Paper:

Educational Activities with a Focus on Robot Strategies – Through the Development of LEGO Manipulation Robots –

Rui Fukui and Tomomasa Sato

7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Department of Mechano-Informatics, The University of Tokyo
E-mail: fukui@ra-laboratory.com, tomomasasato@jcom.home.ne.jp
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This paper reports a robotics educational trial for 3rd grade undergraduate students in Intelligent Cooperative Systems Laboratory at The University of Tokyo. In the trial, we discussed with the students about strategies to realize automatic domino aligning or transferring robots comparing with existing manipulation robots. The students produced prototype robots to confirm the validity of their strategies. These processes prompted the students to understand the importance of adopting the best strategy to realize this target mission with the least effort.

Keywords: robot education, strategy design, manipulation, design optimization, LEGO MINDSTORMS

1. Introduction

This article discusses an educational activity focusing on robot strategies in Mechanical Engineering Seminar, Intelligent Cooperative Systems Laboratory at The University of Tokyo.

What is the Mechanical Engineering Seminar?

At the Faculty of Engineering in The University of Tokyo, there are two mechanics-related departments (Department of Mechanical Engineering and Department of Mechano Informatics), offering 3rd grade undergraduate students with "Mechanical Engineering Seminar," which is a small-group class of lecture and exercise of 1.5 hours per week held in the winter term. In this seminar, each of 26 to 27 faculty members (professors, associate professors, and lecturers) selects one subject and three to four students (minimum of one to maximum of 10) are involved in each subject.

For those who manage the laboratory, this seminar gives an opportunity to evaluate the abilities and skills of undergraduate students each year and to publicize the existence of the laboratory to 3rd grade undergraduate students depending on subject selection. For the 3rd grade undergraduate students, this seminar gives an opportunity to have a better understanding about the laboratory a year prior to their assignments in the laboratory for the senior thesis, and thus both the faculty and students are committed seriously in this seminar.

In 2009, 91 students and in 2010, 112 students took part in the seminar (average students of 3.5 to 3.9 per each faculty member). The seminar, including practical works such as design and implementation, often requires the students to have an extra few hours of self-study after the seminar because the works require more hours than the university-defined class hour of 1.5 hours per week.

Seminar Subject and its Aim

In 2009 and 2010, the Intelligent Cooperative Systems Laboratory invited students to a subject of "Design Strategies of Robot Manipulation," and four students participated each year. This subject was selected focusing on the following points.

There have been demands for practical robots recently but only a few robots meet such demands, thereby raising a question on the whole concept of robotics. This makes us, robotics researchers, admit that we are lacking an attitude to accurately understand social needs and convert them into tangible forms using optimal methods.

With this in mind, we gave the participating students of the seminar one task, intending to let them learn the process to fit robot needs with seeds by introducing the optimal strategy to overcome the task. The term "design" in the subject refers to optimization in every aspect including the style and mechanism, not just in terms of appearance.

In teaching the importance of the strategy design process, the authors formed the following hypotheses and verified them by partially changing curricula of 2009 and 2010.

- Hypothesis 1: If the lecture encourages the students to learn two types of robots, i.e., those that imitate human and those which do not, the students can plan strategies to enable even a simple robot with a mechanism that is incomparable to a human body to carry out stable works.

- Hypothesis 2: If the lecture presents specific examples of mechanisms, students can elaborate strategies in the mechanical structure. In contrast, by providing an environment where advanced programs can be developed easily, the students are prompted to elaborate strategies in the operation algorithm.

This article consist of the following: Section 2 describes the missions given to students, the entire schedule, and LEGO used as a prototype base; Section 3 explains lectures and exercises given to the students in the preparation stage of the prototype exercise; Sections 4 and 5 introduce robots developed by the students including TA (Teaching Assistant) in 2009 and 2010, respectively, and analyze their achievements; and Section 6 gives the conclusion.

2. Robotics Education Through Domino Operation Tasks

This section describes the missions given to the students for this seminar, the entire schedule, and LEGO MINDSTORMS[1] used as a prototype base.

2.1. Missions Given to the Students

We gave the students the following missions. "This seminar asks you to develop actual robots and learn robot-based manipulation. We will give you a task of aligning dominos (in 2009) and transferring dominos (in 2010). Your mission is to plan a strategy to align (or transfer) the dominos with the fastest, most 'aesthetic,' and most efficient method/mechanism, and actually realize the tasks with your robots. Together, let us search what is required for the strategy to manipulate the objects swiftly and securely."

