The Teaching Strategy in e-Learning Based on PID Control and Item Response Theory

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Summary
With the goal of providing instruction with an optimum method to achieve the target given in the learning process of the learner, PID control theory was applied and an assessment was made of the proportion(P), integral(I), and differential(D) of the learner's level of understanding. Using these parameters, a web server system was constructed as a teaching model adopting learning rules extracted from optimum problems. Using the item response theory, problem characteristics were analyzed by obtaining the discrimination power and difficulty level of each problem, and each learner's ability was also estimated. Characteristic functions of one set of tests were identified by combining the problem characteristics obtained. These functions were incorporated in the Matlab simulation software, and referring the learning characteristics of each learner in time series, the relation between the difficulty level of problem determined by manipulation using PID control and the learner's ability was obtained. With this simulation, a method was constructed to optimally arrange learning materials based on the hierarchical learning theory.
Key words:
item response theory, hierarchical learning theory, Matlab, feedback system, PID control

1. Introduction

The rapid advance in information and communication technology in recent years has had a huge impact on approaches to education. Attempts are being made to use information technology in the field of education for quantitative and qualitative improvements through e-learning, and trials or programs are underway at various educational institutions. Individual learning opportunities have expanded, thanks to fewer time and distance restrictions via the Internet. Moreover, with the availability of so many learning materials from the multimedia, there are far more possibilities for effective teaching strategies. Driven by these new technologies, education is now possible using a completely new array of learning approaches and educational environments. However, all of this means a learning process with no teachers present, and there is the risk of leaving learners in isolation when they reach an impasse. At the same time, while learners are free to select their own learning materials, they may have no idea of the learning process or what to study. Therefore, it is necessary to cause the learning process corresponding to learner's characteristic, and make understanding level of the learner reach the target level by the best method.

As for the teaching strategy, there is education either by "drilling in" fixed contents until they are remembered, or "thought training" by considering and inferring. In the present study we undertake mathematical modeling of a strategy to teach with the former "drilling in" approach. In this type of education, one ascertains the learning objectives and types of evaluation, and rule formulation is required. In the drilling scenario one must also build a theoretical context for learning theory with the idea of increasing knowledge.

To solve such a problem, with the application of automatic control theory and other aspects of systems engineering in the field of educational technology, we formulated mathematical model for high level educational strategies, in order to provide problems or explanations suited to the understanding of individual learner and implemented this model on web server using computer technology. Test characteristic functions are obtained through item response theory for the discrimination power and difficulty level that are characteristics of a problem, and through classification and combination the probability of a correct answer according to the learner's ability can be obtained. In addition, using the "theory of learning" that examined the learning behaviors of learners, these functions were applied to modeling of learning support systems. Together with the use of multimedia technology, these were beneficial as a learning support.

Therefore, using a statistical technique by item response theory, we made of liner measure of difficulty of problem and applied it in the guidance order based on hierarchical learning theory. Our purpose is to develop the control system to bring learner's achievement close to the target level efficiently. For that, we enabled the system to provide optimum questions for learner's level of understanding by applying the PID control theory in automatic control. We modeled this system using PID control with simulation software Matlab. We put the test information function obtained by the item response theory into MATLAB and constructed the simulation environment which could optimize the PID parameter. We treated the arithmetical computation and the certification examination for information technology engineer as a case for the evaluation.

Memorization in learning is often dull and boring. In the present study, in order to improve the process of memorization learning, the authors discuss the control of the processes for the learner's efficient memorization. In the learning process, we obtain three parameters, "P", "I" and "D". "P" evaluates the proportion of the learner's present level of understanding. "I" performs the integration of the learner's past level of understanding. "D" does the differentiation of the learner's recent level of understanding. For effective control of the memorization process of learning, the authors have designed the PID control of e-Learning system to be similar to the automatic control of a machine. This system is applied to the arithmetical computation and the certification examination for information technology engineer, and the effect of the control is found to be reasonable.

