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Applying Conversion Matrix to Robots for Imitating Motion Using Genetic Algorithms

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***Abstract*—In this paper, we propose a method using a genetic algorithm (GA) for motion imitation between two different types of humanoid robots. Although motion imitation between humans and robots has been a popular research topic for a long time, the imitation between different types of robots still remains an unsolved task. The selection of the correct joint angles is critical for robot motion. However, different robots have different anatomies, with each joint's position and movable range uniquely defined for each type of robot. This discrepancy is an obstacle when converting a motion to another type of robot. The proposed method uses a genetic algorithm in order to find the conversion matrix needed to map one robot's joint angles to joint angles of another robot. This is done with two objectives in mind; one is to reduce the difference between the sample imitation and the converted imitation. The other one is to keep the stability. Two experiments were conducted; one stable and one unstable experiment. The experiments were made with two different types of robots in a simulation environment. The stable experiment showed a concordance rate of 93.7% with the test motion. The imitation also tested with the real robot and succeeded to keep standing. In the unstable experiment, the student robot keeps its balance for most of the simulation time. It showed a concordance rate of 95.5%, which is slightly higher than that in the stable experiment. These results show great promise for the proposed method as a way to realize motion imitation between different types of robots.**

I. Introduction

There has been extensive research[1][2][3] on the control of robot motion. Some researchers have attempted to control robots with precise command sequences; giving the angles of each joint for each moment. Others have aimed to move robots with abstract commands. However, robots that have complicated structures such as humanoid robots need an enormous amount of data to specify each joint's angle; therefore it is difficult to control humanoid robots with abstract commands.

So far, studies on the imitation of robots' movements have mostly aimed for robots to imitate human motion[4][5][6]. However, the majority of these studies first simplifies the human's motion and then assigns this motion data to robots. These studies are limited in the sense that the degrees of freedom (DOF) or movable ranges of robots' joints are not the same as humans'. This makes it difficult to transfer the human's motion directly to the robot. Tetsunari Inamura et al.[7] proposed a method for motion imitation between robots. However, this study was limited to the reproduction of motion between the same type of robots. Thus, conversion and imitation between robots that have different kind of joint structure, have not attempted yet, as far as we know.

This paper focus on the imitation of motions between different kind of robots. Similar to the differences between joints of robots and joints of human, there is a difference in positions and movable ranges between joints of different types of robots. Moreover, there are some cases where the joint of one robot cannot be directly mapped to the joint of another kind of robot, since it lacks this specific joint. It is the aim of this research to find an optimal conversion matrix for motion imitation by converting joint angles from one robot to another, even if the structures of these two robots are completely different. Genetic algorithm (GA) is proposed to be utilized to determine the optimal conversion matrix.

We estimated that the usage of GA leads to reduction in the amount of learning data required for the joint angles of the robot comparing other methods such as machine learning which needs a lot of training data. As a result, the manual involvement for creating the robot motion can be reduced.

II. Proposed method

The objective of this paper is to verify whether it is possible to map joints between two different types of robots. This is done by finding a conversion matrix which maps the model robot's actions to the imitating robot such that they resemble each other as closely as possible. In this paper, the model robot is called a teacher robot, and the imitating robot is called a student robot.

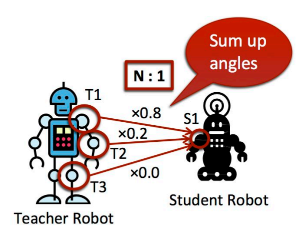

Fig. 1. Mapping each joints

Each joint angle of the student robot is assumed to be composed of a weighted combination of the joint angles in the teacher robot, as shown in Fig.1. The conversion matrix specifies the contribution from each of the teacher robot's joints. This allows neighboring joints to affect the resulting translation. It is natural that the joints in the arm are correlated. Thus, it is assumed to be important to consider the influence of the neighboring joints in order to convert one joint angle. We used a GA to find the best conversion matrix. The constructions of the conversion matrix and chromosome are illustrated in Fig.2. Each column of the conversion matrix is dealt with a part of the chromosome and every column comprises the whole chromosome.

