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Development of Biologically Inspired Educational Robots Based on Gliding Locomotion

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Abstract— **In this paper, two types of biologically inspired educational robots based on gliding locomotion are presented. Gliding locomotion utilizes the difference between two orthogonal reaction forces to propel. Since this locomotion principle is very interesting and difficult to intuitively understand, its way of locomotion effectively evokes intellectual curiosity of students. One actuated degree of freedom (DOF) fish-like educational robot and its lecture program are developed for primary, junior high and high school students. And a snake-like educational robot which can connect arbitrary number of units, and its lecture program are developed for university students. We carried out these programs through several lectures. The results are also discussed in this paper.**

I. INTRODUCTION

Although many educational robotics programs have been worked out to promote science and engineering education funded by governmental organizations such as Science Partnership Project, which is a cooperative educational program with secondary school and university in the field of science and technology in Japan [1], most of these programs merely assemble a commercialized robot kit with an instruction. Two wheeled differential driving mobile robots [2] and walking robots whose walking pattern were fixed and generated by linkage mechanisms are often used in those programs. Although these kits are very cheap and easy to purchase, their basic principle of movement and locomotion are very simple and less room to exercise creativity. Even if the robot is controlled by radio wave, it is very easy to learn how to control the robot.

On the other hand, LEGO mindstorms [3] permits a user to produce various configuration and mechanism, as well as to learn computer programming. However the kit is relatively expensive and thus it is difficult to provide it to each student. Moreover there is no chance to manufacture original parts by hands.

In this paper, we discuss two type of biologically inspired educational robots using gliding locomotion and lectures using them. Gliding locomotion defined in this paper is inspired by a serpentine locomotion of a snake and swimming motion of a fish using fins. Gliding locomotion can attract student's interest because it can generate faster locomotion than student's expectation. Moreover the basic locomotion principle is very interesting but difficult to intuitively understand. Thus gliding locomotion can stimulate student's intellectual curiosity.

Fig. 1. 1 actuated DOF fish-like educational robot "Gyotaro-IIIa"

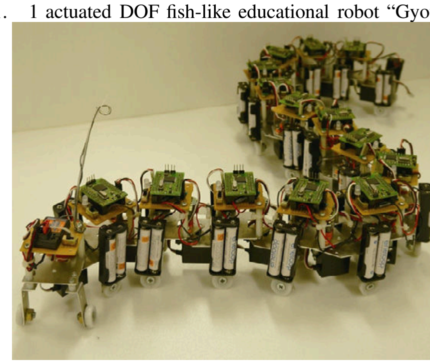

Fig. 2. Snake-like educational robot "ACM-E1"

We develop one actuated degree of freedom (DOF) fish-like educational robot (Fig. 1) for primary, junior high and high school students. We also develop a snake-like educational robot which can connect arbitrary number of units (Fig. 2) for university students.

II. GLIDING LOCOMOTION

In this paper, we define gliding locomotion is:

Propulsion utilizing the difference between two orthogonal reaction forces.

Here, the propulsion principle is explained by the simplest model of skating edge (Fig. 3(a)). While a skating edge has very low friction in the tangential direction, it also has very large friction in the normal direction. When a human applies periodical inner/outer lateral forces without lifting up the legs, a sagittal backward propulsive motion which is orthogonal to the applied force direction is generated (Fig. 3(b)). This propulsive motion can be achieved by the difference of two orthogonal reaction forces.

Gliding locomotion can be regarded as a kind of transmission mechanism because large force but small velocity

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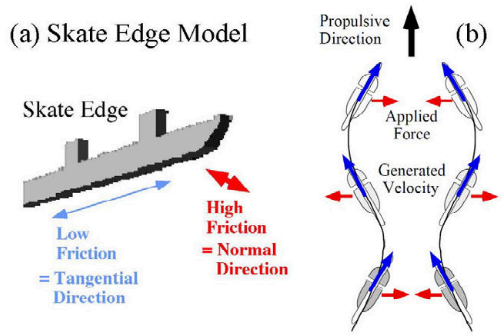

Fig. 3. Skate edge: (a)skate edge model, (b)backward propulsion without lifting up the legs (swizzle motion)

motion in the normal direction is transformed into high speed motion in the tangential direction which is less friction. The ratio of velocity increase is determined by the angle between the tangential direction and the propulsive direction, which is continuously variable. Moreover the mechanical structure, which permits the robot to have the reaction force difference, is very simple mechanism such as edge, passive wheel and fin. It is very important feature of engineering application. Additionally, this locomotion principle is not major in the ground locomotion vehicle, thus it can attract many people's curiosity. This feature is very suitable for children and students.