The slight difference in the missions for each year is intended to prevent imitation of the previous year and encourage the self-motivated strategy planning.

2.2. Entire Schedule

Seminars were held accordance with the schedule shown in **Table 1**. The first two sessions each year were lectures on outlines of robot-based manipulation, and the next two sessions gave basic exercises and expansive exercises to handle LEGO MINDSTORMS. The students are supposed to design and implement demonstration robots in three sessions in the last half.

This schedule was carried out as initially planned, but the demonstration machine design and implementation phases required additional 10 to 20 working hours besides the defined lecture hours to complete the works each year.

To verify Hypothesis 2, we partially changed the curriculum for each year: the expansive exercise in 2009 focused on mechanisms to convert a rotational motion to a translational motion, while that in 2010 focused on operation of LEGO MINDSTORMS using Python, an object-oriented script language, and Bluetooth wireless communication.

Table 1. Whole schedule of seminar.

2009

NO.	Date	Contents
1	10/21	Introduction.
2	10/2	Group work for manipulation strategy (1)
Extra	*10/30*	*Tour for Akihabara parts shops*
3	11/4	Group work for manipulation strategy (2), **Team split**
4	11/11	Basic exercise of LEGOMINDSTROMS
5	11/18	**Expansive exercise of LEGOMINDSTROMS**
6	11/25	Development of demonstration machine (1)
7	12/ 2	Development of demonstration machine (2)
8	12/ 9	Development of demonstration machine (3)
9	12/16	Demonstration (including presentation with slides)
10~	---	Writing reports (for Web page)

2010

NO.	Date	Contents
1	10/20	Introduction, Group work for manipulation strategy (1)
2	10/27	Group work for manipulation strategy (2)
-	11/3	holiday
3	11/10	Basic exercise of LEGOMINDSTROMS
Extra	*11/15*	*Tour for Akihabara parts shops*
4	11/17	**Python exercise for LEGOMINDSTROMS**
5	11/24	Development of demonstration machine (1)
6	12/ 1	Development of demonstration machine (2)
7	12/ 8	Development of demonstration machine (3)
8	12/15	Demonstration (including presentation with slides)
9~	---	Writing reports (for Web page)

2.3. LEGO as a Robot Prototype Base

This seminar is characterized by implementing, evaluating, and experiencing robots based on selected strategies. However, it is unfeasible to produce actual robots starting from mechanical drawing and parts processing within the limited time of 1.5 hours per week. Therefore, we recommended students to develop robots by using LEGO MINDSTORMS [1], which is highly popular as a robotics education platform.

Before using MINDSTORMS, the students were provided with guidance on the schematics to understand the internal electric devices and explanations on the internal structure using disassembly photos, so that they would not use it as if it were a black box. Some slide examples used in the lectures are shown in **Fig. 1**.

When LEGO is used as mechanism parts of robots, limitations in its standard often inhibit the planned strategies from being realized as they are. However, its capability advantage of easy trial and error makes LEGO a very useful material as a robot base used for comparison and examination of strategy merits and demerits.

3. Contents of Lectures and Exercises of the First Half

This section discusses the subject of each lecture, references introduced in the lectures and their intentions, and mechanisms to convert a rotational motion to a translational motion, which were explained as a key structure before the LEGO-based robot development.

1. LEGO MINDSTORM is a registered trademark of the LEGO Group.

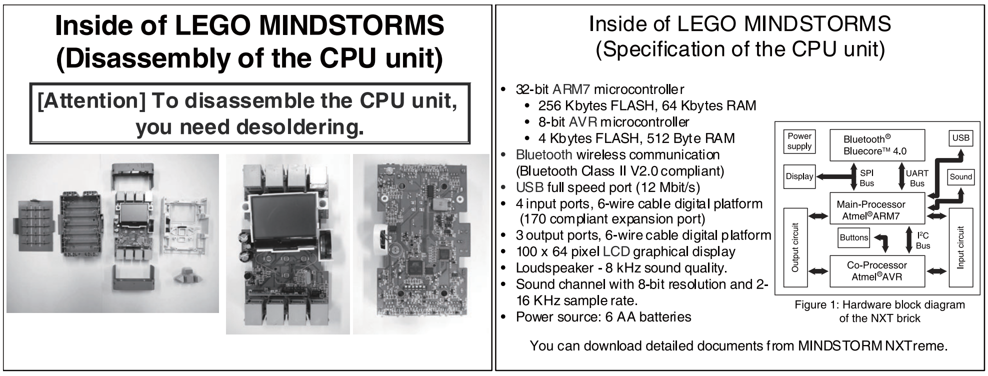

Fig. 1. Slide examples for explanation of LEGO MINDSTORMS inside.

