed Autonomous Robotic System'96, Distributed Autonomous Robotic Systems 2, Springer-Verlag Press, pp.350-361, DARS'96 in RIKEN, Japan, Oct. 29-31, 1996.

[59] Y. Yamaguchi, K. Kometani, and H. Shimizu
Self-Synchronization of Nonlinear Oscillations in the Presence of Fluctuations
J. Stat. Phys. 26, pp. 719-743, 1981

[60] Y. Yamaguchi, Y. Hirakura and H. Shimizu
Analyses of Dynamical Coherence in the Pattern Recognition Model of Oscillator Neural Networks: Holovision
Proceedings of 1993 IJCNN, 159-162 1993

[61] S. Yamamoto, Y. Mae, Y. Shirai, and J. Miura
Realtime Multiple Object Tracking Based on Optical Flows
Proc. 1995 IEEE Int. Conf. on Robotics and Automation, Vol.3, pp.2328-2333, Nagoya, 1995.

[62] Takashi Yasuda, Isao Shimoyama, Hirofumi Mirua
Microrobot locomotion in a mechanical vibration field
Advanced Robotics, Vol. 9, No. 2, pp. 165-176, 1995

[63] Uwe R. Zimmer
Minimal Qualitative Topologic World Models for Mobile Robots
Artificial Neural Networks and Expert Systems '95 November 20-23, 1995, Dunedin, New Zealand

[64] Uwe R. Zimmer
Robust World-Modelling and Navigation in a Real World
Neurocomputing, Vol 13. No 2-4, 1996

[65] Uwe R. Zimmer
General and Specific Models in Complex Robotics Systems – a critique and a proposal
GMD Technical report, January 1997

[66] The International Executive Committee for Robot World Cup
RoboCup: The world cup robot soccer
http://www.robocup.org/RoboCup/

[67] Ad hoc committee on brain science
The Age of Brain Science- Proposed Plan for Brain Science Research Advancement Program
Provisional English Draft, Tokyo, July 1996

[68] Ministry of Education, Science and Culture of Japan
GASRPA – Grant-in-Aid for Scientific Research on Priority Areas – "Intelligent Robot"
http://wwwjuten.lssl.rcast.u-tokyo.ac.jp/index.html

[69] Japan Science and Technology Corporation (JST)
Exploratory Research for Advanced Technology(ERATO)
http://www2.jst-c.go.jp/jst/erato/erato-e/contents-e.html

[70] Japanese Ministry of International Trade and Industry (MITI)
Real World Computing Partnership
http://www.rwcp.or.jp/

[71] The Institute of Physical and Chemical Research (RIKEN)
Frontier Research Program
http://www.riken.go.jp/FRONTIER/PAMPHLET/KENKYUJOHO/kenkyu_E.html

[72] GMD – German National Centre for Information Technology
MITI Budget
http://www.gmd.de/Japan/MITI-Budget

[73] GMD – German National Centre for Information Technology
Robotics in Japan, a collection of groups and projects
http://www.gmd.de/People/Uwe.Zimmer/Lists/Robotics.in.Japan.html