In operation the support for the independent and autonomous learning was feasible by providing the optimum problems, individual instructions and advice, thereby enabling attainment of the target objective levels efficiently. Also, with appropriate hints or explanations, the impasses that can deter learners and make them give up may be avoided, thus allowing them to move ahead freely.

2. Hierarchical Learning Theory and Item Response Theory

In a curriculum, the authors classify hierarchically the learning contents and the learner's achievement. In this section we discuss hierarchical learning theory and item response theory.

2.1 Grouping of Tasks According to Learning Hierarchy Theory

Gagne's hierarchical learning theory is fundamental to methods of hierarchical structuring of learning tasks. According to this theory, the primary significance of the hierarchy is to identify prerequisites that should be completed to facilitate learning at each level. To solve and to understand a certain arithmetical computation, we notice the existence of the prerequisite learning tasks. Particularly, in learning process of the arithmetical computation, only after mastering prerequisite learning tasks, the learner can often solve the problem of the next stage. Thus the order of providing the problem is important. As an approach to the construction of this guidance order, it is insufficient only to analyze the problem structurally. Empirically, it is necessary to examine the difficulty of the problem investigating how the learner understands. In this research, we classified the calculation process, and arranged the learning materials based on the above-mentioned idea so that there was no leap in the difficulty.

We used an item score chart to analyze learner characteristics. The rearrangement in this chart made it possible to clearly view the interior construction and special features (i.e., differences in achievement or non-achievement patterns in reaching learning targets, differences in various learning patterns, etc.). Figure 1 shows the study characteristic on time series. When a score of "1" was given to each learning problem, and "0" was used for a mistaken response, a score chart which consists of the lines N(number of learners) and columns M(number of problems) was obtained. This chart indicated a high correct response percentage in order starting from the left in the abscissa direction, while in the ordinate direction, the high-scoring learners were arranged in the order of "1" and "0" on the rearranged score chart from top to bottom. Of course, many scores of "1" would be distributed on the upper left of the rearranged score chart, and many "0" scores on the lower right. This rearrangement made it possible to clearly view the interior construction and special features (i.e., differences in achievement or non-achievement patterns in reaching learning targets, differences in each learning problem pattern, etc.). Only in the rearranged score chart can the correct number of answers be counted from left to right and indicated by dividing lines. These lines are connected for each learner, and a score distribution curve is obtained that indicates the distribution of the problem achievement characteristics.

When a time axis was added to this two-dimensional chart, which was then used as a three-dimensional chart,

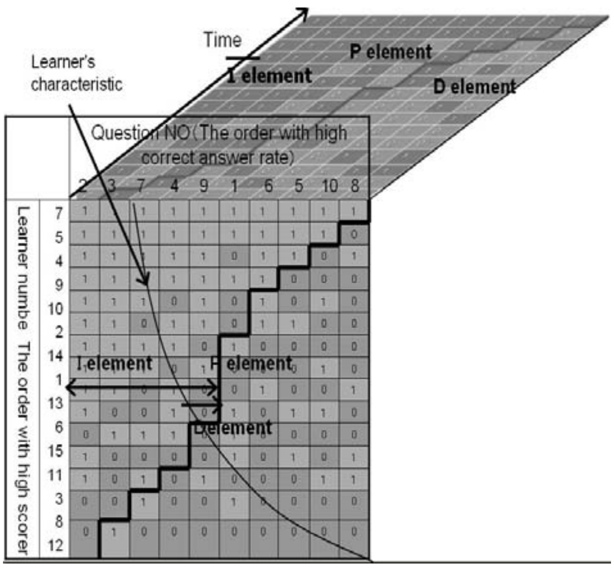

Fig. 1. Study Character on Time Series

the distribution of an individual's achievement characteristics can be understood from a time-series standpoint. Using this time axis, the I component concept indicates the problems consistently correct from past to present, while the P component concept is for all problems correctly answered in the present learning task. The D component concept is for present problems correctly answered which were answered incorrectly earlier. Moreover, as with the two-dimensional chart, the mean was calculated for the students and the achievement characteristic distribution was obtained from a time-series perspective. From the adjacency matrix ***D*** that expresses the conditional association with the learning task, a reachable matrix ***M*** can be obtained. The subordination, foundation, and association of the learning task are assessed with this reachable matrix, and the tasks are grouped and structured.