3.1. Subject of Each Lecture

We now review three lecture subjects and their intentions which outline robot manipulation, set for verification of Hypothesis 1.

What is Robot Manipulation?
We cited a paper by Yoshikawa [2] to define manipulation. We then presented advantages and disadvantages of each of the two main robot manipulations, i.e., those which use human-like strategies (e.g., power grip & precision grip) [3] and those which use strategies different from human (e.g., parts feeders and parallel manipulators).

Force Control and Compliance
We reviewed advantages and disadvantages in introducing a force sensor, required for force control, and explained the concepts of impedance control and hybrid control of position and force [4]. We then introduced various kinds of mechanical flexibility (compliance) classified by the presence of actuators and implementation configuration, and as its example, we explained SCARA robots [5] and RCC (Remote Center Compliance) [6, 7].

Graspless Manipulation and Closure
To help the students broaden the concept of manipulation, we introduced graspless manipulation (pushing, tumbling) [8] and explained the concept of caging. We then explained the concept of Object Closure [9], one of caging, as well as the concepts of Form Closure and Force Closure [10, 11], to enable the students to understand the correspondence of the force control with geometric control (positional control).

We explained force control and compliance of grasping, which is the most common object operation, to graspless manipulation and caging, to show various approaches not just the method initially adopted by human.

Comparing with regular lectures, the lecture contents seem to be excessive for 3rd grade undergraduate students, but we intended to give a comprehensive explanation on the task of manipulation in our lecture.

3.2. References Introduced in the Lectures

We introduced the following six references to guide the participating students who showed further interest in manipulation.

- The Japan Society of Mechanical Engineers (Eds.), “Mechanism – Kinematics of Machinery” [12]

  It is no exaggeration to say that discussions on a robot-based manipulation strategy start with knowing the mechanism of the machine. We recommended this book as the first textbook of mechanism as it includes abundant illustrations.

- The Robotics Society of Japan (Eds.), “Robotics Handbook – 2nd ed” [13]

  This handbook, overviewing the history of robots, is valuable in broadly learning basic technologies. We introduced some excerpts from the book in the lectures.

- Shinichi Hirai and Hidefumi Wakamatsu, “Handling Technology” [14]

  Formulation of manipulation is an important task to link with mechanism and control engineering. We introduced this textbook because of its concise and, easy-to-understand expressions that enable the students to better comprehend manipulation issues.[2]

- Ichizou Nagaoka, “Basis of Handling Instrument Engineering – Overview of Transfer Technology –” [15], The Japan Society of Mechanical Engineers (Eds.), “JSME Mechanical Engineers’ Handbook – Engineering – C3 : Material handling” [16]

  We introduced these two to present manipulation technologies that have already been put to practical use in the fields of logistics and transferring.

- Matthew T. Mason, “Mechanics of Robotic Manipulation” [17]

  This is a comprehensive textbook on manipulation of non-Pick-and-Place strategy such as Pushing strategy and so on. Although this may not be easily understood by 3rd grade undergraduate students, it could become future references.

2. Since it is difficult to purchase this book because it is regrettably out of print, please search for it in libraries, etc.

Fig. 2. Simple line tracer robot.

3.3. Basic Exercise of LEGO MINDSTORMS

In the basic exercise, the students assembled line tracer robots on which a color sensor is mounted onto a wheel robot as shown in **Fig. 2**. The students follow the manual for MINDSTORMS, and performed programming using NXT Software, a development environment on computers. The course for the exercise was a simple oval, which required minor adjustments of control parameters, because only one sensor was used and the radius of the oval was small (about R200 mm). The students successfully realized their target operations without any particular troubles in the both years.

3.4. Expansive Exercise 1 of LEGO MINDSTORMS (Mechanism to Convert Rotational Motion to Translational Motion)

In 2009, we introduced mechanisms to convert rotational motions to translational motions as a task for the students to get used to LEGO-based mechanism design and implementation before starting development of the robots. That was actually a lecture intended to utilize a rotary motor prepared in LEGO MINDSTORMS. At the end of group works, we gave the students a task to design and implement at least one mechanism, each of which answers and examples of model answers were presented in the following week.

Figure 3 shows examples of about 10 types of mechanisms to convert rotational motions to translational motions in the model solution. The exercise proved to be stimulating to the 3rd grade undergraduate students, who had little experiences in mechanism design. In fact, the lectures have greatly affected the students, as can be seen from the mechanisms introduced here which were actively utilized in the demonstration robots shown later.