Gliding locomotion can be observed in serpentine locomotion of a snake, undulatory swimming of an eel and swimming of a fish. Gliding locomotion is also utilized by many mobile robots such as Active Cord Mechanism (ACM) [4], Roller-Walker [5], biped robot skating by swizzle motion [6][7] and Omni-directional vehicle using trocoid curve [8]. Notably, amphibious snake-like robot "ACM-R5" [9], which has passive rollers and solid fins along to the body axis, demonstrates ground locomotion as well as swimming in water using the same control algorithm.

Characteristics of gliding locomotion are summarized as follows.

1) The ratio of two orthogonal reaction forces determines necessary condition of propulsion
2) A kind of continuous variable transmission
3) Simple mechanism
4) Stimulating people's curiosity

Gliding locomotion largely depends on the difference of the two orthogonal reaction forces and absolute magnitude of the reaction force is not so much important. Rather than absolute magnitude, the ratio of two orthogonal reaction forces gives necessary condition of propulsion and characterizes the property of propulsion represented by propulsive force and velocity. Thus, gliding locomotion is effective on low friction surface such as ice. In our previous work, we demonstrated that snake-like robot "ACM-R1" can propel on ice with skating edges [10]. As for the property of continuous variable transmission, a relationship between propulsive force and velocity of roller-skating quadruped robot is particularly discussed in [5].

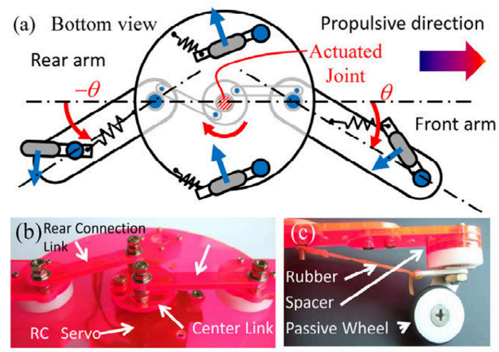

Fig. 4. Basic configuration: (a)structure (red hatched circle: active joint, blue circle: passive joint, servo motor is not shown here), (b)link mechanism, (c)passive caster

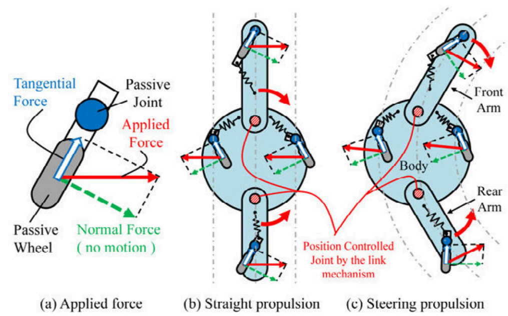

Fig. 5. Basic locomotion principle

III. Development of 1 Actuated DOF Fish-like Educational Robot

For primary, junior high and high school students, one actuated degree of freedom, fish-like educational robot named "Gyotaro-IIIa" is developed. The robot has only one actuator (servo motor), however an operator can control moving velocity and direction by controlling periodic undulation of the arm.

A. Basic Structure

Figure 1 shows overview of Gyotaro-IIIa. The robot consists of front arm, main body and rear arm. Each segment has passive caster(s) whose steering axis is sustained by passive compliance (Fig. 4(c)). (We use a rubber band as an elastic material because of the ease of purchasing and adjustment by students.) When the center link is rotated θ by a RC servo motor mounted under the main body, the front and rear arm are symmetrically moved (Fig. 4(a)) due to the connection links.

The nominal size of the robot is L335mm x W130mm x H70mm and its weight is 385g.

B. Locomotion Principle

Figure 5 indicates the force relationship. Let us think about a single passive wheel shown in Fig. 5(a). When the force is applied to the right direction (red solid vector), the force is decomposed into the tangential direction (white vector) and the normal direction (green dashed vector). Since the friction coefficient in the normal direction is large, the normal force is sustained by the reaction force from the ground, and only tangential component remains. This residual force drives the passive wheel in the tangential direction.