2.2 Modeling of Characteristic Functions Using Item Response Theory

The item response theory was used in this research to understand the difficulty and the characteristic of the problem for the calculation problem etc. In item response theory, the probability of a correct answer to any given question is expressed as a function of the characteristic value to be measured. These functions express the features of questions, and are called item characteristics functions. Thus, the item characteristics function is a probability density function determined from the probability of the correct answer *Pj(x)* for item *j* against learner's ability *x*. If the item characteristic function is determined, then the probability of correct and incorrect answers can be identified, and used to decide the characteristics of the test as a whole.

This system introduces a 3-parameter logic model incorporating a pseudo-chance level for the possibility of a correct answer if the answer is as supposed for multiple-choice type problems, and a 2-parameter logic model for non-selection problems. Item characteristic function *Pj(x)* and item information function *Ij(x)* used are as follows.

$$P_j(x) = c_j + \frac{1-c_j}{1+\exp(-1.7a_j(x-b_j))} \quad (1)$$

$$I_j(x) = P_j^{\,2}(x)/P_jQ_j = 1.7^2 a_j^{\,2}(P_j - c_j)^2 Q_j/(1-c_j)^2 P_j \quad (2)$$

BILOG-MG Ver. 3 was used in the estimation of each parameter, and item characteristic function is obtained. An item information function is obtained with this item characteristic function, to express which level of learner can distinguish correct and incorrect answers with which level of acumen. Similarly, a test information function of problem groups formed with problems having these characteristics can be obtained.

In addition, using the graded response model, which is expanded model of the item response theory model, an attempt was made to apply the mistaken response pattern for multiple choice problems, and the trend in the mistaken response pattern was reasoned by analogy according to ability level. Considering advice by computer matched to these trends, the learner can be provided with a strategy to overcome learning impasses.

We analyzed the multiple choice questions on qualifying examination of information technology engineer as shown in table 1. This table shows the results of analyzing the answer of 80 learners by BILOGMG3.0 as for these problems. Generally, the identification power of the calculation problem is still higher than that of the knowledge problem, and each the value is in the range from 1.0 to 1.8. Similarly, we analyzed the calculation questions on arithmetic operation as shown table 2. This table shows the results of analyzing the answer of 220 learners.

3. Formulation of Mathematical Model

3.1 Feedback Control of Learning Process

The feedback control in the automatic control theory can be applied to the foregoing design idea. We discuss the general learning progress from the point of view of the understanding level (Fig. 2). The left side has a radar graph that shows each level of understanding of a learner in six fields. The difficulty of the problem is classified into five stages, and the boundary is shown in the dotted line. When a learner can completely understand the exercises in all fields, the radar graph forms a hexagon. The right side of Fig. 2 shows the situation in which the radar graph swells outside with the passage of time by the bar chart. The abscissa in the figure indicates time (execution frequency of exercise), while the ordinate indicates the understanding level in each field. When the problem is classified by the difficulty, the problem with a low difficulty is offered to a learner. If the learner reaches the target level in the stage, the problem with higher difficulty is offered to him. The function of this system is to control the understanding level appropriately so as to reach 100%.

The control in the theory of automatic control seeks to detect the difference between the goal and the current state and to move the object so as to eliminate the difference when the object has a goal which should be achieved. This idea of control is applicable not only in the field of industrial technology but also in others such as biology, sociology, and economics. We excogitated the model of

Table 1. Analysis of multiple choice questuion
(Qualifing examination of information technology engineer)