3.5. Expansive Exercise 2 of LEGO MINDSTORMS (Control of MINDSTORMS Using Python)

In 2010, the expansive exercises focused on methods to control LEGO MINDSTORMS using Python. Python is an object-oriented script language which will bring no difficulty in reading and writing to those students who have learned basic programming languages such as C language. In this exercise, the students were not asked to write new programs but asked to set up the environments and understand the sample programs for convenience of time.

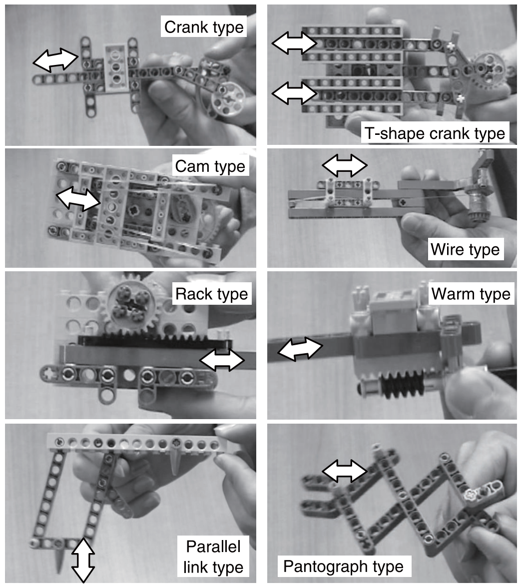

Fig. 3. Examples of convert mechanisms from rotational motion to translational motion.

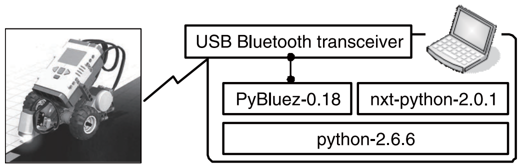

Fig. 4. Configuration of MINDSTORMS with Python.

Similar to the basic exercises, the task was to realize robot-based line trace. **Fig. 4** shows the configuration of the expansive exercises. We used "nxt-python-2.0.1" as a library to operate LEGO MINDSTORMS on Python.[3] Although it took a little bit of time to set up Bluetooth when multiple robots were in the same environment, all the seminar students successfully controlled the robots to undertake the line trace through the PC.

4. Introduction and Analyses of Robots Developed by the Students (2009)

This section will introduce robots developed by the seminar students in 2009, beginning with the details of regulation. Four students, in two groups of two students each, participated in the demonstration as a scored competition. We will present the work of each of the two groups. In this seminar, we asked two 1st grade master program students, as a TA (Teaching Assistant) for cooperation, to produce a demonstration machine with the same regulation range as those of the undergraduate students, and examined differences to verify the effects of this seminar.

3. In this set-up, we used only Bluetooth connection because we failed to appropriately activate USB library although it is capable of working through USB wired connection.

4.1. Regulation Details

Regulation outline is as follows.

- Compete in 'aesthetic in strategy' adopted for the robots to autonomously align 20 dominos, where win and loss are voted by the audience at the competition.

  ⇒ Regulation of aligning as many as 20 dominos requires not a few successful operations but stable and continuous success operations.

- Besides, the following detailed regulations were configured.
  - A human or a robot itself topples the dominos in the end.
  - Dominos are placed at intervals of 10 mm or greater.
  - A human is permitted to manually add dominos in the domino stocker along the way.
  - Any number of dominos can be moved at a time.
  - Each domino contacts the floor on its smallest face in area.
  - Time is measured for reference.
  - The workbench may be provided with informational guides such as markers.
  - The workbench is not permitted to be provided with physical guides.
  - Non-provided parts can be used additionally.

4.2. 3rd Grade Undergraduate Students (Team A)

Overview of the robot developed by the 3rd grade undergraduate students (Team A) is shown in **Fig. 5**. A rack translational mechanism and caging operations are combined to achieve stable domino operations. Locomotion to align the dominos at regular intervals is wheel-driven. The direction in which the dominos are released from the caging state is orthogonal to the travel direction. The number of motor power sources necessary to feed and align the dominos is reduced as much as possible, narrowed down to one. This allows the dominos to be aligned in trajectory by differential wheel drive using two extra motors.[4]

4.3. 3rd Grade Undergraduate Students (Team B)

Overview of the robot developed by the 3rd grade undergraduate students (Team B) is shown in **Fig. 6**. A rack translational mechanism and caging operation are combined to achieve stable domino operations. The domino pushing direction was devised to reduce the domino pushing distance (reduce the rack mechanism in size). Locomotion to align the dominos at regular intervals is wheel-driven. The direction in which the dominos are released from the caging state is parallel with the travel direction.

