Paper:

Practical Education Curriculum for Autonomous Mobile Robot (Project Learning Program for School Based on Subsumption Architecture)

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There are presently no robots around us in our society if we define a robot as an autonomous machine working in the arena of offices, homes, disaster sites, etc., not in factories. Mechatronics, dynamics, and robotics involving humans are a world of strong nonlinearity. This paper investigates the approach to the emergence of the target behavior of an autonomous mobile robot by learning with Subsumption Architecture (SA) to break through the problems of the conventional robotics with the SMPA (Sense-Model-Plan-Act) framework in the real world. It has showed the way things are learned in the real world with SA and has been developed into a practical curriculum for education as an introduction to robotics that has an intellectual and emotional appeal.

Keywords: robotics, practical education curriculum, autonomous mobile robot, subsumption architecture, perception and action

1. Introduction

1.1. Significance and Relevance of New Robotics Education

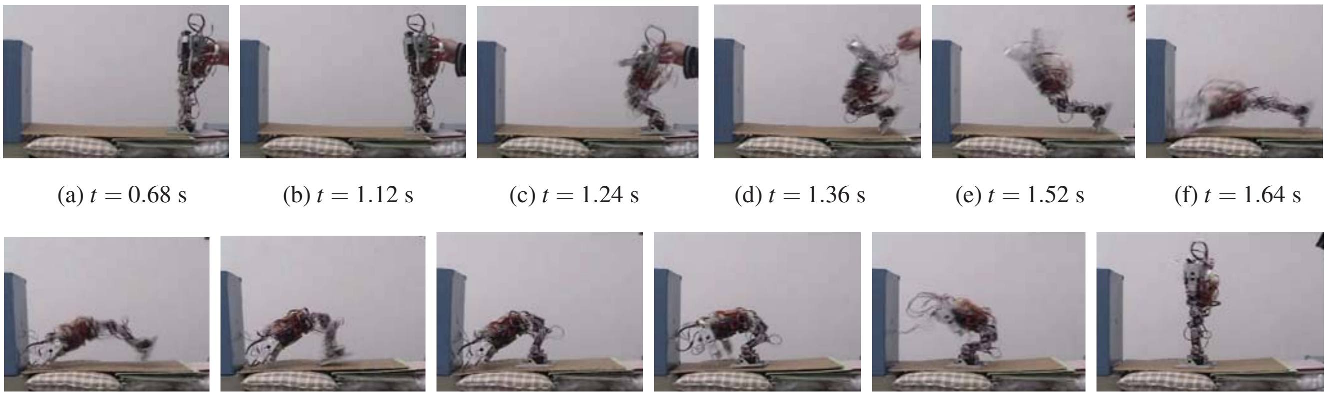
We may say that there would not be even a single robot available around us despite so many years of research if robots were defined as autonomous machines (qualitatively different from conventional machines), such as service robots and care-giving robots, that could move intelligently in our living environments. Expectations for these kinds of robots are very high in today's society with its increase in aged members and fewer children. Industrial robots, which play very active roles in automotive factories and other places, should actually be called sophisticated automatons. It is not only researchers [1–3] but also many other people [4–7] who have become aware of the difficulties or problems with the conventional approach to the development of robots in national projects over the past 20 years.

While there are very high expectations for diverse utilizations of robot technologies, particularly in the private, public, and medical welfare areas, the status quo of current robot technologies is such that they are not in a position to offer specific applications or potentialities to meet the demands of the growing markets [8, 9].

The May 2009 edition of the *Journal of the Robotics Society* in Japan features a special issue on theories for robot control to review the essential theories required for robotics; while a variety of robot control methods are being proposed one after another, many people who have been engaged in the studies on robot control technologies or developments of robots now appear to be confused or skeptical about what they have done so far and what they should do in the future [10].

For example, the generally accepted control of humanoid biped robots is Zero Moment Point (ZMP) control, by which humanoid biped robots are approximated to an inverted pendulum of single mass or table-cart model. In the actual control of robots, however, control methods described in the textbooks often do not work as expected or have limited capabilities to generate rapid movements or robustness of control [11–16], as pointed out by Kajita et al. [17]. Honda's robot ASIMO, walks with a smooth gait, causing some people to believe that ZMP control ensures a stable gait [18]. However, ASIMO in fact depends not only on ZMP control but also on other expertise learned from their trial and error experiences to achieve such a relatively stable gait. Actual unknown environments that vary every moment are full of dangers for robots, demanding an explosive increase in control parameters and calculations in the current common approaches. As robots are expected to move with more agility and flexibility, they become more unrealistic.

Given that robot dynamics are logically nonlinear, mathematically developed general control theories are rarely useful for robot applications, as pointed out by Arimoto [19]. The application of robots with nonlinear multi-degrees of freedom by nature essentially represents the deployment of multi-link systems into nonlinear dynamics and control. We may then righteously claim that the conventional studies have not adequately covered the dynamics or control of such robots that will cause chaos even in two-link systems [20–22].



(a) $t = 0.68$ s (b) $t = 1.12$ s (c) $t = 1.24$ s (d) $t = 1.36$ s (e) $t = 1.52$ s (f) $t = 1.64$ s

(g) $t = 1.76$ s (h) $t = 1.88$ s (i) $t = 1.96$ s (j) $t = 3.04$ s (k) $t = 3.20$ s (l) $t = 3.72$ s

Fig. 1. Simple autonomous shock avoidance upon falling down and instantaneous self-righting of biped robot GENBE-No.5-2005 utilizing instability. It takes only 2.5 sec.

Active studies done over 20 years on the robust control of robots to fill gaps between theories and actual applications prove limited in effects because they only deal with characteristic nonlinearity of robots in connection with linear model set. Thus, future studies should take up the super robust control of robots, taking due account of their physical characteristics [23].

Meanwhile, the "Technical Committee for Robotics Education Study" in the Robotics Society of Japan organized the "2009 Robot Touching Education Symposium" with a view to establishing educational curricula based on the fact-finding surveys for national and international robotics education.

The surveys find that robotics education has the following features or advantages: the shapes and behaviors of robots are so familiar to us that we find it very easy to task them, and as a result we feel very touched or fulfilled; the planning, designing, manufacturing, and presenting of robots can all be accomplished in laboratory settings and the fact that home-made robots do not function at all will offer good opportunities for the cultivation of problem-finding and problem-solving skills or for learning a wide range of basic liberal arts constructively. In short, robotics education embraces very great potentialities. It is also stressed that engineering/technology is so synthetic in essence that it will be more easily understood if theories are learned after hands-on experiences, and that there must be some wisdom hidden behind everything that works successfully. This is why some systematic evaluation methods are needed.

Although the significance of robot contests in educational settings is attracting more and more people's interest [24, 25], it seems at present that the area where robots can contribute is limited only to education.

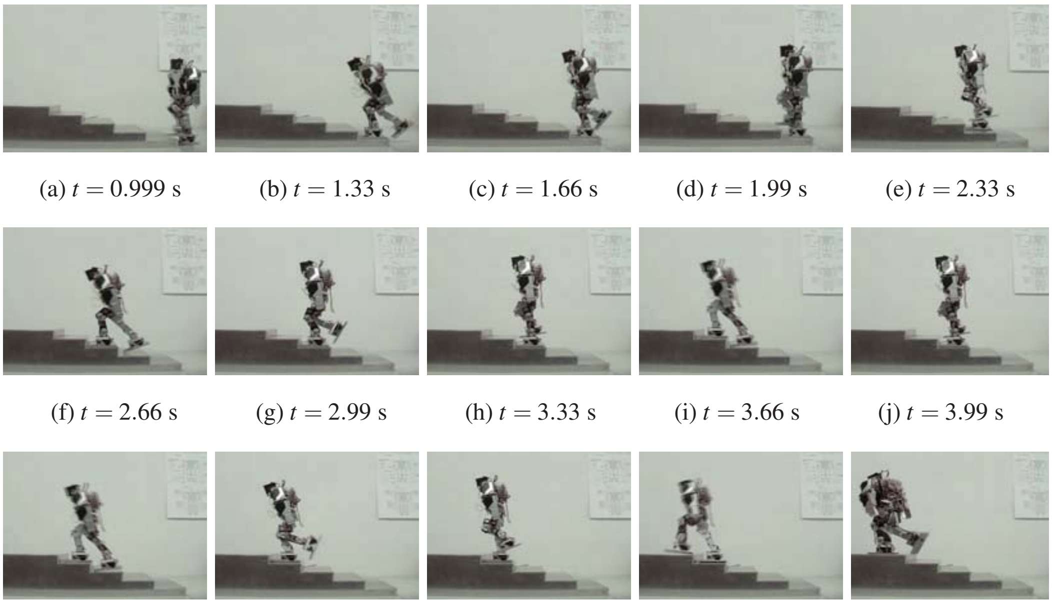
1.2. Generation of ZIZAI Movements of Robots with Control of Surplus Driving Forces that Prevent Robot Movements

The generation of agile ZIZAI movements is based on the dynamics principle that it is equilibrium instability that generates movements and on the state transition in which surplus driving forces are controlled.

As the accelerator and brake are essential parts of an automobile, the prerequisites for humanoid biped robots are not only walking but also autonomous shock avoidance functions upon falling down. For example, **Fig. 1** shows simple autonomous shock avoidance during the falling down and instantaneous rising of a biped robot utilizing instability when it is suddenly pushed from behind. Humanoid biped robots develop dexterous movements by assuming a state (posture) with the control of surplus driving forces that prevent movements through distributed control of all the joints. In this instance, they detect a time derivative of the distance to the front wall with a position sensing detector worn on the body to determine their falling down based on the program with subsumption architecture [26–29].