When the front and rear arm move right side, the main body is moved to left side due to Newton's 3rd law (Fig. 5(b)). All forces in the normal direction sustained by the reaction forces. As a result, the tangential forces drive the robot. If we control the right-and-left bending motion periodically, the robot moves straight in total. We can also control steering direction by introducing an offset to the desired direction, This control method is originally developed for the snake-like robot "ACM-III"[11] and commonly used to control Roller-Walker[12].

C. Detailed Design

It is very important for efficient locomotion to reduce backlash because this robot has only single actuator. Thus we investigated commercially available, low cost component for the passive joints and casters, and found that plastic ball bearings with a screw axis (TOK BEARING CO.,LTD) was the best. (This plastic ball bearing costs only one USD.)

For the initial prototyping named Gyotaro-III, we selected A5052 metal sheet for main structural material. However, it required special machining tools to modify the parts and was relatively difficult for the students. Thus we choose acrylic sheet, which also has color variation, for the main material. In order to make the robot modifiable, the front and rear arm are divided into three parts, and students can change the length of the arm. The height of the passive wheels is also adjustable by inserting spacers. This can modulate force distribution on each wheel. We manufactured these structural parts by a laser-cutting machine in our university's facilities.

A general radio control (RC) servo motor with metal gear (Grand Wind Servo Tech Co.,LTD.) is selected as main actuator, and it is controlled by radio wave transmitter. RC servo motor can be a good example to study servo mechanism and feedback control. As for transmitter and receiver, 1 channel is sufficient. However, we could not find appropriate cost effective one. Thus we choose the lowest price transmitter and receiver with 2 channels. We developed 25 robots in total and direct material cost to prepare for a kit was about 130 USD. Since radio wave transmitter and receiver cost 65 USD, we can reduce the total expense of the kit by selecting much cheaper control device such as infra-red communication device, if available.

D. Educational Program

Various educational program can be developed depending on the student age and study level. As for primary school children, maneuvering experience is a good introduction of robot technology. Adjusting the rubber length and strength by the students may improve the maximum velocity, and race competition will be exciting. As for junior high school students, assembling the whole robot is good for the students to learn how to use basic tools such as a screw driver and pliers.

In this section, we briefly introduce an educational material for high school students using Gyotaro-IIIa. Our motivation is to bridge regular classroom lecture of mathematics

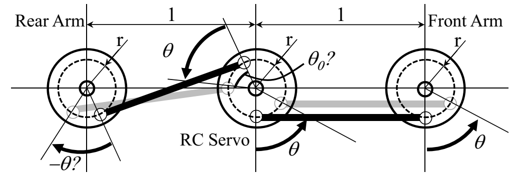

Fig. 6. Design problem for the rear link angle: θ_0 is initial joint angle for the rear connecting link, and gray links illustrate the front and rear arm rotation when RC servo rotates by θ.

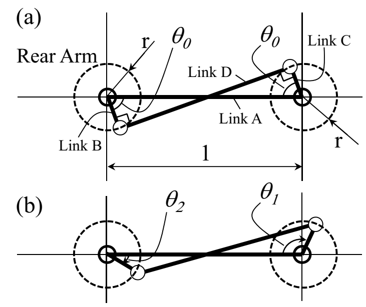

Fig. 7. Link geometry : (a)standard posture, (b)rotated posture

to concrete design problem. We would like the students to feel usefulness and importance of mathematics in solving a real world problem.

Ideally speaking, derivation of a relationship between input command (angle of the center link) and achieved velocity of the robot is the most suitable problem for this educational robot. However the derivation process is very complicated and it is far beyond ability of high school students. Thus we choose the design problem about link length and symmetry of bending angle between the front and rear arm for example, which is tractable for the high school students. Actually we calculated this problem to design link length and joint position, and evaluated symmetry at the beginning of mechanism design. It was essential to solve this problem in order to make this educational robot. The problem is as follows.

The front and rear arm are driven by a center link via connecting link. As for the front arm, the rotational angle θ is identical to the angle of the front arm because the linkage system is equivalent to a parallel four-bar linkage. However, as for the rear arm, the rotational direction should be opposite and the initial length of the connection link and its initial joint position θ_0 are not trivial. Moreover, the rotational angle of the rear angle is different from the center link angle [13], requiring a quantitative estimation of the error (Fig. 6).

These design problem can be postulated as following geometrical problems.

Link A, B, C and D are connected shown in Fig. 7. Assuming link B and D, C and D are orthogonal, respectively, and the length of link A, B, C are 1, r, r, respectively.