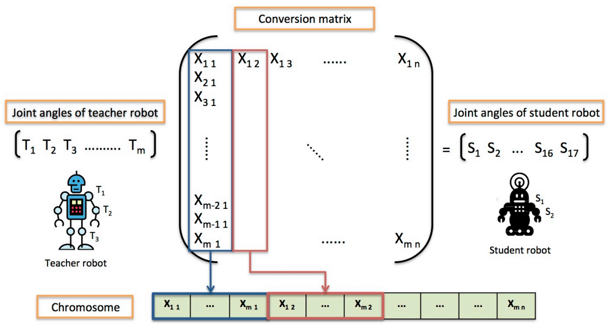

Fig. 2. Construction of conversion matrix and chromosome

In order to find the conversion matrix two objectives were considered: The similarity and the stability of the motion. A fitness function was developed for each of these objectives. Three methods of combining these fitness functions were investigated. The similarity evolution mainly considers the similarity of the imitation. Joint angle data for two different motions were prepared, one training motion and one test motion. For the teacher robot, both motions were created manually, whereas only the training motion were needed for the student robot. When training the student robot, the conversion matrix was applied to the teacher robot's joint angle data at a specific moment in time. The converted joint angle of the student robot was then compared with the ideal imitation data (the manually created training motion). The fitness function was defined in such a way that the smaller the difference of the joint angle between the converted imitation and the ideal imitation the higher the fitness value. The conversion matrix that had the highest fitness value in the last generation was considered as the optimal conversion matrix. This optimal solution was then applied to the test motion, that is a motion different from the one used in the learning phase. The conversion matrix was used to map the teacher motion to a motion for the student robot, after which was decided whether it had been able to properly imitate the teacher robot's motion. The process of the similarity evolution is illustrated with Fig.3.

The other objective of this paper was the stability evolution. Kim et al.[8] investigated how to keep the stability when converting a motion from a human to a robot. This study used a complex calculation that confirmed the stability of the robot, both kinetically and dynamically. We aimed to simplify the process and evolve the stability of the student robot by using GA.

As mentioned earlier, three different methods were used to evolve the conversion matrix. The first method, *the similarity*

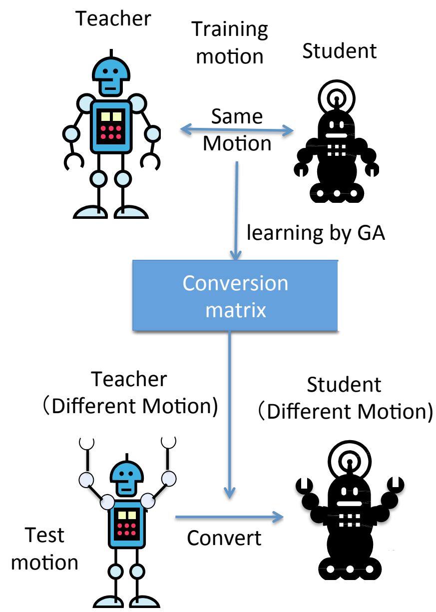

Fig. 3. The process of similarity evolution

method, uses only a similarity measure as its fitness function. The second method, *the mixed method*, instead uses a fitness function that consists of a combination of the same similarity measure and a stability measure. These two measures are multiplied and thus both are considered during the whole evolution. The last method, *the separated method*, first finds the conversion matrix with the similarity method, but then continues to evolve the best individuals using the stability measure only.

We assumed that the separated method would be the most effective. The reason is that the similarity of the motion is considered to be the most important factor at the beginning of the evolution. Considering the stability too early in the process might cause an alienation from the motion of the teacher robot, and the main objective of this study, i.e. to imitate motions, cannot be accomplished even if the student robot can stand.

III. Experiment

A. Experiment environment

HOAP-2[13], made by Fujitsu Automation Inc., was used as the teacher robot. KHR-2HV[14], made by Kondo Science Inc., was used as the student robot. HOAP-2 has 25 DOF and KHR-2HV has 17 DOF. In this paper, we used both a robot simulator and a real robot. Webots PRO 7.0.1[15] was used as the robot simulator.

The parameters of GA are shown in Table I.

