Performance Skill Acquisition of Handstand from Backward Giant Circle Using a Rings Gymnastic Robot

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Abstract—We have already proposed the “rings gymnastic robot” aiming at an application to gymnastic coaching. We have been also focusing on performance skill acquisition and obtained the skill of backward giant circle by using various models step by step. In order to apply the skills obtained by the robot to coaching, many skills collected by a three-dimensional model and experiments are required. However, a handstand has been only realized by two- and three-link models of the robot in two-dimensional plane. In this paper, the performance skill of handstand is newly acquired based on the three-dimensional model, as the next step.

I. INTRODUCTION

The rings event is one of men’s apparatus gymnastics. The ring exercises have the characteristics that the apparatus, namely rings, can move in all directions freely, i.e., free-floating characteristics at gripping point [1]. This is a different point from other gymnastic events and therefore its motion property is totally unique. The rings have been mainly studied in the field of biomechanics since the late twenty century. Chapman and Borchardt [2] have recorded the forces acting on gymnast’s hands during a backward giant circle. Such studies on rings mainly discuss the results obtained by motion measurements of actual gymnasts’ performances.

On the other hand, we have already proposed the “rings gymnastic robot” [3]. In the approach using the rings gymnastic robot, it is possible to analyze not only performances according to body type and characteristics for each gymnast but also feats that nobody has ever done, unlike the approach based on the above-mentioned motion measurements. The purpose of studies on the rings gymnastic robot is to understand ring exercises through the robot and to apply the acquired skill to gymnastic coaching. In other words, it is to acquire the performance skill through the robot and to transfer the skill from the robot to gymnasts (to improve their motions) respectively. In researches on the rings gymnastic robot, fuzzy control is adopted to control the robot. Because information on how to generate forces required in a performance is useful for the gymnastic coaching, as indicated in the area of sports biomechanics [4]. In addition, if the control strategy is represented as “if-then” rules, it is easy for gymnasts to understand the knowledge to realize the performance, as compared to reading the time-series data.

So far we have been mainly studying the skills acquisition, which is the first purpose of our research as mentioned above, of some performances. The performance skill of backward giant circle has been already acquired by using not only two- and three-link models of the robot in two-dimensional plane [3], [5], [6] but also a three-dimensional model considering arm abduction [7] step by step. On the other hand, the skill of handstand has been only obtained with the two- and three-link models [3], [5], [6] and it has not been acquired yet in the three-dimensional model. In order to apply performance skills to gymnastic coaching as the final objective, we further need to acquire skills of various performances by simulations based on the three-dimensional model and experiments.

From this fact, in this paper, we acquire performance skill of a handstand from backward giant circle by the three-dimensional model in an evolutionary manner as the next step. Note here that a backward giant circle and handstand are the compulsory requirements in the rings event, and therefore they are important performances. The performance skill is described by fuzzy control rules. Parameters of the fuzzy control rules are searched with a genetic algorithm (GA). In acquiring the handstand skill, fitness functions incorporating the joint angles throughout handstand are adopted from the viewpoint of the skill and appearance of handstand [8]. Finally, the effectiveness of the skill is illustrated by a three-dimensional animation based on simulation results.

II. THREE-DIMENSIONAL MODEL OF RINGS GYMNASTIC ROBOT

We have already proposed the three-dimensional model considering arm abduction of the rings gymnastic robot [7]. In this section, we show the model as shown in Fig. 1. In the modeling, torso and head (link 1), thigh (link 2), shank-foot (link 3), and arm (link 4) are assumed as one rigid link. Six degrees-of-freedom, that is, each two degrees-of-freedom (flexion/extension and abduction) at right and left shoulder joints and each one degree-of-freedom at hip and
knee joints can be driven. It is assumed that the robot’s motion is symmetric with respect to \( X-Z \) plane. \((x_1, z_1)\) is the coordinates of mass center of link 1, \( \theta_1 \) is the angle between \( Z \)-axis and link 1, \( \theta_2 \) is the angle of hip joint, \( \theta_3 \) is the angle of knee joint, and \( \theta_4e \) and \( \theta_4a \) are the angles of flexion/extension and abduction at the shoulder joint respectively. Note that \( \theta_3 \leq 0 \) is satisfied due to the characteristics of the knee joint and the angles at the shoulder joints rotate in the order of \( \theta_4e \) and \( \theta_4a \).