In the recent enthusiastic studies on humanoid biped robots, autonomous emergences of shock avoidance while falling down due to unpredictable disturbances and instantaneous self-righting are the prerequisites for humanoid biped robots and should be given priority over walking. However, there are very few studies under way on such essential requirements for robots. Robot technologies of "Japan, Big Power for Robots" have not reached the level that meets the expectations of earthquake disaster sites. Robots mentioned in the publication entitled "Japan, Big Power for Robots" are in fact industrial robots that have developed keeping pace with the progress in advanced mechanical technology, electronics technology and mechatronics, which is an aspect even researchers sometimes misunderstand [5–7, 9, 30–32]. On the home page of its customer service center, Honda Motor Co., Ltd. made the following honest and candid response to the topic of "to dispatch ASIMOs to the recovery operations of the nuclear power plant accidents": "Honda has developed ASIMOs to be of service to human beings, but regretfully they have not yet reached a technical level that can fulfill such tasks" [a].

Figure 2 shows a humanoid biped robot going up the stairs by controlling surplus driving forces that prevent



(a) $t = 0.999$ s (b) $t = 1.33$ s (c) $t = 1.66$ s (d) $t = 1.99$ s (e) $t = 2.33$ s

(f) $t = 2.66$ s (g) $t = 2.99$ s (h) $t = 3.33$ s (i) $t = 3.66$ s (j) $t = 3.99$ s

(k) $t = 4.33$ s (l) $t = 4.66$ s (m) $t = 4.99$ s (n) $t = 5.33$ s (o) $t = 5.66$ s

Fig. 2. GENBE-No.4 going up the stairs with legs of 10° of freedom with instability.

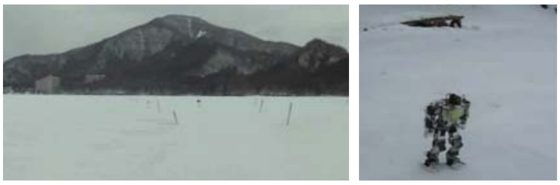


Fig. 3. Humanoid biped robot that walks and runs on the ice and snow on Lake Haruna.

movements through distributed control of all the joints; despite torque shortage, it easily walks up a stair step in about one second [26, 33]. It can also run on the ice and snow at any speed at will, as shown in **Fig. 3** [34].

Tachibana's [35] reference to Philosopher Vico's witty remarks that "truth lies in the fact of manufacturing things itself" would best apply to robotics. Like sports, art, and entertainment, robots should be evaluated on "how well they perform" rather than on "how they are presented in textbooks." Robots, which are supposed to coexist with nature, living creatures, or humans, "can correctly be evaluated only when they are actually operated." Textbooks or manuals are something that should come out after that. Robots will be "completely useless if they cannot fulfill specific functions," and, in that sense, we need to change the ways of thinking from Descartes' "I think, therefore I am" to non-Descartes' "I am, therefore I think" [26, 36, 37].

1.3. Introduction to Robotics Starting with Humanoid Biped Robots

Most basic and essential definitions of robots would describe robots as having motor functions similar to those of living things (human beings or animals) or as having intelligent functions in addition to motor functions.

We have developed the "Practical Education Curriculum Starting from Humanoid Biped Robots" [38, 39], intended for project-type courses for small groups of a few students, starting from freshmen in robot systems departments at universities. The reasons why we start the introductory course of robotics with "humanoid biped robots" include the following: humanoid biped robots are multi-degree-of-freedom systems that are difficult to control; dexterous movements can only be achieved with a variety of knowledge, and dexterous movements performance can easily be evaluated by anybody, so that the whole picture of learning and its outcomes can be made visually available to anybody. The developed practical education curriculum aims at cultivating skills to develop specific practices and problem-solving experiences into general methods.

Freshmen at universities are required to take the course Manufacturing Humanoid Biped Robots I and its Exercise I, and sophomores (second-year students) take the courses Manufacturing Humanoid Biped Robots II and its Exercise II and Manufacturing Humanoid Biped Robots III and its Exercise III, each for three hours per week for an annual total of 15 times. Juniors (third-year students) take the course Autonomous Mobile Robot Projects I, II, where their assignment is to realize autonomous behaviors of humanoid biped robots by assembling components and programming their perception and element behaviors through the subsumption architecture method, using the experimental results of different sensors (**Fig. 4**) and various generated behaviors. They continue trial and error problem solving until the robot contest at the end of the term.

While teachers offer instructions or advice that are necessary for the accomplishment of the project, students are

Angle(deg)		-90 (on one's back)	-60	-30	0(upright)	30	60	90 (on one's stomach)
Measurement times	1	147	168	216	293	363	414	428
	2	138	156	211	289	369	419	432
	3	140	156	212	287	373	415	434
	4	144	163	210	289	367	419	442
	5	143	160	217	301	364	414	433
	6	133	165	209	295	367	419	429
	7	140	162	217	293	368	415	432
	8	142	166	217	293	365	417	442
	9	142	158	209	298	361	422	433
	10	139	161	209	292	360	414	433
Average		140.8	161.5	212.7	293	365.7	416.8	433.8
Standard deviation		3.795	4.116	3.622	4.243	3.917	2.821	4.709
Standard error		1.200	1.302	1.146	1.342	1.239	0.892	1.489

Angle(deg)	Measurement	Standard deviation	Standard error
90	434	4.709	1.489
60	417	2.821	0.892
30	366	3.917	1.239
0	293	4.243	1.342
-30	213	3.622	1.146
-60	162	4.116	1.302
-90	141	3.795	1.200

Measurement times (N)

Standard deviation :σ

$$\sigma = \sqrt{\frac{\sum_{n=1}^{10}(X_n - M)^2}{(N-1)}}$$

Standard error :E

$$E = \sqrt{\frac{\sum_{n=1}^{10}(X_n - M)^2}{(N-1)N}}$$

Relative error

$$\frac{\left|[\text{Theoreticals}]-[\text{Measurements}]\right|}{[\text{Theoreticals}]} \times 100$$

Amplitude A :	147	(sin: half of the maximum value (90 [deg]) and minimum value (-90 [deg]))
Constant B :	293	(A/D value at 0 [deg])

θ[deg]	-90	-60	-30	0	30	60	90
sinθ	-1.00	-0.87	-0.50	0.00	0.50	0.87	1.00
A*sinθ+B	147	166	220	293	366	420	440

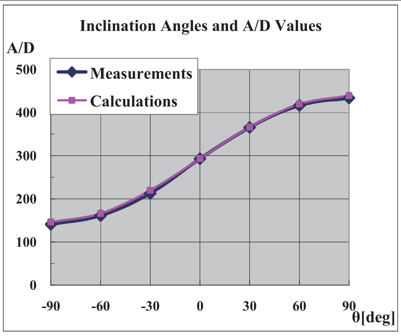


Fig. 4. Example of computer-aided measurement of characteristics of sensors using C and Excel in the project.

free to think out their own methods of achieving the assigned goals and repeatedly use trial and error until the project is completed. Students may refer to related papers to analyze any problems or improvements in attempts to document it into manuals or systematize their own methods. Upon reading the latest technical papers, such as journals of the Robotics Society of Japan, students will notice that such technical papers assume a lot of unrealistic things. For example, with reference to "turning using foot slip" [40], students' reports contain the following statements:

Assumption in papers (1): Robot's behaviors are slow enough to be free from inertia forces. Frictional forces have predominant effects.

Question: Given that characteristics of robots lie in the repetition of the start/stop and acceleration/deceleration motions, the assumption in the papers shall never apply to the behaviors of robots. In other words, robust generation of start/stop motions is an important issue for robots.

Assumption in papers (2): Assume that the dynamic friction coefficient and static friction coefficient are equal.

Question: The assumption does not work in reality or must be unrealistic. It should be an important issue to realize robots that can produce robust behaviors independent of the magnitude of frictional forces.

Assumption in papers (3): Assume that the floor surface is horizontal and frictional forces applied to the feet are uniform and constant.

Question: In reality, robots are subject to the effects of inclination of the floor surface or contact conditions of the feet, so the assumption must be unrealistic. The realization of robots robust against floor surfaces that have a variety of inclinations and frictions should be an important issue. Priority in analysis and design should be given to robots that will constructively make dexterous movements over robots that may be right in theory but do not behave as expected.

The above-mentioned questions, though the basics of daily physics, may only come to the minds of unsophisticated freshmen or sophomores who have no preconceptions. Graduate students or researchers who give priority to writing papers than the realization of robots may fail to notice the above-mentioned questions. These problem-finding and problem-solving gropes are only experienced through the actual operation of robots, which is an extremely important experience in cultivating problem-solving skills. All students will accumulate know-how to document it in their own manuals with no preset solutions [33, 34, 38, 41].

Papers on robots contain such a variety of assumptions or prerequisites that students can get to tell the world of simulations from the real world. To further enhance the effects of learning on the students, sophomores learn about simulations in the course Autonomous Mobile Robot Design using the 3D robot simulator Webots (produced by Cyberbotics) [39], which is then followed by the experiments in the course for juniors Autonomous Mobile Robot Projects I and II.

The main practical assignments for the students are as follows: generation of motions by servo motor control in the course Manufacturing Humanoid Biped Robots I and its Exercise I, measurements of dynamic characteristics of sensors using C-language, and simple subsumption architecture programming based on perception and actions in the course Manufacturing Humanoid Biped Robots II and its Exercise II, generation of complex motions and programming with C-language in preparation for the robot contests in the course Manufacturing Humanoid Biped Robots III and its Exercise III. In the first semester of the first year, freshmen learn, through attending the lectures and preparing reports, a variety of views on or ways of thinking about the relationships between humans (nature) and robots (science and technology) in the course Introduction to Human Robotics.

For example, basic themes of the lectures are as follows:

- Why has the robot industry not grown as expected?
- Can we learn robotics in the same way that children learn something new?
- Information-oriented society and barriers for robots.
- Information-oriented society and human emotions.
- Can robots coexist with humans?

- How much can robots recognize environments?
- Why do robots find it difficult to do dexterous manual work?
- Is robotics science, engineering, scientific engineering, engineering science, or application?
- How did the studies on humanoid biped robots get started?
- What is the bipedal walking mechanism of the fabulous ASIMO, developed by Honda Motor Co., Ltd.?
- What are the applications of humanoids?
- History and trends of studies on intelligent robots.
- Utility and limits of pet robots.
- What is human robotics?