TABLE I. The parameters of GA

	Similarity Evolution	Stability Evolution
Population	150	50
Generation	5000	50
Elite size	15	3
Mutation rate	0.03	0.8
Crossover rate	0.6	0.0

The reason that the parameter of the crossover rate is zero in the stability evolution is to keep the diversity. Since the imitation is almost completed in the similarity evolution, the change needed in the stability evolution is extremely small. However, if the crossover has occur with two chromosomes that one is changed and one is not changed, the change might be disappear. To avoid this problem, we decided the crossover rate as 0.0%. These data were composed of time series data from zero seconds to five seconds, which were separated into eighty sections. The reciprocal of the difference between the student robot's joint angle data of the sample imitation and the student robot's joint angle data of the converted imitation was used as the fitness value. The fitness function thus performs a least-square error minimization.

The expression of fitness function in this experiment is as follows.

$$f_i = \frac{1}{\sum_{k=1}^{N} \sum_{l=1}^{M} \left(t_{kl} - s_{kl}\right)^2} \tag{1}$$

In this equation, f_i is the fitness value of individual i. N is the number of joints. M is the time, t_{kl} is the k:th joint angle of the student robot in the sample imitation at the time l. s_{kl} is the k:th joint angle of the student robot in the converted imitation at the time l. The fitness function is defined such that the smaller the denominator, that is the difference between two joint angles, the higher the fitness value.

As a measure of the stability, we used a fitness value which was in proportion to the time from the start of the simulation to the moment that the robot fell down, that is the chromosome that could stand for a long period of time was more likely to survive the evolution. The gyro sensors mounted on the student robot was used for judging when a robot should be considered fallen. The fitness value was increased during the time when the value of sensors did not make any big changes. If the change of a sensor value exceeded a certain threshold, the student robot was assumed to have fallen down and the fitness value would stop increasing. We used Webots to verify the stability of a robot. We made the student robot moved with the converted motions in Webots.

In this paper, we conducted two experiments. The first experiment was a stable experiment. The objective of this experiment was to compare the three methods, the similarity method, the mixed method and the separeted method. In the stable experiment, we attempted to make the student robot imitate a simple motion, in which only the arms were used. The second experiment was an unstable experiment. The objective of this experiment was to confirm the stability of the imitating motion created by the proposed method. Thus, we attempted to make the student robot imitate a kicking motion, which is an unstable motion. Since the foot area of the teacher robot is large enough to support its body stably only using one foot, the teacher robot can kick without moving its arms. On the other hand, the foot area of the student robot is smaller and the position of the center of gravity is higher than that of the teacher robot. Thus the student robot easily falls if it merely imitates the motion of the teacher robot. In the unstable experiment we aimed to verify that a stable imitation is achieved by the proposed method even if the original motion is unstable.