No	Title in question	Field of question			low ← difficulty → high					Item Response Theory	
		Volume	chapter	section	1	2	3	4	5	Identification Power	Difficult Degree
1	Radix transformation	2	2	2	○					1.21	0. 44
15	Effective digits of floating points	2	2	4				○		1.04	1. 63
14	Blocking factor and number of storage records	6	2	2				○		0.89	−1. 72
49	Characteristic of CD-ROM	6	2	4				○		1.21	0. 98
16	Performance of computer system	8	5	1		○				1.43	2. 21
74	Explanation of patent	10	1	1		○				1.02	0. 54
2	Kind of expressible information	1	1	1		○				1.18	3. 12
3	Decoding of Humming sign	1	1	1			○			0.87	−3. 5
4	Marginal evaluation of relative	1	1	1				○		0.65	−1. 23
5	binary decision tree	1	1	4			○			0.52	−0. 78
6	Computational complexity of string manipulation	1	2	3			○			0.74	−1. 57
7	Characteristic of linear list	1	3	3			○			1.02	1. 23
8	Suitable file for search by binary decision tree	1	3	4			○			1.21	2. 83
9	Concept of internal alignment technique	1	3	5				○		0.89	0. 42
10	Recursive program of factorial calculation	1	3	7		○				0.95	0. 83
23	Characteristic of program	1	4	1			○			0.75	−1. 02
11	Expression of expression by reverse-polish notation	1	4	6				○		0.68	−1. 85
24	Processing of compiler	1	4	6				○		0.92	2. 15
30	Compilation technique - lexical	1	4	6				○		0.55	−2. 47
17	Characteristic of RISC and CISC	2	1	1			○			0.68	0. 38

Table 2. Analysis of the calculation questions on arithmetic operation

No.	Question	Identification Power	Calculation Error of Identification Power	Difficulty Degree	Difficulty Degree of Calculation Error
(83)	7× 0	0.2	2.17	−11.3	
(1)	4＋3	1.3	0.67	−3.8	2.82
(4)	9＋1	2.0	0.64	−3.1	0.46
(2)	8＋0	2.0	0.60	−3.1	0.40
(14)	9－0	2.0	0.70	−2.9	0.25
(13)	5－1	1.9	0.43	−2.8	0.27
(15)	3－3	1.6	0.36	−2.8	0.34
(3)	6＋7	1.6	0.22	−2.5	0.17
(28)	5＋2＋1	2.0	0.34	−2.4	0.13
(6)	50＋6	2.0	0.33	−2.4	0.12
(16)	14－1	2.0	0.33	−2.4	0.12
(8)	2＋80	2.0	0.32	−2.4	0.11
(18)	12－2	2.0	0.32	−2.3	0.11
(5)	32＋4	2.0	0.30	−2.2	0.09
(20)	10－4	2.0	0.29	−2.2	0.09
(31)	8－2－1	1.7	0.27	−2.2	0.12
(29)	4＋6＋3	2.0	0.21	−2.1	0.08
(34)	10－5－4	2.0	0.28	−2.1	0.08
(9)	30＋40	2.0	0.28	−2.1	0.08
(7)	5＋42	2.0	0.28	−2.1	0.08
(23)	12－10	2.0	0.28	−2.1	0.08
(21)	40－10	2.0	0.27	−2.0	0.08
(40)	5－2＋1	1.7	0.25	−2.0	0.09
(24)	64－60	2.0	0.26	−1.9	0.07
(27)	100－60	2.0	0.19	−1.9	0.06
(10)	12＋20	2.0	0.26	−1.9	0.06
(17)	97－5	2.0	0.26	−1.9	0.06
(19)	15－8	1.7	0.17	−1.8	0.07
(12)	40＋37	2.0	0.26	−1.8	0.06
(11)	73＋24	2.0	0.18	−1.8	0.05