Q1: Derive the length of link D.
Q2: Derive the angle of θ_0.
Q3: Derive the relation between θ_1 and θ_2.

The link length l_D is calculated from the Pythagorean theorem.

$$l_D = \sqrt{1-4r^2} \tag{1}$$

θ_0 is given by inverse trigonometric function.

$$\theta_0 = \cos^{-1} 2r \tag{2}$$

Due to the geometrical constraint of this linkage system, the following equation about θ_1 and θ_2 should be satisfied.

$$(r\sin\theta_1 + r\sin\theta_2)^2 + (1 - r\cos\theta_1 - r\cos\theta_2)^2 = 1-4r^2 \tag{3}$$

By simplifying above equation, we obtain the following relation.

$$3r + r\cos(\theta_1-\theta_2) - (\cos\theta_1 + \cos\theta_2) = 0 \tag{4}$$

Directly solving Eqn.(4) about θ_2 gives the relation between θ_1 and θ_2. However it is complicated. Thus we introduce transformed variables $\alpha = (\theta_1+\theta_2)/2$ and $\beta = (\theta_1-\theta_2)/2$, and simplifying about α as following.

$$\alpha = \cos^{-1}\left(\frac{r(1+\cos^2\beta)}{\cos\beta}\right) \tag{5}$$

These mathematical calculation are tractable for high school students. Therefore above-mentioned questions can be very good exercises for high school mathematics.

To derive the actual length of the link, we have to calculate Eqn(1), Eqn.(2) and Eqn.(5) with concrete numerical values using a scientific calculator. However we didn't believe that all high school students have a scientific calculator. Thus we did a preliminary survey to high school students whether they had experienced using a spread sheet software (Microsoft Excel). Then it turned out that almost all of the high school students had already used a spread sheet software. Therefore the students can derive concrete numerical values using a spread sheet software without buying a science calculator.

The actual design value of the length between the center axis and the rear joint axis is $45mm$, the length of link B, C are $10mm$. Therefore, we obtain $l_D = 40.3mm$, $\theta_0 = 63.6deg$. In this case, the maximum angle error between $(\theta_1-\theta_0)$ and $(\theta_2-\theta_0)$ in the range of $-45 \le \theta \le 45deg$ is about $3.5deg$, which is sufficiently small, indicating the almost symmetric bending.

As we explained above, we can show the students that trigonometric functions and simplification of the equations are essential for the actual mechanical design problem even in such a simple linkage system. Moreover, this example also shows a way of numerical analysis and approximation, which is one of the most important aspect in engineering. In this section, we introduced a mathematics related educational material. Of course we can focus on physics using force and velocity vector as well.

IV. Development of a Snake-like Educational Robot with an Arbitrary Number of Units

This section describes a snake-like educational robot named "ACM-E1" for university students. The most remarkable feature of this robot is to connect arbitrary number of units.

A. Basic Concept

We started to design this robot for an annual seminar program organized by the Robotics Society of Japan. The expected participants were young university students or engineers in private companies studying robotics. This seminar was a paid seminar and we assumed total cost for the educational robot kit was about 65 USD, which was acceptable for many university students. The purpose of the seminar was to learn how to use a micro controller with input signals (sensors) and output signals (actuators). The participants could learn the basis of robotics by assembling a simple robot.

When we think about the cost limitation, available controller, sensors and actuators are inevitably limited. Especially number of actuators is utmost two. Therefore two wheeled differential mobile robots are widely used for the educational robots.

Here, we change our mindset. We propose not to make many small robots but to make ONE hyper-redundant snake-like robot by all participants (Fig. 2).

A planar snake-like robot with passive wheels such as [10] has serially connected equivalent units and it does not need to make a special heterogeneous unit. This property is suitable for carrying out a workshop from organizer's point of view. Moreover, one unit requires only one servo motor, which is cost effective and minimal set of input/output study using a micro controller. Each unit merely produces one DOF bending motion around the vertical axis, and can not produce propulsive force alone. However if we serially connect many units controlled by a very simple rule, the robot can produce sufficient propulsive force. This property is very academically attractive since this phenomenon is related to distributed control or subsumption architecture. Additionally, in order to understand serpentine locomotion, mechanical analysis is essential. Thus this robot can be a good introduction about an academic research for young students/engineers.