Letting the generalized coordinate be \( q = [x_1 \ z_1 \ \theta_1 \ \theta_2 \ \theta_3 \ \theta_4e \ \theta_4a]^T \), the dynamic equation of the model derived using the Lagrangian formulation is given by

\[
M(q)\ddot{q} + h(q, \dot{q}) + g(q) = Q, \quad (1)
\]

where \( M(q) \) is a \( 7 \times 7 \) symmetric mass matrix, \( h(q, \dot{q}) \) is a \( 7 \times 1 \) vector of centrifugal and Coriolis terms, \( g(q) \) is a \( 7 \times 1 \) vector of gravity terms, and \( Q \) is a \( 7 \times 1 \) vector of generalized force terms. Note that \( 2w_r \), a distance between the fixed points of rope, \( 2w_s \) is a length between right and left shoulder joints, \( \phi_1 \) and \( \phi_2 \) are rope angles, \( \tau_i (i = 2, 3, 4e, 4a) \) is input torque, and \( T_i \) is torque caused by an impedance at each joint and expressed as

\[
T_i = -k_i(\theta_i - \bar{\theta}_i) - b_i \dot{\theta}_i, \quad (2)
\]

where \( k_i \) and \( b_i \) denote a spring constant and a viscous damping coefficient respectively, and \( \bar{\theta}_i \) indicates an angle in a basic posture.

### III. Procedure for Acquiring Skill

Although this paper is focused on the handstand skill, a handstand from backward giant circle is adopted as the whole objective performance. In order to realize such a performance, it is divided into two basic exercises, i.e., a backward giant circle and a handstand. A fuzzy controller is prepared for each basic exercise. One of the controllers is selected according to the situation. Parameters of the fuzzy control rules are searched with a two-stage approach as shown in Fig. 2. In Fig. 2 \( k_h \) denotes the discrete-time instant at which the controller for backward giant circle is switched to that for handstand. In the first stage, parameters of the control rules for backward giant circle are obtained by the first GA. In the second stage, those for handstand are determined by the second GA. Here, a backward giant circle before handstand is performed by using the best controller acquired in the first stage. In this paper, the already obtained skill of backward giant circle [7] is used as the best one and rule parameters for handstand are only determined by the fitness functions proposed, because the objective performance is only handstand.

### IV. Control Rules for Handstand

The realization condition of handstand has been already proposed for a robotic motion in two-dimensional plane [3]. A motion in the above three-dimensional model is symmetric with respect to \( X-Z \) plane. Therefore, we can construct fuzzy control rules to do a handstand based on its condition.

As shown in Fig. 3, the angle between \( Z \)-axis and force vector \( F = [F_x \ F_z]^T \) acting on the robot’s mass center \( G \) is expressed as

\[
\psi = \arctan(2F_x, F_z). \quad (3)
\]

Also, the angle between \( Z \)-axis and a straight line connecting \((x_0, z_0)\) to \((x_g, z_g)\) is written by

\[
\psi' = \arctan2(x_0 - x_g, z_0 - z_g), \quad (4)
\]
A handstand can be realized if $\psi$ and $\psi'$ are equal. Therefore $s_h$ is given as one of the inputs to the antecedent part of the fuzzy reasoning. The input torque depends on the angle $\phi_1$ between Z-axis and the rope and on its rate $\dot{\phi}_1$ as well as $s_h$, so that $\phi_1$ and $\dot{\phi}_1$ are also given as the inputs to the antecedent part.