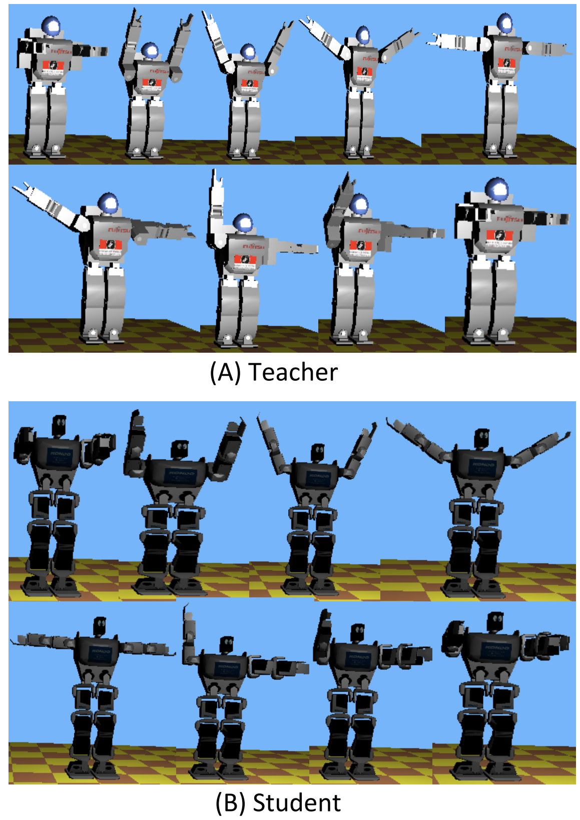

Fig. 4. The training motions used in the stable experiment

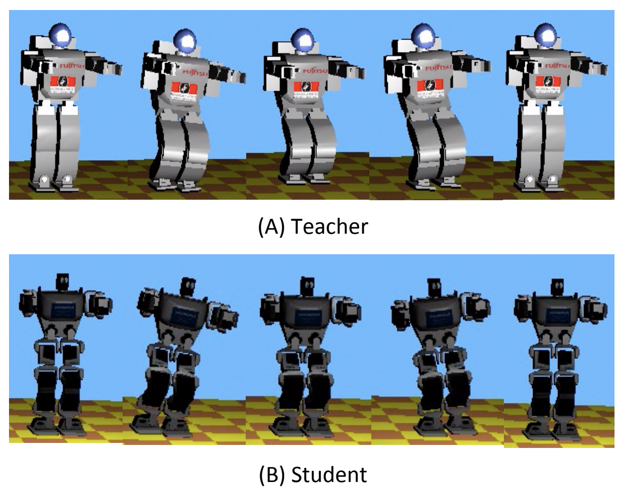

Fig. 5. The training motions used in the unstable experiment

The training motions of the teacher robot and the student robot that were used for the learning in the stable experiment and the unstable experiment are shown in Fig.4 and Fig.5. Four joints were used in the training motions for each robot in the stable experiment. This motion was to raise and rotate their arms. On the other hand, seven joints of the teacher robot and eight joints of the student robot were used as the training motions in the unstable experiment. The robots did bending and stretching as they rotated their knees.

B. Result

1) Stable experiment: The results of each method in the stable experiment are shown in Fig.6. This graph shows the change of the concordance rate, that is the similarity between the joint angle data obtained by using the conversion matrix and the ideal imitation of the training data.

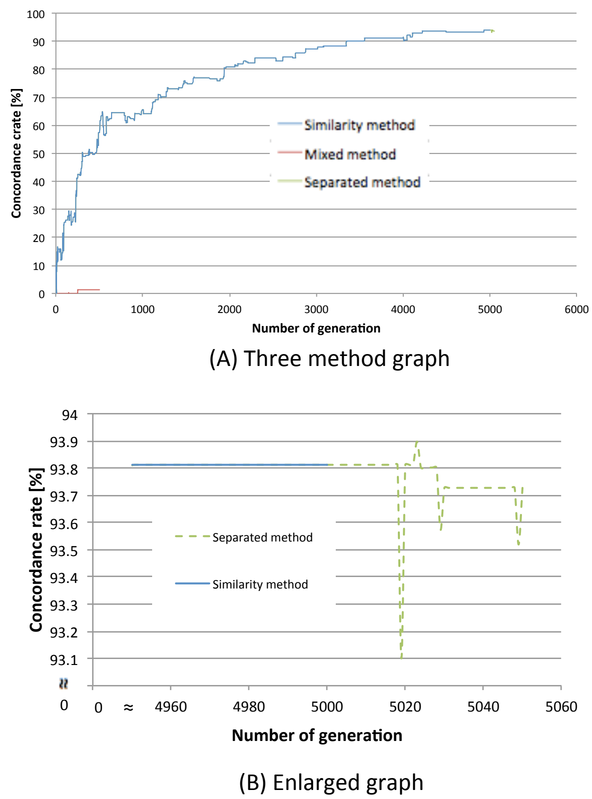

Fig. 6. The change of concordance rate with each methods in stable experiment

The mixed method only achieved a very low concordance rate as seen in Fig.6. It took around a week to calculate even 500 generations. The stability evolution needs to use Webots, but moving robots in Webots is much slower than calculating the similarity only. Thus the calculation time of the mixed method was about ten times as long as that of the other two methods. On the other hand, both the similarity method and the separated method achieved a higher concordance rate as the number of iterations increased. The difference between the similarity method and the separated method was the use of the stability evolution. In Fig.6, the separated method still kept evolving even after the evolution using the similarity method has stopped. Even when the evolution enters the next phase of the separated method, where the stability criteria is used, the similarity only displays small decline from the converged optimum. The final concordance rate was 93.7%. The similarity method surpassed the separated method in the terms of the similarity of joint angles between the ideal imitation and the converted imitation. This difference is however not noticeable in the resulting motion. The stability is therefor more important than keeping this small similarity improvement.