4. With MINDSTORM, up to three motors can be used on one controller.

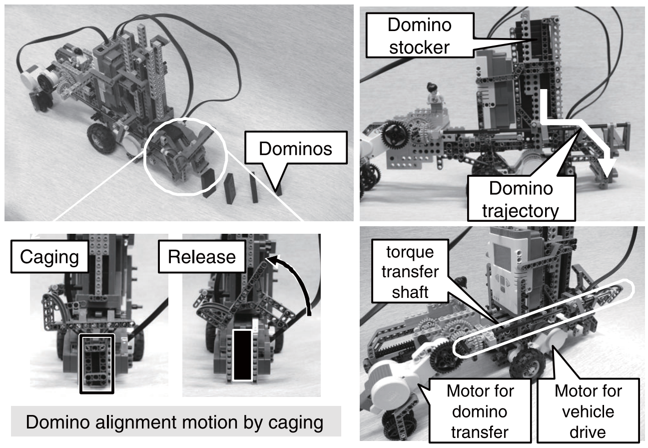

Fig. 5. Demonstration robot produced by Team A.

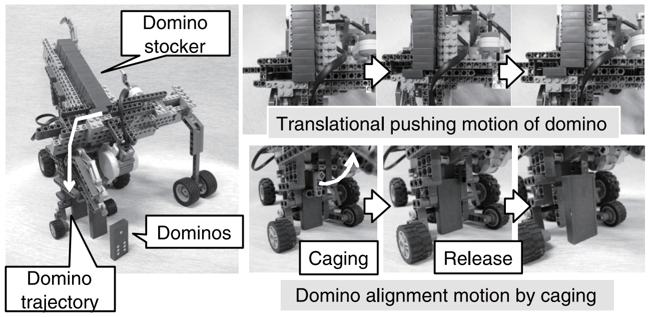

Fig. 6. Demonstration robot produced by Team B.

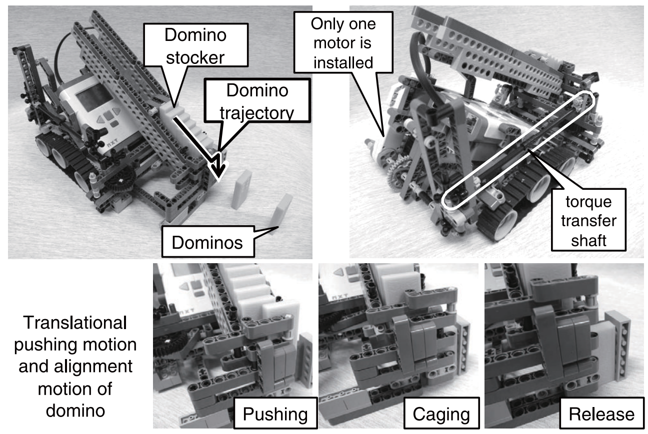

Fig. 7. Demonstration robot produced by team TA.

4.4. 1st Grade Master Program Student (TA) Team

Overview of the robot developed by the 1st grade master program student (TA) team is shown in **Fig. 7**. A crank translational mechanism and caging operations are combined to achieve stable domino operations. Domino pushing motions and caging frame forming motions are common. Locomotion to align the dominos at regular intervals is realized by the rubber track method. The above domino operations and locomotion drive are linked together with a torque transferring shaft and thus domino aligning motions are realized using only one motor. The direction in which the dominos are released from the caging state is perpendicular to the travel direction.

4.5. Motion Results of the Robots and Their Analyses

All the three teams, Teams A and B of the 3rd grade undergraduate students and the TA team, successfully achieved the domino aligning motions as required. Please refer to the movies [a] for motions. There were differences in the dominos' alignment, speed, and robustness, depending on differences in strategies and mechanisms adopted. More specifically, (1) among the directions in which the dominos are released from the caging state, a direction perpendicular to the travel direction has a lower contact risk in movement and thus the dominos can be aligned stably and thickly, and (2) reduction in the number of power sources makes software coding easy but results in many limitations at the initial state of the domino aligning, thereby requiring elaborated adjustments.

The three teams successfully achieved robots that actually move, indicating that we sufficiently conveyed the importance of strategies because they understood and utilized the strategies based on the concept of caging introduced in the lectures.