In addition to the above-mentioned basic themes, the following topic assignments may be given:

- Consider the animation "Princess Mononoke" from the perspectives of science and technology (robot) and nature (human).
- Consider the legendary speech made by Steven Jobs at the commencement ceremony from the perspective of robot development.

Those lectures for freshmen and sophomores are further developed into the courses Design Principles of New Intelligent Robot I and II for juniors (third-year students of universities). Main themes discussed in the lectures include why robots cannot play an active role at earthquake disaster sites and what technologies or developments will make robots more actively operable at such disaster sites.

Figure 5 shows the presentation and contest of autonomous biped robots at the end-of-term examination for Project III, and **Fig. 6** is an example of the subsumption architecture [26–30, 42] that provides the basics of the movements shown in **Fig. 5**. **Fig. 7** shows an example of evaluation sheets for the presentation (contest); the evaluations are made on the following items: idea (concept), technology (reproducibility, robustness), art (aesthetic movement), and effort. It is not just teachers but also Teaching Assistants (TAs) and students who do the evaluations of the lectures on the criteria set by TA's performance; performance close to that of TAs on each evaluation item may score a perfect five (5) on the 5-point scale of evaluation and performance exceeding that of TAs may score over the perfect score of five. Extremely low or high scores need to be accompanied by appropriate comments. We can see that TAs play an important role in the practical robot education curricula, which in turn demonstrates the educational effect of the TAs themselves, providing valuable opportunities to practice teaching to the students who wish to become teachers in the future. In the lectures, while TAs give some advice or demonstrations based on the same themes as already taken up in the graduation

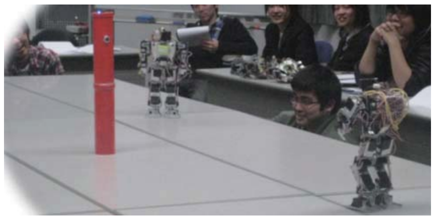


Fig. 5. Presentation and contest of autonomous biped robot in the Project III.

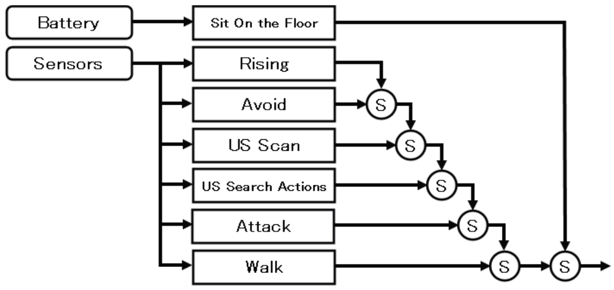


Fig. 6. Example of subsumption architecture in the project.

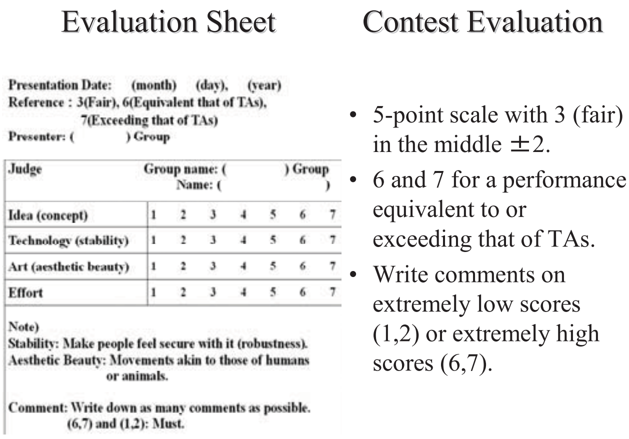


Fig. 7. Example of estimation sheet in the contest.

work or seminars, they also instruct the students to challenge their own ideas as a group as much as possible. Students with individual differences in ability are instructed to cooperate to achieve their group goals.

Figure 8 shows an example of overall evaluation results by groups for the presentation (contest), which also contains evaluations on the items of idea (concept), technology (reproducibility, robustness), art (aesthetic movement) and effort. Evaluations for individual students are made based on their reports on acquired know-how or innovations.

Figure 9 shows the various scenes of the educational curriculum and presentation of humanoid biped robots: (a) lecture; (b)–(c) students involved in the lecture; (d) hands-on training of high school students; (e) training workshop for technical high school teachers; (f) hands-on training for elementary school students.

Hands-on training sessions are provided to 5–6 schools on demand every year as a part of the regional cooperation

Group	Idea	Technique	Art	Effort	Total Score
1	19	21	22	23	85
2	19	18	19	22	78
3	17	13	16	20	66
4	17	16	17	21	71
5	19	19	19	22	79
6	18	18	18	22	75
7	21	23	23	24	92
8	21	22	23	22	89
9	14	13	15	19	61
10	19	17	18	21	76
11	23	24	24	24	95

Group	First Place	Second Place	Third Place
Total Score	95(No.11Group)	92(No.7Group)	89(No.8Group)
Idea	23(No.11Group)	21(No.7,8Group)	-
Technique	24(No.11Group)	23(No.7Group)	22(No.8Group)
Art	24(No.11Group)	23(No.7,8Group)	-
Effort	24(No.7,11Group)	-	23(No.1Group)

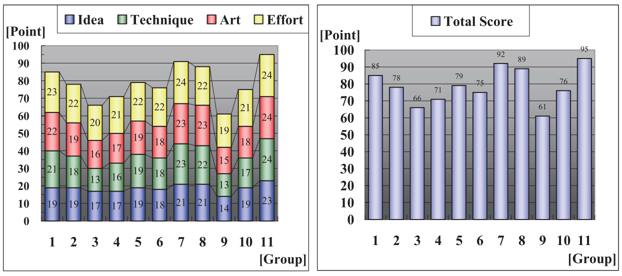


Fig. 8. Example of estimated results in the project.

activities. In addition, the practical educational curricula on humanoid biped robots have been adopted about eight times so far at the Super Science High Schools (SSH) and as a theme of the Science Partnership Projects (SPP) (on which reports have already been prepared). Those lectures were reported on in the following publications: Sankei Shimbun (March 23, 2010), Nihon Keizai Shimbun (evening edition) (December 16, 2009), Jyomo Shimbun (March 6, 2008), Kiryuu Shimbun (March 6, 2008), TV Saitama (October 12, 2005), Asahi Shimbun (Saitama edition) (October 9, 2005), Saitama Shimbun (October 7, 2005), Nikkan Kogyo Shimbun (September 8, 2005), Nikkan Kogyo Shimbun (September 5, 2005), and Nikkan Kogyo Shimbun (September 1, 2005). They were also reported in the school news of the involved high schools and elementary schools.

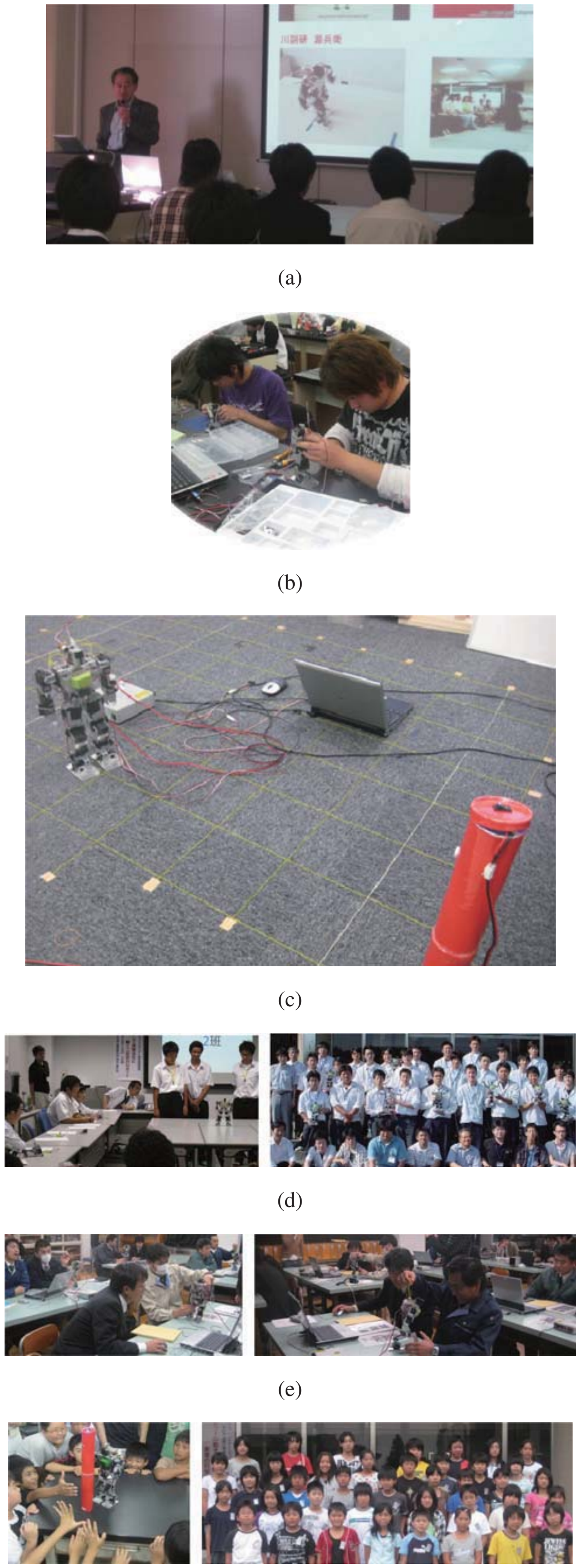
1.4. Practical Educational Curriculum on Autonomous Mobile Robots

Conventional model-based intelligent robots, designed to seek accuracy, speed, and efficiency, recognize the external world with sensors, construct an internal model of it, plan actions, and act (SMPA: Sense-Model-Plan-Act, **Fig. 10**). Such a serial approach, however, has following disadvantages.

(1) Lack of robustness: An error in any module designed for a particular function would result in a fatal failure at the final stage of action, as shown in **Fig. 10**.