The teacher robot's motion in the stable experiment is

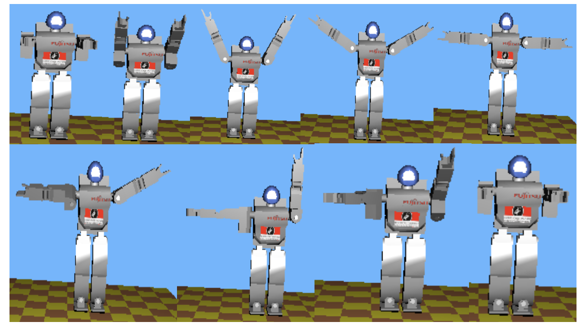

Fig. 7. The motion of teacher robot in stable experiment

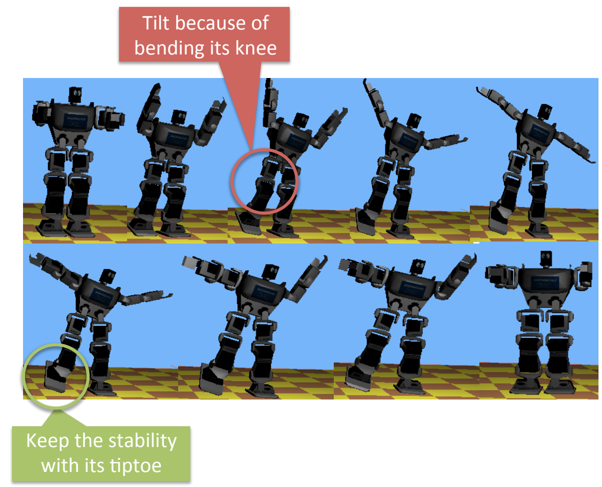

Fig. 8. The created imitation of student robot by separated method in stable experiment

shown in Fig.7. This manually created motion used four joints of the teacher robot. The imitation of the student robot derived from the conversion matrix evolved by the separated method is shown in Fig.8. The resulting arm motions were similar to the motion retrieved when using the similarity evolution. However, the motion of legs differed from both the teacher robot and those obtained using the conversion matrix evolved by the similarity method. We conducted experiments with the student robot to make the student robot not only in the simulator but also in the real world. We fed the imitation joint angles data which is shown in Fig.8 into the real robot. The Fig.9 shows that the real robot moved in the same way in reality as suggested in the simulation environment.

2) Unstable experiment: In the unstable experiment, we used the kicking motion of the teacher robot shown in Fig.10. This manually created motion used four joints of the teacher robot. It is much harder to remain stable during a kicking motion than a motion such as the one used in the stable experiment.

The converted imitation fell down just after the simulation has started when we used the similarity method in the unstable experiment. In an attempt to improve the stability, we tried the separated method and retrieved the result shown in Fig.11. The student robot was able to keep upright longer than when the similarity method was used, although the stability was slightly

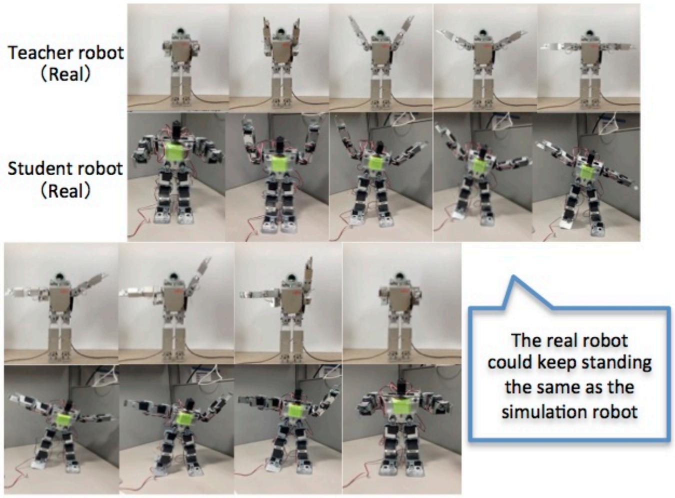

Fig. 9. Comparing motions between simulation robot and real robot in stable experiment