The fuzzy control rules on input torques $\tau_i$ ($i = 2, 4e$) to hip joint and flexion/extension at shoulder joint are described as follows:

- **Rule 1:** If $s_{ih}$ is $1^D_i$ and $\phi_{ih}$ is $1^E_i$ and $\dot{\phi}_{ih}$ is $1^F_i$ then $\tau_i = 1^c_i$ 
- **Rule 27:** If $s_{ih}$ is $2^D_i$ and $\phi_{ih}$ is $2^E_i$ and $\dot{\phi}_{ih}$ is $2^F_i$ then $\tau_i = 2^7_i$.

If all inputs are zero, the handstand is stable; in this case, the input torques have to be zero. In order to satisfy such a condition, a triangular and two trapezoidal functions shown in Fig. 4 are used as the antecedent membership functions for each input. The parameters of the membership functions for each input are tabulated in Table I. Note here that the antecedent grade is given as the product of the grade for each membership function.

Joint impedance is adjusted by changing the spring constant $k_i$ ($i = 2, 4e$) at each joint according to the following equation:

$$k_i = \begin{cases} \gamma_i |k_i| & \text{within range of motion} \\ k_i & \text{otherwise} \end{cases}$$

where $\gamma_i$ denotes a changing rate for the spring constant $k_i$. While doing a handstand, $\gamma_i$ is kept to be an output value from the controller for backward giant circle at the transition from backward giant circle to handstand.

### V. ACQUISITION OF RULE PARAMETERS WITH GENETIC ALGORITHM

In this section, we describe GA used to determine the parameters of control rules and deal with fitness functions in the GA. In order to consider the skill and appearance of handstand, we introduce the fitness functions incorporating the joint angles throughout handstand, as in the case of the three-link model [8].

#### A. Genetic algorithm

In GA, the number of individuals is 60. A uniform crossover is used with a crossover rate of 0.6 and a mutation rate is 0.01. A tournament strategy with 3 individuals is adopted in the selection. An elite strategy of 6 individuals is used in an alternation of generations.

In the fuzzy control rules for handstand, the consequent constants $1^c_i$ ($i = 2, 4e$), whose fuzzy labels are all Z in the antecedent part, are set to zero. Other 52 constants, i.e. $1^c_i-13^c_i$ and $15^c_i-27^c_i$, are determined with GA. The search spaces of these consequent constants are set in the range of $[-100, 50]$ for $i = 2$ and $[-50, 100]$ for $i = 4e$.

#### B. Fitness functions

In simulations in evaluation process of GA, the fuzzy controller for backward giant circle is selected at the beginning, and then it is switched to that for handstand at $k_h$. The handstand skill is evaluated successively while the controller for handstand is selected.

The fitness function is given by

$$f_h = f_{h1} + f_{h2},$$

where $f_{h1}$ denotes a stability of the handstand and $f_{h2}$ evaluates the joint angles throughout handstand. By minimizing this fitness function, we anticipate acquiring a desirable handstand from the viewpoint of not only its skill but also appearance.

$f_{h1}$ is written in detail by

$$f_{h1} = f_{h1}' + 10 f_{h1}'',$$

where

$$f_{h1}' = \frac{1}{k' - k_h + 1} \sum_{i = k_h}^{k'} |s_h(i)|$$

$$+ \max\{|s_h(k_h)|, ..., |s_h(k')|\},$$

and

$$f_{h1}'' = p.$$  

$f_{h1}'$ is the sum of the mean and maximum values of $|s_h|$, which represents a stability of the handstand. $f_{h1}''$ denotes a penalty in the case where the handstand is unsuccessful. On the other hand, $f_{h2}$ in (7) is further expressed by

$$f_{h2} = f_{h2}' + f_{h2}'', $$

where

$$f_{h2}' = \frac{1}{k' - k_h + 1} \sum_{i = k_h}^{k'} \{ |\theta_2(i)| + |\theta_4c(i)| \}$$