(2) Difficulties related to development methods: Even if each module may function properly in certain ideal conditions, they often do not work as designed when they are all integrated. If a new function is added somewhere in any functional module, it will affect the design specifications of other functional modules so that all modules need to be redesigned from the beginning [36, 37, 43, 44].

On the other hand, behavior-based robots with the Subsumption Architecture (SA) proposed by Brooks (**Fig. 11**) have simple behaviors or element behaviors built up in parallel with resultant increases in performance. As a result, even in the case of failure in any higher-level action, lower-level actions are executed to prevent a fatal failure.



(a)

(b)

(c)

(d)

(e)

(f)

Fig. 9. Scenes of educational curricula and presentation of autonomous biped robot.

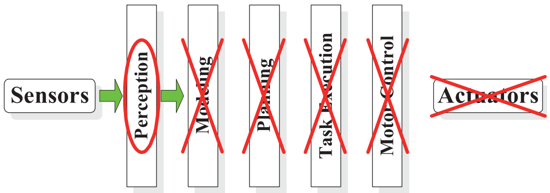


Fig. 10. Conventional model-based robot.

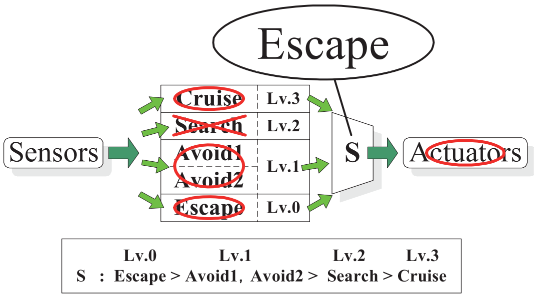


Fig. 11. Example of subsumption architecture.

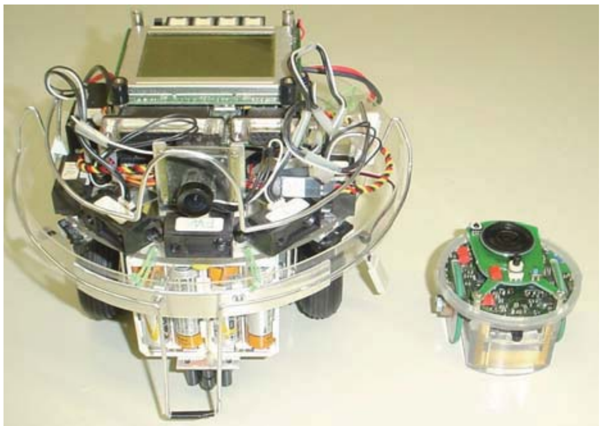


Fig. 12. Mobile robot-2004 (left) and e-puck robot (right).

This allows us to improve the performance of robots to suit the real world as found necessary [36, 37, 43, 44].

We know some people criticize behavior-based robots with SA for the "inability to realize more sophisticated intelligence than reflexive behaviors" or for the "inability to learn" [45]. It would generate no favorable outcome, however, to incorporate into robots learning in the traditional sense [36, 37] as Brooks claimed that "learning is dead" [30]. Other people may take such behavior-based robots with SA in a narrower sense that "behaviors described in the mutually independent stimulus/reaction system cannot output integrated behaviors such as travel towards the destination while avoiding obstacles on the route" [46, 47]. One study has compared SA with learning to adjust versatile behaviors [46], which, however, we do not always agree with, particularly in connection with how to build up basic behaviors (element behaviors) and with the learning evaluation criteria. Unless one takes such robots with SA as a complex system, one will never really understand the essence of intelligent robots. Element behaviors do not always need to be limited to simple reflective behaviors, but Brooks' intelligent robots as a complex system based on SA are susceptible to such misunderstanding [48–50].

Many people in Japan often misunderstand robots with subsumption architecture [42], but the remarkable performance of the cleaning robots "Roomba" and "PackBot" recently dispatched to the Great Eastern Japan Earthquake disaster sites has made the general public much better aware of such robots [b, c]. Strangely enough, however, there are very few researchers in Japan who put such robots into practice. This may be one of the main reasons why there are very few Japanese-made robots put in active operations at earthquake disaster sites.

In this paper, we first introduce an autonomous wheeled robot with subsumption architecture, and then we refer to the development of a learning program for the Autonomous Mobile Robots course for the university juniors in succession to the Humanoid Biped Robot project for university freshmen and sophomores.

2. Case Studies on Autonomous Wheeled Robots with Subsumption Architecture

In order to solve the above-mentioned essential problems with SMPA-based robots in actual environments, we have proposed a new approach to the development of human robotics. In this approach, both designers and robots learn through trial and error tasks assigned to them in actual environments so that such learning results can be built up as reflective element behaviors with as little intervention of calculations between sensors and motors as possible [29].

The robot on the left side of **Fig. 12** is the autonomous mobile robot Mobile-2004 we manufactured for the case study. The robot is equipped with a Motorola 68332 (25 MHz, 32 bit CPU) controller and a CCD camera on its front to capture the colors in front of it. It takes about 0.3 sec to capture colors, which is so much longer than the processing of other functions that we have shortened the color discrimination time by converting RGB at the center point of the visible image into hues (0–252) instead of discriminating between all of the visible colors with the CCD camera. In anticipation of an obstacle approaching at high speed, the robot is equipped with two servo motors so that it can instantaneously move transversely or obliquely by steering the drive tires within about 180°. The HiTEC HSR-5995TG servo motors have a torque of 30 kg-cm and a speed of 0.12 sec/60° (in operations at 7.4 V). The robot has drive tires on the left and right sides and an auxiliary wheel (ball caster) on the front and rear. Drive tires on the left and right sides of the robot are fitted with a DC motor. The servo motors, though they could be connected directly to the controller, are connected to the battery for direct power supply to prevent possible malfunction due to current reduction of the servo motors. The battery consists of six single-three type rechargeable batteries (nickel-hydrogen storage cells 1.2 V, 2230 mAh

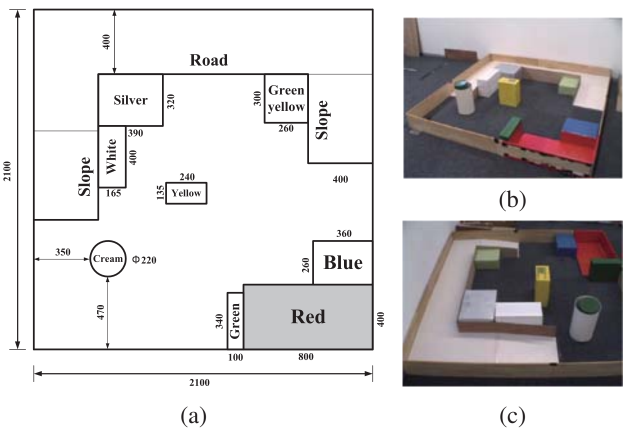


Fig. 13. Experimental environment IV.

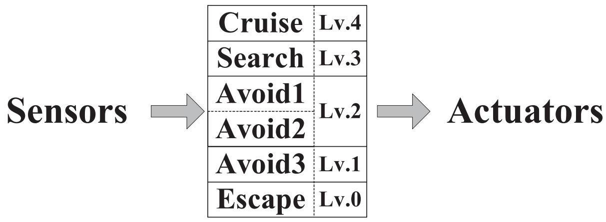


Fig. 14. Subsumption architecture of autonomous Mobile-2004.

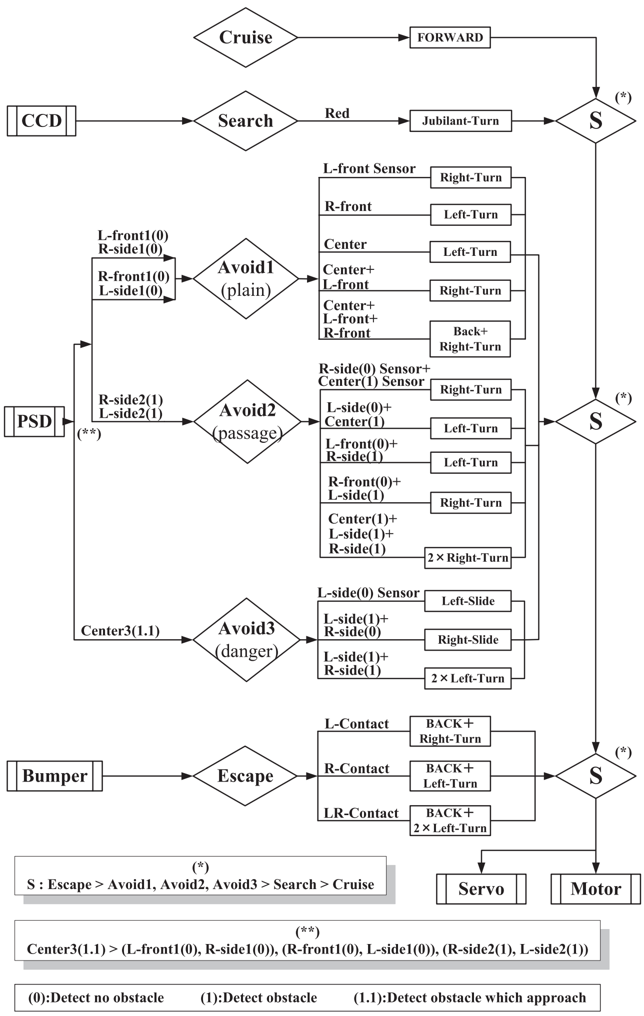


Fig. 15. A behavior control subsumption architecture of autonomous Mobile-2004.

made by Panasonic) to make it as light as possible. The robot is about 185 mm in diameter, 152 mm in height (at its highest point), and 1.23 kg in weight (including the battery). The bottom surface of the CCD camera is positioned at a height of 112 mm. The distance between the left and right drive tires is 116 mm, and the robot is inclined forward by 4.3°.