No.	Question	Identification Power	Calculation Error of Identification Power	Difficulty Degree	Difficulty Degree of Calculation Error
(44)	10－6＋4	2.0	0.25	−1.8	0.05
(46)	59＋32	1.4	0.39	−1.7	0.49
(66)	839－4	2.0	0.40	−1.7	0.22
(55)	215＋746	2.0	0.40	−1.7	0.22
(25)	96－25	2.0	0.17	−1.6	0.04
(50)	73＋28	2.0	0.38	−1.6	0.19
(57)	626＋279	1.4	0.24	−1.6	0.31
(65)	284－53	2.0	0.37	−1.6	0.18
(22)	76－20	2.0	0.25	−1.5	0.04
(61)	125－71	2.0	0.35	−1.5	0.15
(60)	72－26	1.6	0.34	−1.5	0.22
(74)	3× 2	2.0	0.35	−1.5	0.15
(75)	8× 1	2.0	0.34	−1.4	0.14
(78)	2× 5	2.0	0.33	−1.4	0.12
(87)	324× 2	2.0	0.42	−1.3	0.26
(81)	9× 6	2.0	0.23	−1.3	0.08
(62)	173－95	1.4	0.32	−1.3	0.21
(68)	712－361	2.0	0.32	−1.3	0.10
(82)	7× 7	2.0	0.23	−1.2	0.08
(63)	112－19	1.9	0.31	−1.2	0.10
(80)	5× 9	2.0	0.31	−1.2	0.09
(71)	534－438	2.0	0.31	−1.2	0.08
(79)	8× 7	2.0	0.30	−1.1	0.07
(77)	6× 8	2.0	0.30	−1.1	0.07
(70)	922－229	1.6	0.19	−1.1	0.10
(72)	504－126	2.0	0.30	−1.0	0.06
(86)	27× 3	2.0	0.31	−0.9	0.12
(107)	0.3＋0.5	2.0	0.28	−0.8	0.09
(112)	0.7－0.6	2.0	0.28	−0.7	0.09
(108)	4.2＋5.3	2.0	0.27	−0.7	0.08

CAI applied according to this notion of control (Fig. 3).

In general, there are two types of automatic control system, the closed-loop type and the open-loop type. If a control signal is not disturbed by unexpected turbulence and the characteristics of the controlled object are completely understood, there is no need for feedback control. The reason is that the controlled object responds as expected according to the scheduled control signal. On the other hand, if the characteristics of the controlled object cannot be completely understood, processing for adjustment is needed by continuously examining its reaction to a control signal. This method is applicable when there is turbulence. In this system, we assume the initial characteristic of a learner is uncertain, and it is difficult to expect his reaction completely in the learning process. Therefore, we adopted the feedback control to continually observe his reaction and thus comply with various factors. In this CAI, as shown in Fig. 3, the control signal (the optimal level of the exercise) is calculated based on a set value (achievement level) and the feedback signal (data on learning record) in the control operation part. This signal is outputted to the controlled object (learner), and measurement (exam result) is returned again as a feedback signal. In this control system, it is possible to control so as to bring a measurement (exam result) close to a set value (achievement level).

The CAI evaluates the learner's situation from three points of view. For a temporary situation, the CAI evaluates the proportion, which is the difference between the learner's temporary understanding level and the target level. To evaluate the past history of the learner's accumulated understanding, the CAI calculates the integration, which is the integral of all past levels of understanding. To estimate the future understanding level of the learner, the CAI calculates the differentiation, which guesstimates the future understanding level. Through the feedback process, the parameters "P", "I", and "D" determine the control strategy for the learning process at the next step. The PID control raises the temporary learner's level of understanding to the target one through repeated feedback processes.