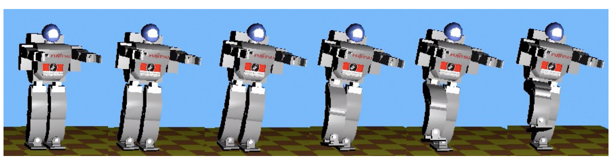

Fig. 10. The motion of teacher robot in unstable experiment

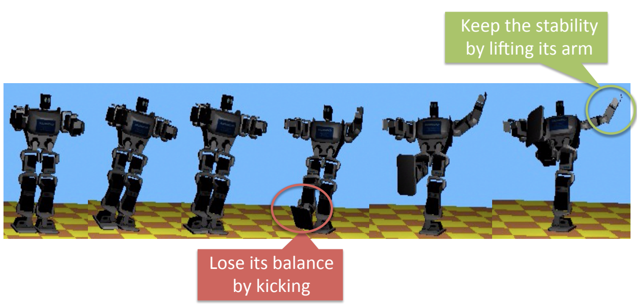

Fig. 11. The imitation of student robot by separated method in unstable experiment

worse than when the separated method was used in the stable experiment. As seen in Fig.11, the resulting motion from the unstable experiment brings the student robot to lift its arm, which means that the fitness value in terms of the similarity has decreased. However, unlike the teacher robot, the student robot can not lift one of its legs while keeping both arms straight because of its different structure. The student robot needs to keep its balance with its left arm raised in order to lift its right leg. Indeed, a sample motion that is attached to the student robot, KHR-2HV, also raises its left arm when it lifts its right leg. This fact shows the significance of the result of the unstable experiment.

The change of the concordance rate of training data in the unstable experiment is shown in Fig.12. Although the rate decreased during the stability evolution, the decrease was limited to a small percentage. As a result, the final concordance rate was 95.5%, which is slightly higher than that in the stable

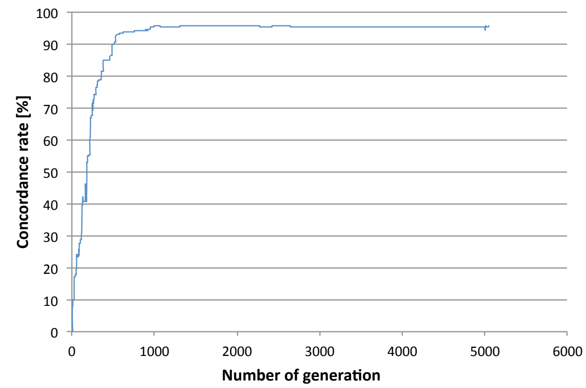

Fig. 12. The change of concordance rate in unstable experiment

experiment. The first column of the conversion matrix evolved by the separated method is shown in Table.II. This part of the conversion matrix converted joint angles of the teacher robot into joint 1 of the student robot. The ideal joint angle of the student robot, manually calculated was 0 degrees, while the converted angle was 0.06 degrees.

TABLE II. THE CONVERSION MATRIX AND CONVERTED ANGLE OF JOINT 1 OF STUDENT ROBOT IN UNSTABLE EXPERIMENT

Joint Num.	Teacher angle	Conversion matrix (First column)	Calculated angle
1	3.53	-0.10	-0.35
2	0.00	9.5	0.00
3	0.00	-0.70	0.00
4	0.00	0.45	0.00
5	7.06	0.55	3.88
6	-3.53	0.75	-2.65
7	0.78	0.05	0.04
8	0.00	-0.50	0.00
9	0.00	0.0	0.00
10	0.00	-0.40	0.00
11	7.06	-0.20	-1.41
12	-3.53	-0.20	0.71
13	0.78	-0.20	-0.16
14	0.00	0.15	0.00
15	0.00	-0.50	0.00
16	0.00	-0.60	0.00
17	0.00	-0.30	0.00
18	0.00	-0.80	0.00
19	0.00	-0.40	0.00
20	0.00	0.15	0.00
21	0.00	0.85	0.00
22	0.00	0.35	0.00
23	0.00	-0.30	0.00
24	0.00	0.55	0.00
25	0.00	0.45	0.00
Converted angle			0.06

The original joint angle data of the teacher robot, the ideal (manually calculated) joint angle data and the converted joint angle data of the student robot obtained from the separated method at one time step are shown in Table.III.