Figure 13 shows the experimental environment IV, where the robot is supposed to move all around by avoiding an obstacle or collision, make a dextral turn, and express great joy upon the discovery of the color red. Sensors consist of a position sensing detector, a touch sensor, and a CCD camera to distinguish colors.

The speeds of obstacles approaching at high speed are calculated as relative speeds to the robot from the differential values of the position sensing detector. Obstacle avoidance Avoid 1 represents an element behavior on the plane, obstacle avoidance Avoid 2, an element behavior in a narrow passage, and obstacle avoidance Avoid 3, an element behavior against a high-speed approaching obstacle. Since the emergence conditions for obstacle avoidance Avoid 3 meet the emergence conditions for obstacle avoidance Avoid 1 or Avoid 2, priority is given to Avoid 3 in the control architecture so that the robot can return to Avoid 1 or Avoid 2 behaviors after completing Avoid 3 behaviors. **Fig. 14** shows the processing system of the subsumption architecture, and **Fig. 15** shows the behavior architecture in the subsumption architecture.

Figure 16 shows the video photo frames of the movements of the robot up to the destination: Frame (1) shows the starting point, and Frame (10) shows the point where it finds the color red.

Figure 17 shows the video photo frames during the 1/3-sec interval during which the robot avoids an obstacle approaching at high speed, a ball with a relative speed of 70 cm/s, while it is searching for the color red. Frame (4) shows the robot when it is about to move swiftly sideways to avoid the ball.

Figures 18–20 show the objective behaviors of the robot (searching for red) when it recognizes a human being as a dynamic obstacle and tries to avoid a collision with it. **Fig. 18** shows the behaviors of the robot as it recognizes as a dynamic obstacle human legs moving in the experimental environments and tries to search for the color red while avoiding the dynamic obstacle. **Fig. 19** shows the behaviors of the robot recognizing a human hand as a dynamic obstacle and trying to avoid it. **Fig. 20** shows the behaviors of the robot as it recognizes as a dynamic obstacle a human being lying outside the experimental environments (in a real environment) and tries to avoid it. These video photo frames demonstrate the ability of the robot to behave as flexibly as a living creature without modeling (or maps) of the surrounding environment.

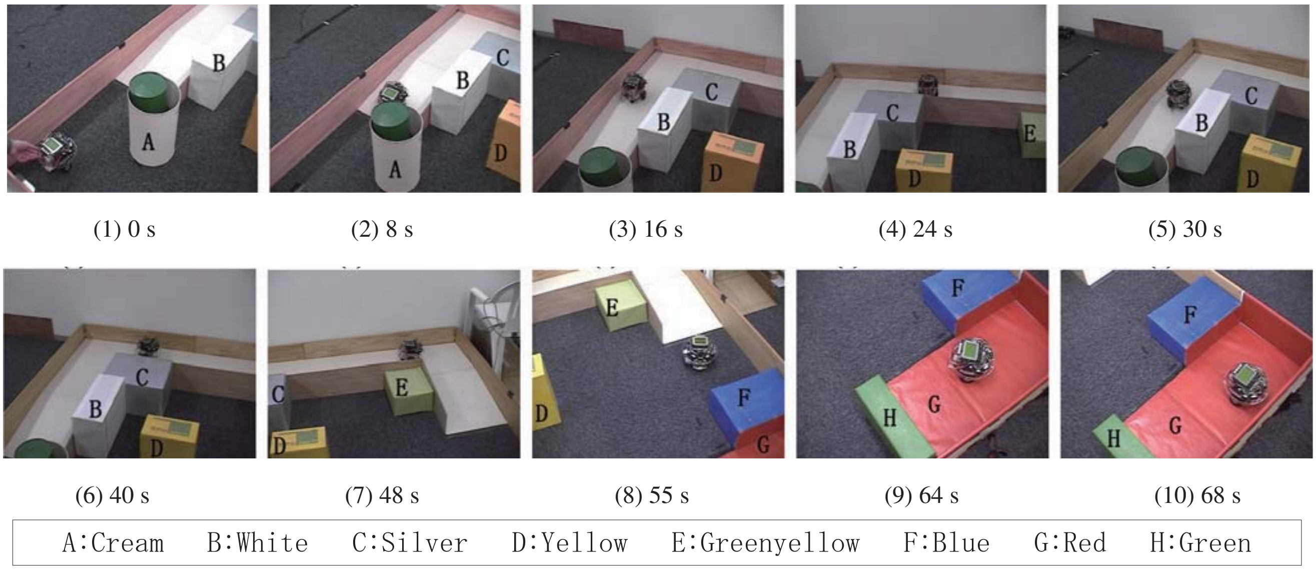


Fig. 16. Autonomous and objective behaviors of Mobile Robot-2004 with SA (Escape, Avoid 1, Avoid 2, Avoid 3, Search, Cruise) for searching for the color red and using a CCD camera with high-speed approaching obstacle avoidance in a new, unknown environment.

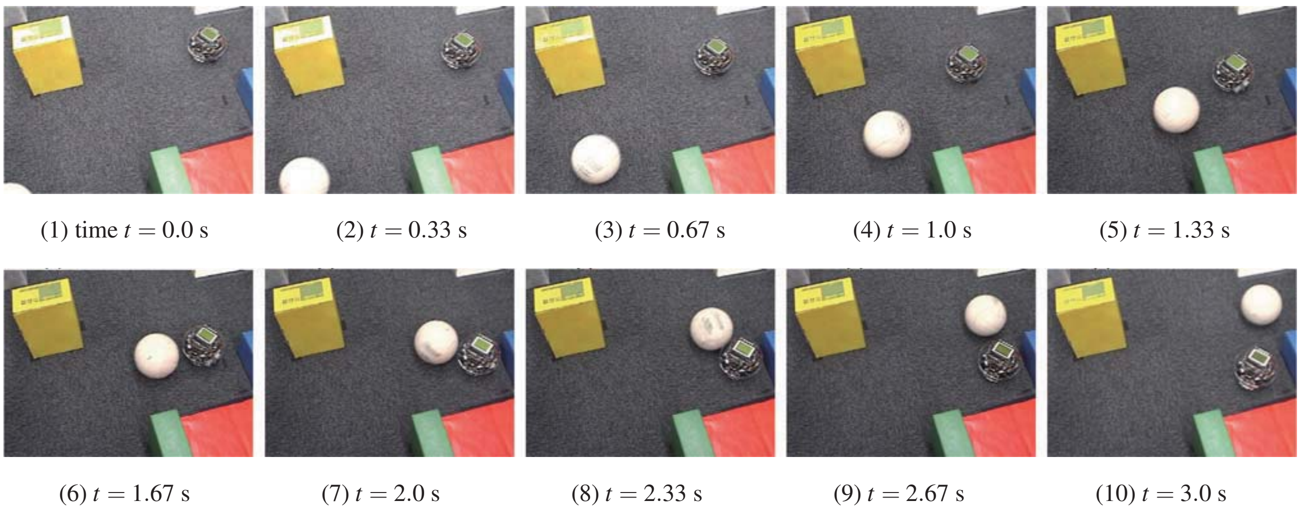


Fig. 17. Avoidance (B) of Mobile Robot-2004 against an approaching ball with a relative velocity of 60 cm/s while searching for the color red.

3. Development into Lectures on "Autonomous Mobile Robot Project"

We have developed a practical learning program for autonomous wheeled robots with subsumption architecture. The program is intended for project-type lectures for a small group of a couple of juniors (third-year university students) in the robotics department. Using the experimental results of various sensors and a variety of generated behaviors, perception and element behaviors are programmed by the subsumption architecture method to realize autonomous behaviors of mobile robots. Students continue hands-on training to solve problems by trial and error until the end-of-term examination or the presentation of their robots.

Figure 12 (the right side) shows the e-puck robot we have adopted for the project-type lectures. The e-puck is a highly extensible intelligent robot that was developed as a new type of tool for research and education in 2004 in a joint project by the Autonomous Systems Laboratory, the Swarm Intelligent System Research Group, and the Intelligent Systems Laboratory at the Lausanne School of the Swiss Federal Institute of Technology. For the learning program, we have used Cyberbotics' 3D robot simulator Webots in combination with an experimental prototype e-puck.

In a total of fifteen 90-minute lectures in Autonomous Mobile Robot Projects I and II, students learn a variety of intelligent processing techniques, such as skills to analyze, design, and implement the project through the operational experiments of autonomous mobile robots. Moreover, they are expected to enhance problem-solving skills by summarizing what they have learned constructively from the perspective of the intelligent control of robots.

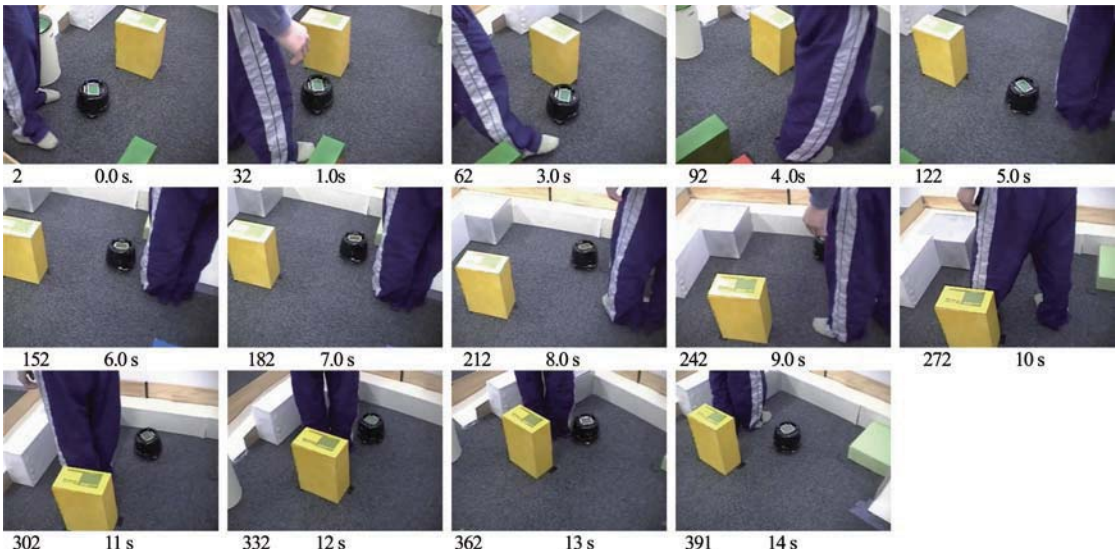


Fig. 18. Robot-2003 behaviors while avoiding moving human legs as obstacles.