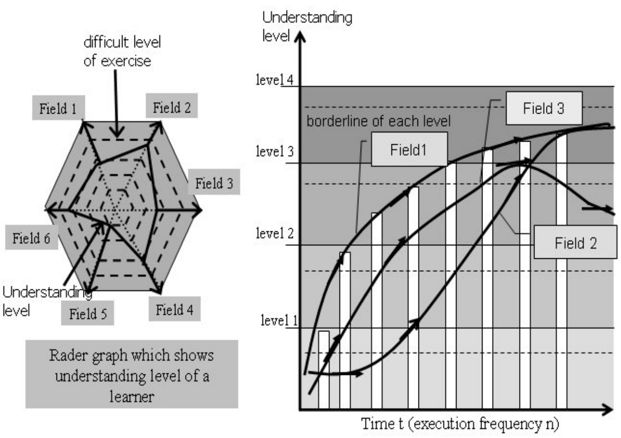

Fig. 2. Characteristic of Understanding Level

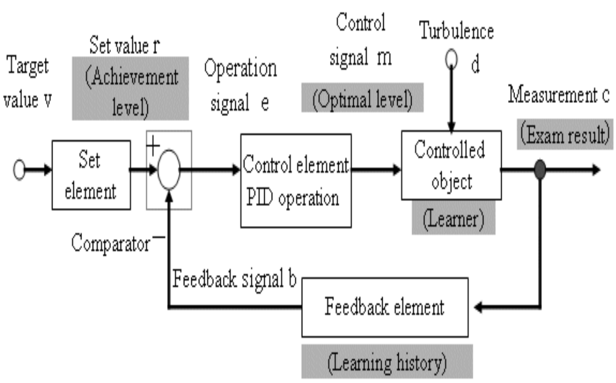

Fig. 3 Feedback Control Model

3.2 PID Control Model by MATLAB/Simulink

A characteristic of feedback systems is that response speed and response accuracy are generally antagonistic. If emphasis is placed on response speed, the response series vacillates and response accuracy declines, increasing the degree of instability. Thus, if problems that are easy given the learner's ability are continued, the time until the goals

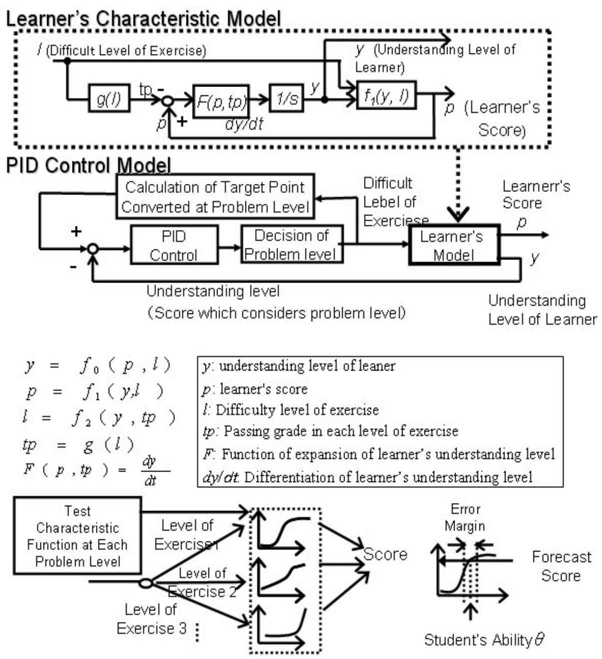

Fig. 4. Learner's Characteristic Model as Controlled System

are achieved lengthens. Conversely, if the problems are too difficult, rapid results drop off and the degree of difficulty vacillates.

To analyze the characteristics of such systems, we developed a dynamical system simulation model using learner's transfer function expressed with a differential equation. The time needed to reach the target level was minimized by the system evaluation. The PID control model is expressed by the following equation for the continuous model and discrete models. In this equation, e is the difference between the target value and the actually measured value. Respective evaluation constants for proportion, integral and differential components must be multiplied to obtain the operation amount.

$$m = Kp \cdot e + Ki \int edt + Kd \frac{de}{dt} \quad \text{(continuous mode)} \qquad (3)$$

$$m = Kp \cdot e + Ki \int edt + Kd \frac{de}{dt} \quad \text{(discrete model)} \qquad (4)$$

Next, let us consider a model of learner characteristics. For the difficulty and the characteristic of the problem, we obtain the test information function using the item response theory mentioned above, and put it into MATLAB. With reference to the item response theory and item score sheet, for the learning model of the learner we used a model expressed with a differential equation in which the ability level of various learners is expressed as time (number of times) on the horizontal axis, and the level of learning on the vertical axis.

Fig. 4 shows the model that we designed, and the learning characteristic model of the learner is corresponds to controlled object in fig. 3. As shown in Fig. 4, the understanding level of learner (*y*) is a function of his score (*p*) and difficulty level of exercise (*l*); the score of the learner is considered to be a function of the determined learner's understanding level (*y*) and difficulty level (*l*). Moreover, the difficulty level of exercise (*l*) to give the learner is thought to be a function of the understanding level (*y*) and the target point (*tp*) in each level of exercise. This *tp* is a function of the level of difficulty (*l*) determined in relation to the nature of the problem. This learner characteristic model corresponds to the control object.