IV. DISCUSSION

In this paper, the student robot succeeded to imitate the teacher robot's motion by evolving the conversion matrix with GA. However, some joints moved unexpectedly in the converted motion imitation. Some movements were important for keeping the robots' balance, while others interfered with the robots to stand stably. There are two reasons for this.

TABLE III. THE JOINT ANGLE DATA OF STUDENT ROBOT IN UNSTABLE EXPERIMENT

Joint Num.	Student(Ideal)	Student(Converted)
1	0.00	0.18
2	0.00	-2.55
3	3.53	3.18
4	-7.06	-3.53
5	-3.53	0.00
6	-0.78	2.65
7	0.00	-2.82
8	-3.53	-1.41
9	7.06	8.30
10	3.53	6.88
11	-0.78	-1.94
12	90.0	94.6
13	0.00	1.06
14	0.00	-3.53
15	-90.0	-97.4
16	0.00	2.82
17	0.00	1.94

First, the fitness function may have been too simple to deal with this problem. In this paper, the expression (1) was used to calculate the fitness value in terms of the similarity. However, this expression minimizes the squared error, which is the most basic error estimation. Thus, it is hard to predicate whether or not this method is accurate. There probably exists another fitness function which can calculate the fitness value more accurately. Moreover, we used the time length that the robot kept standing as a fitness value in terms of the stability. However, this is also very simple and might not enough to check its stability. We have to find another fitness function, such as considering the center of gravity of the robot.

Second, the learning was insufficient. In this paper, we have only used one training motion for each task. Presumably, an increased amount of training motions would introduce a diversity in the learning that would lead to a better estimate of the conversion matrix.

Based on these, there are three problems that are interesting for future work.

First, it is important to find the proper parameters for GA, such as the probability of mutation. In order to inspect what values that achieve the best results, the conversion matrix should be evolved using as many different training motions as possible.

Second, we have to consider how to deal with the problem of joints that did not move in the original training motion. It does not seem strange for some joint angles to differ slightly from the training data. However, if the joint angles that did not move in the original motion starts to move in the motion converted by the conversion matrix the difference will be noticeable between the teacher robot's motion and the student robot's imitation. A difference in the joint angles of the legs also imposes a risk of falling. Thus, it is necessary to find a way to avoid giving mobility to joint angles which did not move originally.

A concrete method to realize this purpose is to impose penalties in the fitness function. This will give individuals that introduce a motion to originally stationary joints a lower fitness value and thus reduce their change of survival. However, moving joints which did not move in the manually constructed motion is not always a bad result. As shown in the unstable experiment, it is sometimes useful to move unexpected joints in order to keep the balance. This kind of conversion process is hard to obtain if human were to convert the joint angles manually. We have to consider a balance of both the similarity and the stability of the motion.

Finally, we need to increase the number of the joints that are used for motions. In this paper, the maximum number of joints we used was only eight. However, the real robots have around twenty degrees of freedom. Most of the robots used in the real world also have over eight degrees of freedom for its movement. To be use of practical use, this method needs to deal with a larger data of joint angles.

V. CONCLUSION

In this paper, we proposed a new method of motion imitation between two different types of robots. In order to convert the joint angles, we searched for the optimal conversion matrix using GA. For evolving the conversion matrix, we used three method; the similarity method, the mixed method and the separated method. In order to investigate which method is preferable for the objective to imitate motion with keeping the robot's balance, we conducted the stable experiment. The separated method showed the best result as expected. The obtained matrix was then used to map an unseen motion from the teacher robot to the student robot, which was able to imitate the motion satisfactory, both in the simulation environment and in a real world setting.

When the conversion matrix had been further evolved with the stability criteria using the separated method in the unstable experiment, the robot had also managed to find a way to keep its balance while performing the motion. Humans might be able to find a conversion matrix that converts the angles directly. However, it is difficult for humans to take the stability of the motion into account. For the robot to remain stable some unexpected joints motion might be required that is hard to find manally. It seems that only using the similarity evolution will not be enough to evolve satisfactory stability even if the number of chromosomes and iterations are increased. Thus, our proposed method that considered both the similarity and stability as fitness values could make good results to imitate motion while keeping its stability.

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