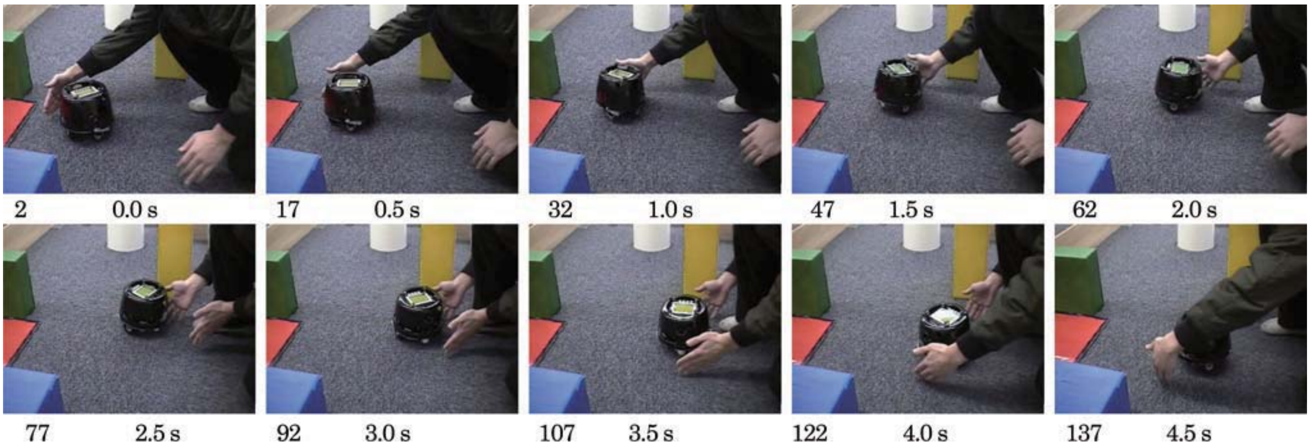


Fig. 19. Robot-2003 behaviors while avoiding moving human hands as obstacles.

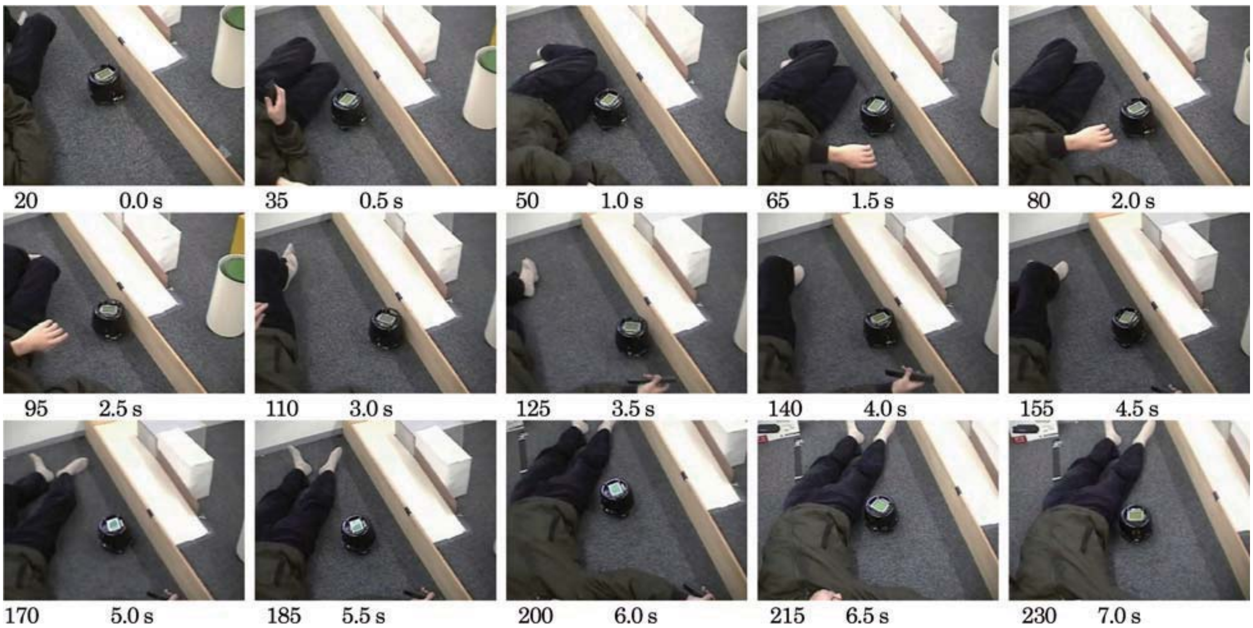


Fig. 20. Robot-2003 behaviors while avoiding a moving human body lying down outside of the experimental environment.

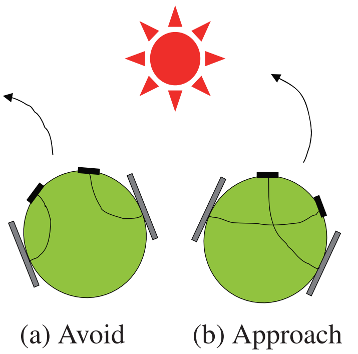


Fig. 21. Approach and avoidance of Braitenberg vehicles.

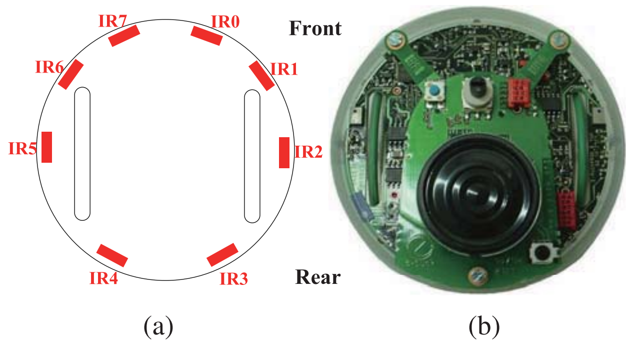


Fig. 22. E-puck robot and locations of IR sensors.

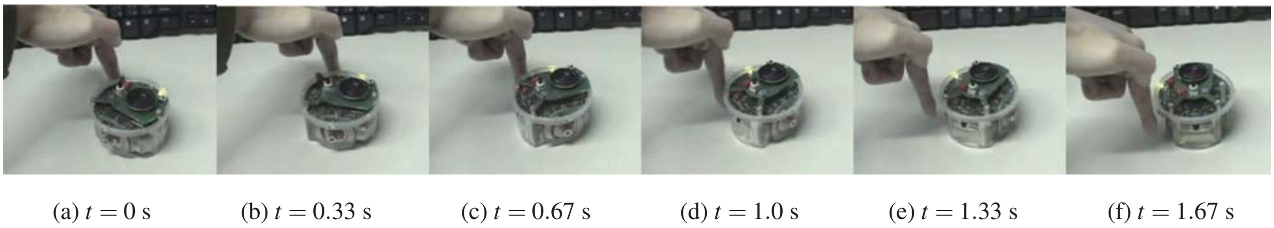


Fig. 23. Obstacle avoidance behaviors of e-puck robot.

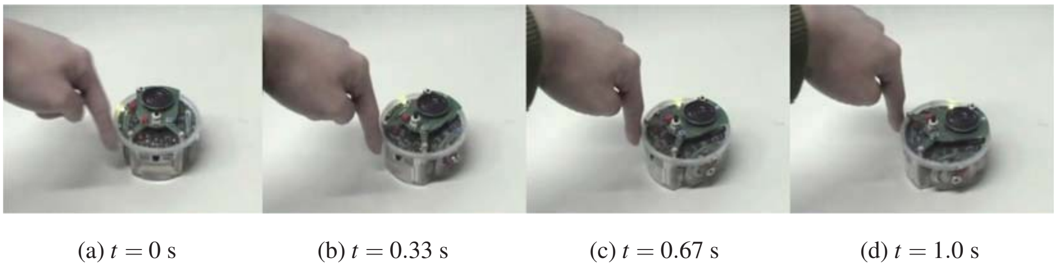


Fig. 24. Approach behaviors of e-puck robot.

Figure 21 is a conceptual rendering for approach and avoidance of Braitenberg vehicles. **Fig. 22** shows a plan view of the e-puck robot and an arrangement of IR sensors, and **Figs. 23** and **24** are video photo frames of the avoidance and approach experiments using the e-puck robot and IR sensors IR1 and IR6. A simple subsumption architecture program using a PC will allow us to experiment on the desktop the movements of robots as natural as those of animals.

The first half of Autonomous Mobile Robot Project I covers tutorial contents, such as the introduction of the case studies, basic usage of the e-puck robot, and its versatile functions. In the latter half of the course, students program actual operations of robots and carry out various assignments. More specifically, course content is as follows.

First Session: Overview of the project-type lectures, important notes, and attendance records. Students are voluntarily placed into groups of two members each (in principle).

Second Session: Explanation of the components and construction of the robot (IR sensor, CMOS camera, LED, reset switch, rotary switch, power LED, connector for in-circuit debugger MPLAB ICD2, power switch, loudspeaker, add-in board, microphone, step-motor, and others). After that, basic demonstration of the robot, including LED lighting in the direction of inclination based on the information from the 3D acceleration sensor, changing sounds of the loudspeaker according to four kinds of acceleration, obstacle approach and avoidance behaviors, and changing the robot's direction towards the sound source with three microphones, is conducted.

Third Session: Project development with the integrated development environment MPLAB IDE in the program, making files, execution of C-language program, and execution of sample program with MPLAB ICD2.

Fourth Session: Downloading the program into the e-puck robot with MPLAB ICD2 and executing it.