Fig. 5 shows the models thus far explained, designed with the simulation software called Matlab/Simulink. The learner's character model is seen above, while the PID control model for the learner control is shown below. The learner's characteristic model outputs the score and the understanding level of learner using his ability at the point in time when he addresses the problem level. Part of the learner's character model is the student part of the PID control model. In the PID control model, the difficulty of the problem which should be provided to learner next time is calculated by PID operation based on the score and the understanding level.

The signal of the difficulty level of the problem calculated by the control element can be observed in time series, and similarly the score and the understanding level of the learner under the difficult level of problem can be observed. The respective signals also can be observed for the P, I, and D elements in arithmetic unit of PID. Fig. 6 shows the output signals for each of the elements from simulations as a sample.

4. Analysis of PID Parameter Characteristics

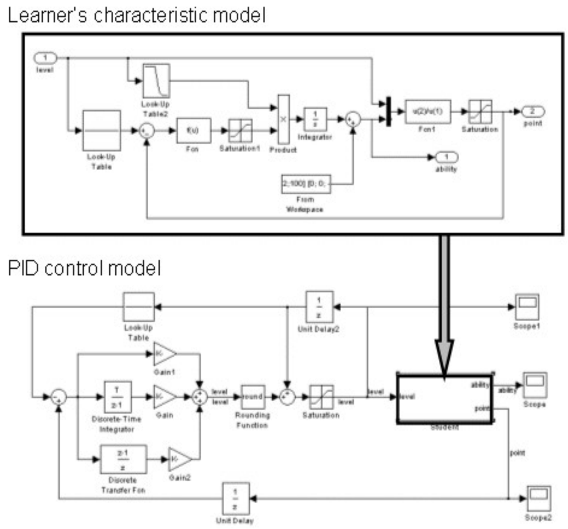

Fig. 5. Learner's Characteristic and PID Control Model (MATLAB/Simulink)

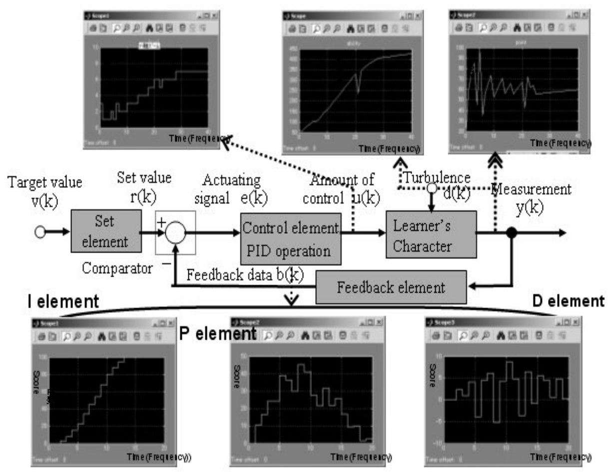

Fig. 6. Character of Learning Process

In this section we discuss the results of simulation. Fig. 7 presents in graphic form the understanding level of the learner following the exercise *N* repeat. At that time, the understanding level of the learner is evaluated by the difficulty level of the exercise following the *N* repeat. The Fig. 8 on the left indicates when only the *Kp* parameter is moved, and with difficulty level of exercise for the 10th, 15th and 30th exercise, respectively. The larger *Kp* parameter can be made to achieve a higher level more quickly but it oscillates at over 10. This is because the problems given are too difficult and inappropriate in relation to the learner's level of understanding. The right-hand figure also indicates when only the *Ki* parameter is moved, but oscillation occurs with more than *Ki*=1.

Likewise, Fig. 8 shows the understanding level of the learner after 15 and 30 exercises with both *Kp* and *Ki* parameters moving. The left-hand graph shows the learner level at the 15th time, and the right-hand graph shows the learner level at the 30th time. Since the two parameters of *Kp* and *Ki* are moved, each parameter can be used over a wide range, enabling a higher rate of response. Also, the range of the non-oscillating *Ki* is expanded, and stability is obviously higher as well.