$$f_{h2}'' = \max\{|\theta_2(k_h)|, ..., |\theta_2(k')|\},$$

$$\max\{|\theta_4c(k_h)|, ..., |\theta_4c(k')|\}.$$
as a failure. In this case, $k_{fh}$ is satisfied until the maximum angles of hip and shoulder joints throughout handstand. $f_{h2}'$ denotes the biggest angle out of the maximum angles of hip and shoulder joints throughout handstand. $p$ and $k'$ in (9)–(13) are given as follows. If $|s_h(k)| > \pi/90$ [rad] is satisfied, then its handstand is treated as a failure. In this case,

$$p = (k_{fh} + 1) - k_p$$

$$k' = k_p$$

are used and calculation of the individual is stopped. Here, $k_p$ is the discrete-time instant at which the above inequality is satisfied and $k_{fh}$ denotes the predefined final discrete-time instant in simulation. On the other hand, if $|s_h(k)| \leq \pi/90$ [rad] is satisfied until $k_{fh}$,

$$p = 0$$

$$k' = k_{fh}$$

are given.

### VI. Simulation Results

In this simulation, physical parameters for rope shown in [3] were used. Physical parameters of the robot [9], range of motion for each joint [10], spring constants and viscous damping coefficients set in accordance with the angle for each joint [7] are shown in Tables II–IV, respectively. Note that the spring constants and viscous damping coefficients were adjusted by comparing the animation of the robot with the moving images of the actual gymnast’s performance. The Y-directional parameters related to the rope and the shoulders were given by

$$w_r = 0.25 \text{ [m]}, \quad w_s = 0.18 \text{ [m]}.$$

The angles in basic posture were set to $\theta_{iu} = 0$ [rad], $\theta_3 = 0$ [rad], $\theta_{le} = \pi$ [rad] and $\theta_{le} = 0$ [rad], because the objective performance is a backward giant circle and handstand. The simulation time was 5 [s] and the sampling period was 1 [ms].

The parameters of fuzzy control rules were optimized by genetic operations of 5000 generations. The simulation results performed by the obtained skill are shown in Fig. 5. The graphics sequence based on the results is depicted in Fig. 6. From these results, it is confirmed that the robot properly realizes a handstand from backward giant circle. The results also show that the realization condition for handstand is effective for the three-dimensional model as well as the two-dimensional one, i.e., two- and three-link robots. In addition, we reconfirm that the skill of backward giant circle acquired in [7] is appropriate for transition to handstand.

Figs. 7 and 8 show the simulation results and graphics sequences of performances in the evolutionary process of GA, respectively. The handstand is not realized for 3 [s] in Fig. 8 (a). Impossible shoulder motions are found in Fig. 8 (b). With the alternation of generations, the joint angles throughout handstand decrease. These results show that the fitness functions considering the joint angles work well for acquiring a
better handstand from the viewpoint of its appearance as well as skill.

VII. CONCLUSION

In this paper, the skill of handstand has been newly acquired using the three-dimensional model. The skill was described by the fuzzy control rules. The parameters of the rules were determined with GA. The fitness functions of the GA incorporated the joint angles throughout handstand to consider both of its skill and appearance. The simulation results showed that the acquired skill was effective for realizing a desirable handstand. The validity of the fitness functions was illustrated through the performances in the evolutionary process of GA.

We need the two stages in this case to determine the performance, i.e., a handstand from backward giant circle. For acquiring the same performance, we will try to use GA only once by constructing new fitness functions and anticipate getting more smooth transition from backward giant circle to handstand. Also, reduction of the number of the rules for handstand will be required, because it may be difficult for
Fig. 8. Three-dimensional graphics sequences of performances acquired in evolutionary process. (a)-(d) Genetic operations of 1, 20, 50 and 60 generations, respectively.

gymnasts to understand the 54 rules directly.

REFERENCES