Fifth Session: Downloading the program into the e-puck robot with attached software bootloader and radio communication function BlueTooth, and practicing radio communication between PC and e-puck, as well as downloading the LED-flashing program with the PC software Tiny Bootloader through radio communication.

Sixth Session: Checking, with the attached software

E-puck Monitor, operations of various components installed in the e-puck robot (IR sensor, LED, step-motor, CMOS camera, loud speaker).

Seventh Session: Doing the same checking of the components as in the sixth session, this time with the software Hyperterminal attached to Windows XP instead of the attached software E-puck Monitor. Unlike E-puck Monitor, which visually displays input values of IR sensors and others, the Hyperterminal displays numerical input values at the sensor test. Activate the Hyperterminal to establish the communication function. If successfully connected, the screen displays a list of commands and any keying of commands will transmit data from the e-puck robot.

Eighth Session: Learning with the simulation software Webots how to simulate the robot's avoidance of collision with an obstacle through IR sensors. Activate the Webots, generate a field, arrange an obstacle such as a wall, and then operate the e-puck robot on the simulator.

Ninth Session: After explanation on the step-motor installed in the e-puck robot, develop the program to drive the motor and operate the e-puck robot to perform forward, backward, and circular movements with the program to ensure the basic movements of the robot.

After accomplishment of the above-mentioned assignments, a program to radio-control the e-puck robot is to be developed with the radio communications using the Hyperterminal and BlueTooth. The robot is made to perform various behaviors by altering the motor revolutions with keyed inputs. In addition, an autonomous program is developed by replacing the inputs with sensor inputs or others.

The first half of the course Autonomous Mobile Robot II covers tutorial contents such as the introduction of case studies, and the latter half of the course entails programming actual operations of robots and carrying out various assignments. More specifically, course content is as follows.

First Session: Program with C-language to transmit sensor inputs to PC, check the characteristics of IR sensors, and document as a report the experimental data with Microsoft Excel.

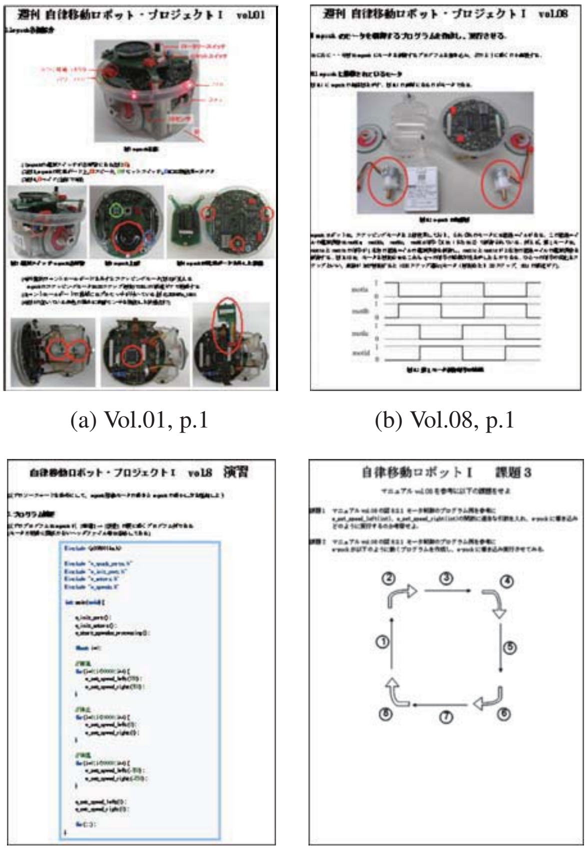
Second Session: Operate the robot to make obstacle avoidance behaviors with IR sensors in combination with control of the motor.

Third Session: With the developed program subroutine, develop a program to change over the run mode with a rotary switch in the new main routine and execute it.

Fourth Session: Experimentally examine the characteristics of floor sensors for line tracing experiments to adjust the positions to install the sensors.

In the next location, each group of students is told to set up a simple experimental environment to execute the program to see whether the robot can recognize a black line.

Next, with a simple sample program that lights the No.1 LED when the No.1 floor sensor recognizes black, students take part in robot line-tracing contests. In the contest using the course that has its layout altered annually by TAs, student groups operate their robots to measure the running time, which is included in the end-of-term report together with problems they have experienced and their comments as well.



(a) Vol.01, p.1 (b) Vol.08, p.1

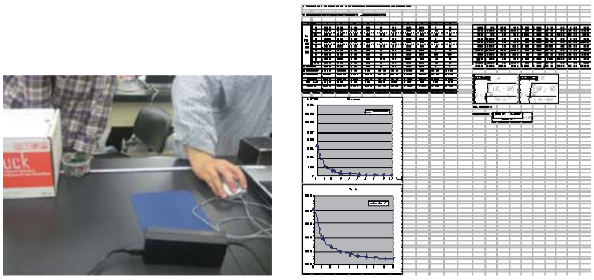
(c) Vol.08, Exercise (d) Vol.08, Practice Theme

Fig. 25. Example of weekly textbooks.

The above-mentioned assignments are the minimum requirement to earn credits. After the assignments are carried out, in order to compare the simulations with the experiments, experiments are performed to operate actual e-puck robots with the program developed by the 3D robot simulator.

Figure 25 shows an example of textbooks that have been developed. **Fig. 25(a)** shows page 1 of Vol. 01 for the weekly Autonomous Mobile Robot Project I, which is for use in the second session of the course. **Fig. 25(b)** is page 1 of Vol.08 (for the ninth session). **Fig. 25(c)** is Vol.08 for exercises. **Fig. 25(d)** is a sample exercise: after learning the drive principle of step-motors, students develop a program to drive the motor and operate the robot to realize the basic movements of going forward, backward, and in a circle. Exercise and practice themes are described in the appendices of these text books.

Figure 26 is related to the first session of the course Autonomous Mobile Robot Project II. **Fig. 26(a)** shows the development of a program to measure the characteristics of IR sensors and the experiment. **Fig. 26(b)** shows an example of a report on exercises. **Fig. 27** shows a part of the textbook describing for reference an example of a



(a) (b)

Fig. 26. Measurement of IR-sensor characteristics and an example of report.

自律移動ロボット・プロジェクトⅡ　vol.01

・・・今回は e-puck に搭載されている IR センサの特性を調べて表にまとめ考察する.

1. IR センサ測定実験

1.1 実験用プログラム

配布した irsensor フォルダの中の irsensor.c の main の部分に下記のプログラムを書き込む.

```
int main(void) {
	e_init_port();
	e_init_uart1();
	e_init_ad_scan();

	char c;
	int i,j,n;
	int ir_delta[8]={0,0,0,0,0,0,0,0};

	i=j=0;

			uart_send_static_text("¥f¥a"
						"初期化開始 - 機体の近くに物を近づけないで下さい¥r¥n");
			e_set_led(8, 1);
			calibrate_ir_sensors(ir_delta);
			e_set_led(8, 0);
			uart_send_static_text("初期化終了 2 を押すと測定開始¥r¥n¥n");

while(1){

			e_getchar_uart1(&c);

			switch (c) {

			case '1':

				uart_send_static_text("¥f¥a"
							"初期化開始 - 機体の近くに物を近づけないで下さい¥r¥n");
				e_set_led(8, 1);
				calibrate_ir_sensors(ir_delta);
				e_set_led(8, 0);
				uart_send_static_text("初期化終了 2 を押すと測定開始¥r¥n¥n");
				c=0;
				break;

			case '2':

			for(j=0;j<10;j++) {
				n=e_get_prox(j);
				buffer[i++]=n&0xff;
				buffer[i++]=n>>10;
				sprintf(buffer,"%d¥r¥n",
					e_get_prox(0)-ir_delta[0]);
				uart_send_text(buffer);

				wait(100000);
				}

				uart_send_static_text("¥r¥n");
				c=0;
				break;
				}
			}
}[EOF]
```

Fig. 27. Computer aided measurement program of IR-sensor characteristics with C-programming language.

computer-aided program to measure the characteristics of IR sensors.

Figure 28 shows the experiment as well as the contests of such robots to develop a program that will make the robot with floor sensors capable of recognizing a black line according to the measurements of its characteristics.

Figure 29 shows the experiment to send the program developed by the Cyberbotics' 3D robot simulator Webots to an actual e-puck robot and get it to behave accordingly; this is in order to compare the results between simulations and experiments. **Fig. 30(a)** is a photo of the actual robot, and **Fig. 30(b)** is a robot image display on the 3D robot simulator.

Figure 31 shows the autonomous obstacle avoidance behaviors of the robot in the simulation and experiment.

Figures 32–34 are instantaneous still images of the robot during various line tracing tasks in the simulation and experiment. **Fig. 35** shows an example of the course for the end-of-term examination assignment, and **Fig. 36** shows scenes from the execution of the assignment in the simulation and experiment.

Figure 37 shows an autonomous mobile robot autonomously line-tracing the course while avoiding an obstacle in the simulation and experiment. **Fig. 38** shows some photo frames of the experiment (**Fig. 37(b)**); they show how the robot detects an obstacle on the line, avoids it, and returns to the line to continue its tracing behaviors.