Next, the upper figure on Fig.9 shows the characteristics of *Kd* parameter, which indicates the understanding level of the learner after the 30th exercise. Where the learner's score shows no large variation, there is a slight improvement owing to the *Kd* parameter. Also, oscillation occurs when *Kd* reaches more than 2. The lower figure on Fig. 9 indicates the change rate in the difficulty level of exercise when an abnormal decrease occurs due to the poor scoring of the learner. If the integral element *Ki* is made larger, the difficulty level does not decrease much compared to the present problem; however, when the integral component *Kd* is made larger, obviously a lower-level of difficulty is output.

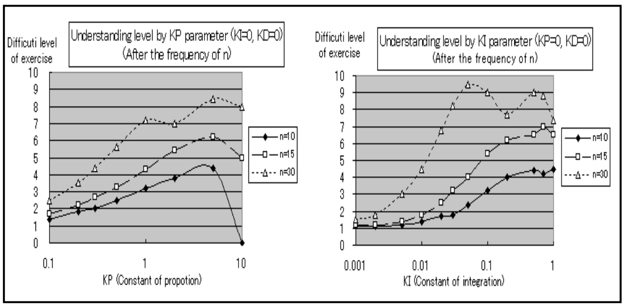

Fig. 7. PID Parameter Characteristic by Simulation (1)

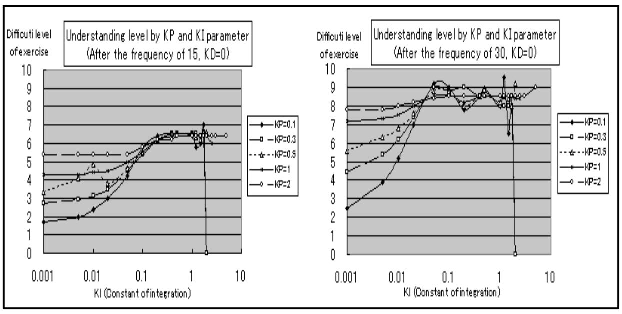

Fig. 8. PID Parameter Characteristic by Simulation (2)

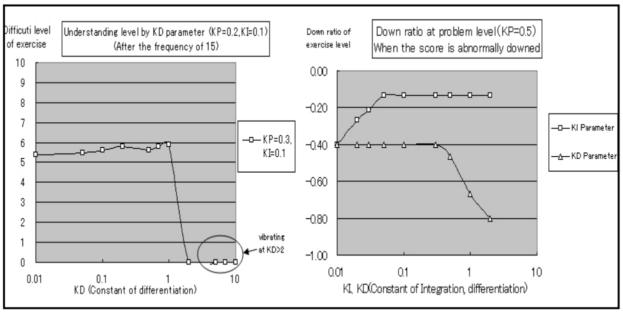

Fig. 9. PID Parameter Characteristic by Simulation (3)

5. Conclusion

With the goal of providing instruction with an optimum method to achieve the target given in the learning process of the learner, PID control theory was applied and an assessment was made of the proportion(P), integral(I), and differential(D) of the learner's level of understanding. Using these parameters, a web server system was constructed as a teaching model adopting learning rules extracted from optimum problems. Using the item response theory, problem characteristics were analyzed by obtaining the discrimination power and difficulty level of each problem, and each learner's ability was also estimated. Characteristic functions of one set of tests were identified by combining the problem characteristics obtained. These functions were incorporated in the Matlab simulation software, and referring the learning characteristics of each learner in time series, the relation between the difficulty level of problem determined by manipulation using PID control and the learner's ability was obtained. With this simulation, a method was constructed to optimally arrange learning materials based on the hierarchical learning theory.

As examples of this method, we developed web server system for the arithmetic computation and a certification examination for information technology engineer, but systems can also be developed for other fields using the same method. An environment in which PID parameters could be analyzed and evaluated was established, and the characteristics of each parameter were analyzed. In the future, their appropriateness will need to be verified.

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Biography

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