On the other hand, as a result of the lectures presenting not only the concepts of caging, etc., but also specific structures to convert the rotating mechanism to a translational motion, all the robots utilized the translational motion introduced in the lectures.

With full respect for the students' spontaneous design abilities and creativities, we should have given them opportunities to allow overall design from the beginning with only one or two examples of translational motions.

Differences between the undergraduate students and the master program students were in number of power sources, robot body compactness, etc., which were raised by differences in the challenging spirit to the task and experiences in design.

Just for information, the audience voted for Team A of the two undergraduate student teams. It seems that this resulted based on the expectations toward development in domino aligning variations, etc., which was realized by giving two degrees of freedom in locomotion.

5. Introduction and Analyses of Robots Developed by the Students (2010)

This section will introduce robots developed by the seminar students in 2010. Each of the students and one TA developed one robot in 2010, i.e., five robots were developed in total.

5.1. Regulation Details

The regulation outline is as follows.

- The robots autonomously transfer 20 dominos from Area 1 to Area 2 in the environment of **Fig. 8**. They compete in time to finish transferring all the dominos. We also award a technology prize to a robot with 'aesthetic in strategy' besides the award for carrying out the task in the shortest time.

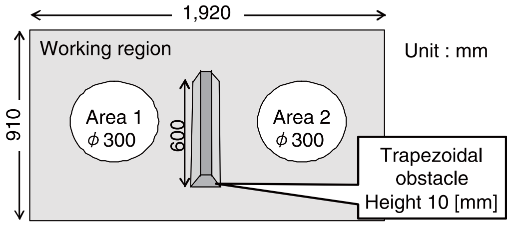

Fig. 8. Robot motion environment for domino transfer task.

  ⇒ Time is included in the evaluation points so that motions are required to be not only stably continuous but also efficient.

- In addition, the following detailed regulations were configured.
  - Time limit is five minutes, and if the transferring is not finished within the time limit, the winner is decided according to the number of dominos in Area 2.
  - A state of starting is arbitrary but the dominos are not allowed to be mounted on the robots.
  - Any number of dominos may be moved at a time.
  - The robot body may be arbitrary in size.
  - The robots may be divided into two or more.
  - Dominos and robots falling off from the working region may be returned to the center of Area 1.
  - The working region may be provided with an arbitrary number of informational guides such as markers.
  - The working region may be provided with one physical guide (up to 150 mm in size).
  - Non-provided parts can be used additionally.

We will now introduce the robots developed by the students (3rd grade undergraduate students and 1st grade TA master program student). Unlike the section for 2009, this section will give explanations categorized with the adopted strategies.

5.2. Push/Pull Strategy

The two 3rd grade undergraduate students and the TA student adopted a push/pull strategy. Although those adopting the push/pull strategy basically shared avoidance of obstacles, three different approaches were taken when caging the dominos.

- Fence Enlargement: A strategy adopted by one of the 3rd grade undergraduate students, in which the fence was made as large as possible maintaining the margin distance to obstacles and the whole fence was transferred to get the dominos together (**Fig. 9**).
- Adoption of a Pushing Actuator: A strategy adopted by the other 3rd grade undergraduate student, in which an active broom was prepared next to the cage and the broom actuated to push the dominos into the cage (**Fig. 10**).

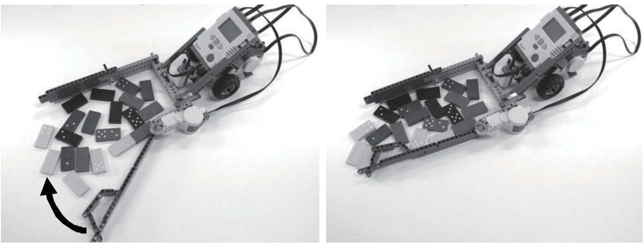

Fig. 9. Pushing robot with large fences.

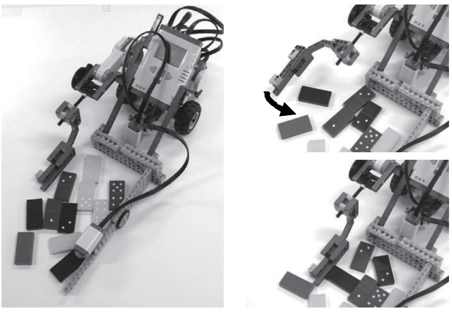

Fig. 10. Pushing robot with active broom.