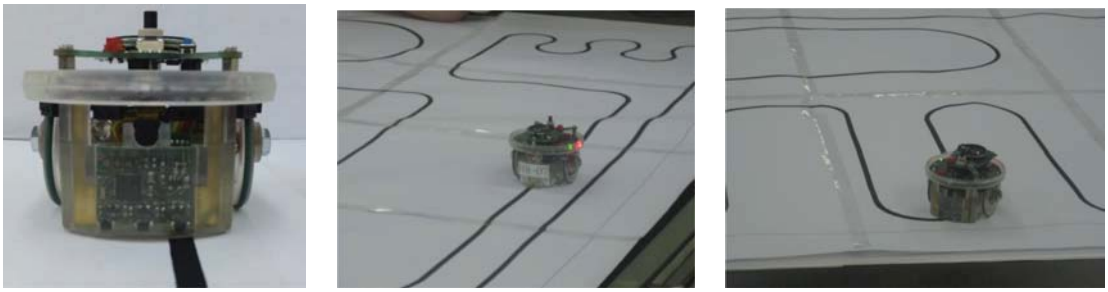
Figure 39 shows scenes from the lectures on the Autonomous Mobile Robot Project. **Figs. 39(a)** and **(b)** show scenes from the setting up of the experimental environment. **Figs. 39(c)** and **(d)** show scenes from the development of the remote-controlled operational program as well as from the preparations for and carrying out of the contest. **Fig. 39(e)** is a picture of a large competition course developed by TAs for multi-player, hands-on training in which eight robots can compete at a time. **Fig. 39(f)** is a scene from the hands-on training of high school students. **Figs. 39(g)–(l)** are scenes from the hands-on training of elementary school students in the Science Partnership Project (SPP) of the Science Development Society and the special science education.

These photos of various scenes from the project-type lectures on autonomous mobile robots seem to illustrate well that such practical educational curricula attract not only university students but also many other students, ranging from high school to elementary school students. Parts of the mass media, such as newspapers, as well as high schools and elementary schools where hands-on training was actually held showed such keen interest in this project that they reported on it very positively.

Nevertheless, the analysis and summarization of the effects of the project-type lectures on autonomous mobile robots from various angles, including the questionnaire surveys, remains a future issue.

4. Conclusion

In this paper, pointing out the problems involved in the status quo of robotics as well as the significance and relevance of a new style of robotics education, we have developed project-type educational curricula, based on the constructive subsumption architecture method, for university students in the department of robot systems. We have done this with a view to cultivating the skills to develop their hands-on training in specific exercises and problem-solving experiences into general methods. Introducing several case studies on constructive robot development, we have developed and put into practice the educational curricula on autonomous mobile robots, curricula consisting of the compulsory course How to Manufacture a Humanoid Biped Robot I and its Manufacturing Exercise I for freshmen (first-year university students), How to Manufacture a Humanoid Biped Robot II and its Manufactur-



(a) (b) (c)

Fig. 28. Line tracing experiment of autonomous robot with floor sensors and the scenes from project contest.

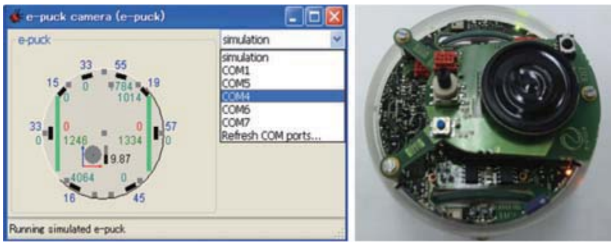
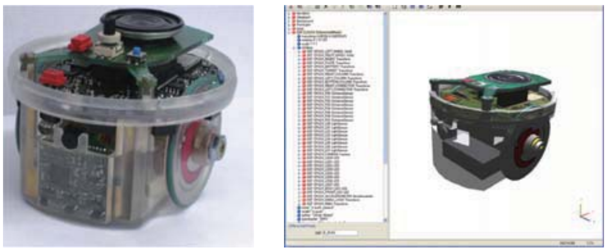
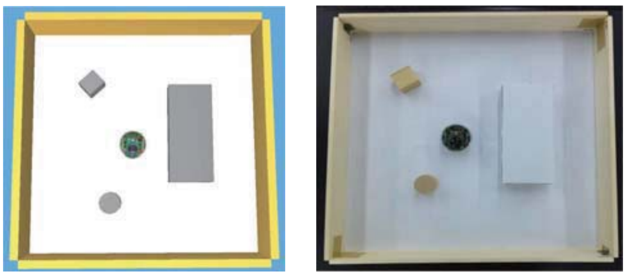


Fig. 29. Robot simulator and forwarding program to autonomous robot.



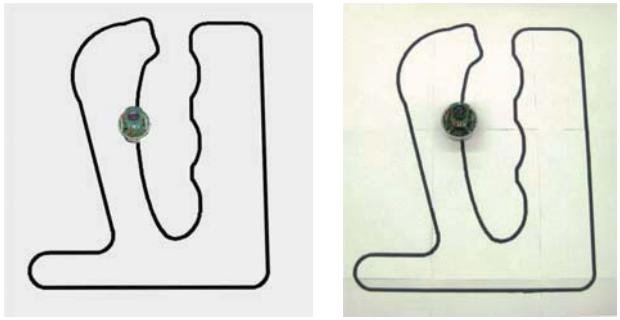
(a) Robot for experiment (b) Robot for 3Dsimulator

Fig. 30. Robot for experiment and 3D simulator.



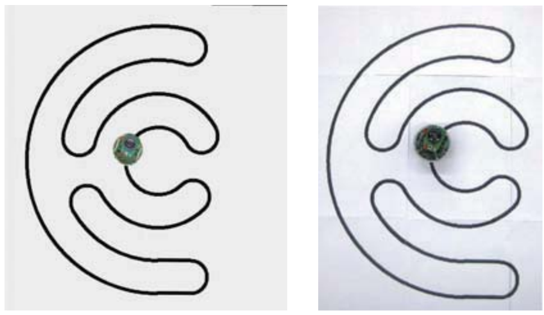
(a) Simulation (b) Experiment

Fig. 31. Autonomous obstacle avoidance with comparison between simulation and experiment.



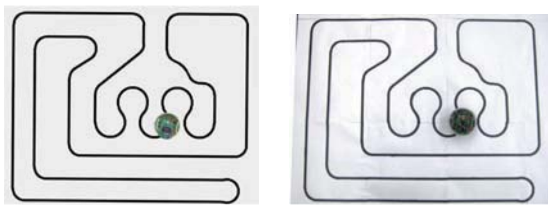
(a) Simulation (b) Experiment

Fig. 32. Simulation and experiment (I).



(a) Simulation (b) Experiment

Fig. 33. Simulation and experiment (II).



(a) Simulation (b) Experiment

Fig. 34. Simulation and experiment (III).

ing Exercise II, and How to Manufacture a Humanoid Biped Robot III and its Manufacturing Exercise III for sophomores (second-year students of university). These courses, which each meet three hours per week for an annual total of fifteen times, are then followed by the courses Autonomous Mobile Robot Projects I and II for juniors (third-year university students).

The introduction to robotics starts with the course Humanoid Biped Robot because Humanoid Biped Robots constitute a multi-degree-of-freedom system which is difficult to control and requires a variety of areas of expertise to realize dexterous behaviors, as well as because anybody (including elementary school students) can easily tell good ones from bad ones or the whole picture of learning, and its outcomes are very visible to anybody.

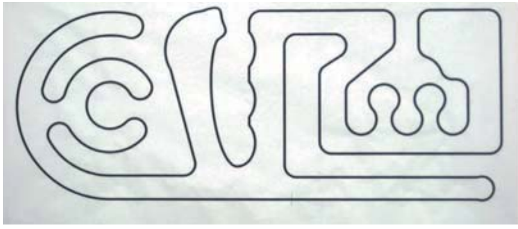
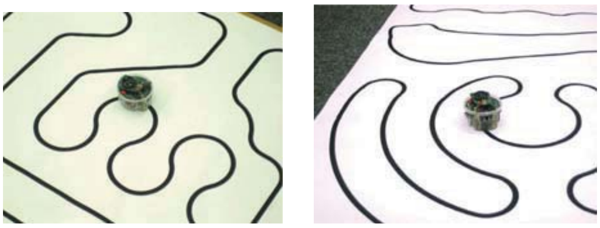
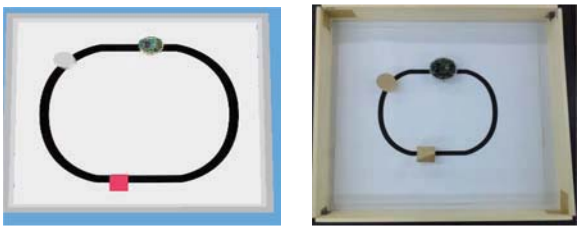


Fig. 35. Experimental environment in final competition.



(a) Simulation (b) Experiment

Fig. 36. Scenes from the finale of the autonomous mobile robot competition.

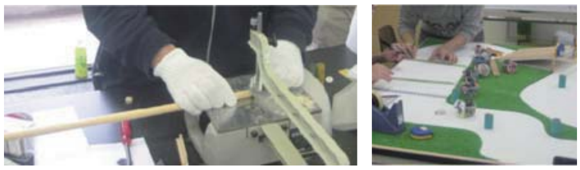


(a) Simulation (b) Experiment

Fig. 37. Line tracing with obstacle avoidance.

$t = 24.63$ s $t = 28.97$ s $t = 31.83$ s

Fig. 38. Experimental behavior of autonomous mobile robot with SA during line tracing with obstacle avoidance.



(a) (b)

(c) (d)

(e) (f)

(g)

(h) (i)

(j) (k)

(i)

Fig. 39. Scenes related to the educational curricula and the presentation of autonomous mobile robot.

Mori [51] points out that the meaning of "robot is a synthesis" refers to synthesis in the real sense of the term; changes in just a part of a robot will affect the all parts of the robot, in which sense synthesis may be something that cannot be analyzed or has an essential hidden quality that will "disappear if analyzed." In addition, Mori also points out that "you will only see when you actually manufacture it" is a very important attitude towards robotics and that you just get down to manufacturing it if you do not know its contents [52, 53]. Citing the maxim of Matsuo Basho, "do not follow the trail of the ancients but explore the places the ancients have not pursued," Mori adds, "If you would follow an example of your forerunners, you should also follow their individualistic and creative attitudes."

We hope that interest in science will be raised in the course of learning dexterous technologies and that interest in science will in turn yield philosophies.

Acknowledgements

Last but not least, we extend our sincere thanks to Dr. Takashi Gomi (Applied AI Systems, Inc.) for his kind cooperation in this study. We are also very grateful to the peer students in our laboratory for their arduous cooperation in the form of graduation work of graduate students as well as teaching assistants.

References:

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