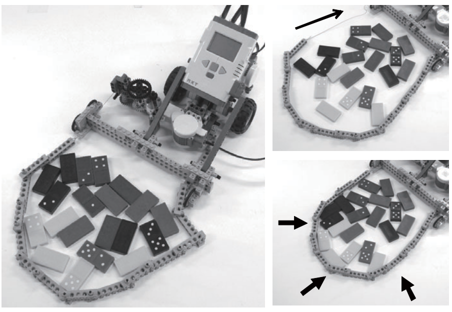

Fig. 11. Pulling robot with a soft cage.

- Adoption of a Soft Cage: A strategy adopted by the TA student, in which a net-like cage was prepared by connecting blocks and the cage was contracted to get the dominos together (**Fig. 11**).

5.3. Lift-Up Strategy

The other two of the 3rd grade undergraduate students adopted this strategy. This strategy required the robot to overcome the obstacle in the center while lifting up the dominos. To achieve lifting up the scattered dominos, the students made the following attempts.

- Use of the Trapezoidal Obstacle: A strategy to push a dustpan-shaped structure to the trapezoidal obstacle to bring the dominos on the dustpan (**Fig. 12**).
- Use of the Edge of the Working Region: A strategy to lift up the dominos by pushing them to a lift-up structure prepared in advance at the edge of an 11 mm thick plate used for the working region (1920 mm $\times$ 910 mm) (**Fig. 13**).

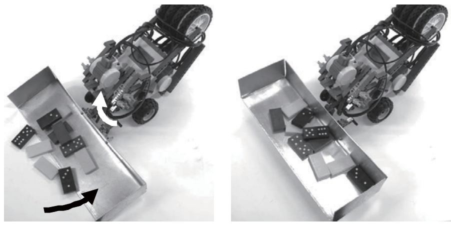

Fig. 12. Lift-up robot with a large dustpan.

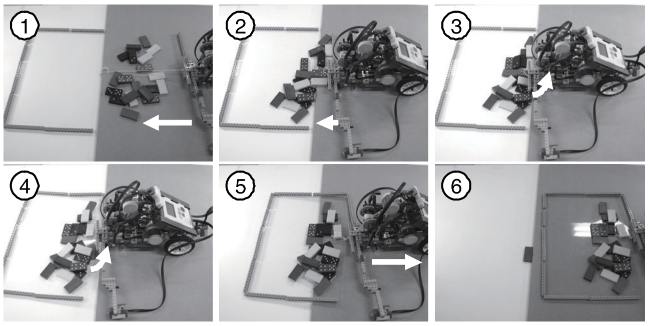

Fig. 13. Lift-up robot utilizing edge step of working region.

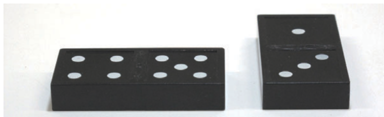

Fig. 14. Domino: transfer target.

5.4. Robot Motion Results and Their Analyses

As a result of the domino transfer task with the five robots, no robots have successfully transferred all 20 dominos. Please refer to the movies [a] for motions. A push strategy adopting a large cage transferred the largest number (19) of dominos, followed by a strategy using the working region edge transferred 17 dominos and the robot adopting the soft cage transferred 15 dominos. The one using the dustpan transferred only a few dominos because the dominos got stuck on the trapezoidal obstacle, and the one using the broom to push the dominos into the cage transferred no dominos because it failed to arrive and stop at Area 2.

In transferring, the push strategy was better than the lift-up strategy because the radius of the corner of the dominos (**Fig. 14**), the transfer target, was very small and it was thus difficult to insert a structure under the dominos.

In that sense, the strategy using the edge of the working region is a breakthrough to lift up the dominos regardless of their shape, and thus the technology prize was given to the robot using this strategy.

Against the initial prediction, no student used Python, introduced in the expansive exercises, as a program development environment and all of them used the NXT Software, supplied with MINDSTORMS, to develop their programs.

6. Conclusions

6.1. Summary and Discussions

This seminar facilitated the students to learn that even a relatively simple mechanical structure can successfully carry out complicated works such as aligning dominos and transferring dominos with appropriate strategies such as caging and pushing adopted for achieving a specific task. The students' reports indicated their consciousness to adopt the simplest means to achieve their goals [b], thereby ensuring that the target of this seminar, "the students learn a process of matching robot needs with seeds," was achieved.

Hypothesis 1 (if the lecture introduced the students with two types of robots, i.e., those that imitate human and those that do not, the students can plan strategies to enable even a simple robot to carry out stable works) was validated because the students adopted strategies at least beyond ordinary human works in view of the important keywords (caging and pushing), which were introduced in the lectures, although the arbitrary condition control of introducing only one side could not performed from the view point of educational fairness.

Hypothesis 2 (presentation of examples of mechanisms will facilitate the students to elaborate strategies in mechanism and preparation of program development environments will facilitate their strategies with elaboration in algorithm) was not necessarily validated. Because strategies with elaboration in algorithm were not adopted in 2010, in which Python was introduced, although strategies with elaboration in mechanism were adopted in 2009, in which examples of translational motions were presented in the expansive exercise using LEGO.

The students experienced that the NXT MINDSTORMS Software sufficiently ran robots to achieve the works without complicated recognitions, thereby hindering promoted use of Python, leaving an issue that the mission configuration was not appropriate to verify the hypotheses.

The change in curriculum affects developed robots' mechanisms themselves rather than strategies themselves. More specifically, a great difference between the both years lies in that the robots of 2010[5] have a poor mechanism in which the basic robot body of a line trace robot was used as it was whilst those of 2009 adopted a robust base structure different from the line trace robot.

While in 2010 we did not present specific structures, the students created a strategy (use of the working region edge) unimaginable to the faculty. This indicates a negative correlation between the lecture contents and variety in strategies to be adopted (the less explained in the lectures, the more variation of strategies increases).

The students found great difficulty in ensuring a basic rigidity of the robots in the both years. It is necessary for the faculty to teach students how to utilize the knowledge of material mechanics and what structure should be used in creating structures with sufficient rigidity.

Finally, despite disadvantages of parts limitations in structure design and limitations in actuators and sensors variations, LEGO MINDSTORMS is an effective teaching material for the students to experience overall from robot strategy planning to implementation in a short period.

6.2. Future Prospects

The results of 2010 indicate that the given mission was not perfectly completed. The limitation of the extremely small radius of the dominos, transfer targets, inhibited various strategies from being adopted. Thus, we are planning to give the students of the next year a task of transferring objects such as a sphere to which more innovative strategies (e.g., rolling and throwing) can be adopted.

We intend to further analyze the correlation between the lecture contents and variation in strategies so that the students will autonomously plan their strategies and recognize the importance of strategy design in robot development. In addition, our future issues include searching for methods to convey approaches in the basic structure design useful in robot body design even if the mechanism is not as specific as the translational motion.

5. There is a difference in labor that each student needed to produce a robot by himself, though.

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Name:
Rui Fukui

Affiliation:
Assistant Professor, Department of Mechano Informatics, Graduate School of Information Science and Technology, The University of Tokyo

Address:
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Brief Biographical History:
2004-2006 Engineer, Mitsubishi Heavy Industries, Ltd.
2009 Ph.D. at Department of Mechano-Informatics, The University of Tokyo
2009-2011 Project Assistant Professor, Department of Mechano-Informatics, The University of Tokyo

Main Works:
- "HangBot: a Ceiling Mobile Robot with Robust Locomotion under a Large Payload (Key mechanisms integration and performance experiments)," In Proc. of Int. Conf. on Robotics and Automation, pp. 4601-4607, 2011.
- "Home-use object transfer/storage robot system with compliant strategy and mechanism (Commodities management and its extended application of daily life support for the elderly)," J. of Robotics and Mechatronics, Vol.23, No.4, pp. 532-543, 2011.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Institute of Electrical and Electronics Engineers (IEEE) Robotics and Automation Society

Name:
Tomomasa Sato

Affiliation:
Professor, Department of Mechano Informatics, Graduate School of Information Science and Technology, The University of Tokyo

Address:
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Brief Biographical History:
1876 Researcher, the Electrotechnical Laboratory (ETL), the Ministry of Industrial Science and Technology
1991 Professor, the Research Center for Advanced Science and Technology (RCAST), The University of Tokyo
1998 Professor, the Department of Mechano-Informatics, The University of Tokyo

Main Works:
- "Development of a tiny orientation estimation device to operate under motion and magnetic disturbance," The Int. J. of Robotics Research, Vol.26, No.6, pp. 547-559, June 2007.
- "Environment-Type Robot System "Robotic Room" Featured by Behavior Media, Behavior Contents, and Behavior Adaptation," IEEE/ASME Trans. on Mechatronics, Vol.9, No.3, pp. 529-534, 2004.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Society of Instrument and Control Engineers (SICE)
- The Japanese Society for Artificial Intelligence (JSAI)
- The Institute of Electrical and Electronics Engineers (IEEE) Robotics and Automation Society (RAS)