B. Control Architecture

A serpentine locomotion can be generated by shifting a desired bending angle from the front segment to the rear segment with a certain time delay[11][10]. Each joint angle is controlled by a micro controller mounted on each unit. Thus, it seems that electric communication between micro controller is essential. (We discuss the desired angle for the

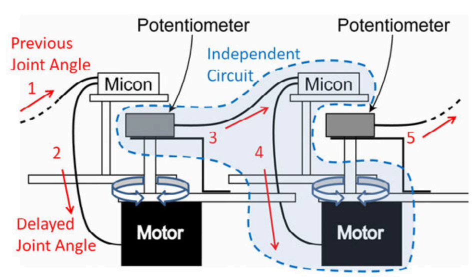

Fig. 8. Desired joint angle is transmitted through electrically independent circuits by physically connected potentiometers.

head unit later, because it receives desired bending angle by a radio control system.)

There are several communication standards between micro controllers such as RS232C, RS485, I2C, CAN and so on. However, in order to serially connect micro controllers, two communication ports are required, increasing the micro controller's cost. Moreover, electric cable connections also increase and we may need countermeasure against electric noise.

Therefore, we propose to make each electric circuit completely independent shown in Fig.8. Each unit is electrically independent but mechanically connected. Each unit measures the bending angle of the former unit by using a potentiometer powered by own electric source. The measured value is stored in the array of the micro controller program. Each unit tries to follow the angle of the former unit with a certain time delay.

This architecture does not require electric communications, cable connections and complicated software between micro controllers. Moreover we can connect an arbitrary number of units whenever we want.

We choose H8 micro controller (Akizuki, AKI-H8/3694F) and RC servo motor, which is the same as Gyotaro-IIIa, and total parts cost of the 1 DOF control system is about 45 USD.

C. Mechanical Design

The main structural parts consist of five parts (three kind of parts) using 1mm aluminum sheet shown in Fig. 9. Total cost of the mechanical parts for one kit by a external manufacturing company is 14 USD when we order 50 sets. Of course if we have sufficient time, it will be a good opportunity for the students to experience metal processing to make these parts. We also consider not to requiring a special tool to assemble the robot. This kit can be assembled by a standard tool kit like [14].

D. Desired Command for the Head Unit

In order to generate serpentine locomotion, the head unit has to make a periodic oscillatory movement. Of course micro controller can generate a sinusoidal oscillation for the head unit, but the robot can not be manually controlled. Thus, we decided to control the head unit by manual input via a radio control system. An operator manually generates oscillatory command. The steering motion is also achieved by adding an offset to the steering direction. Overview of the head unit is shown in Fig. 10.

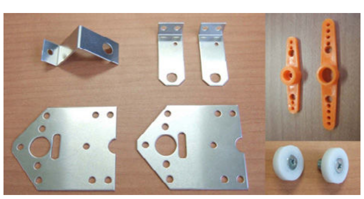

Fig. 9. Major structural parts for one unit

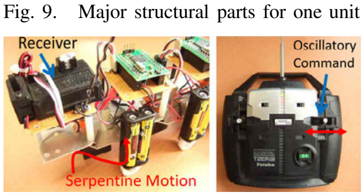

Fig. 10. Desired joint angle for the first segment to generate serpentine motion

V. Practice

A. Fish-like Educational Robot

So far, we have organized the demonstration of Gyotaro-III and Gyotaro-IIIa for primary and junior high school students. Over 500 students enjoyed controlling Gyotaro (Fig. 11). We also rend out them to external science museum in four different places for several weeks.

As for high school students, we organized five lectures and 70 students experienced assembling Gyotaro-IIIa so far. In this section, we report about the first lecture, taking place in a part of Super Robotics Program organized by Waseda prep school and our laboratory in 2011. The lecture consisted of two days. On the first day, the students focused on assembling. Then we asked the students to increase the maximum velocity of Gyotaro-IIIa during three days at home. After three days, we did a race competition.

Fig. 12-13 shows the robot which won the first and the second prize in the final competition. Fig. 12(left) has the longer front arm and Fig. 13(right) uses coil springs instead of rubber band.

Fig. 14 shows the final race competition. The maximum velocity depended on not only the performance of the mechanism, but also on the way of controlling such as oscillation amplitude or frequency. The maximum velocity of the normal kit was about 0.3 m/s. However, with elaborately tuned rubber bands and longer arm, the maximum velocity reached 0.9 m/s, suggesting that this robot has large potential to be improved.

B. Snake-like Educational Robot

We have conducted two lectures using snake-like educational robot. The first lecture was held in RSJ seminar entitled "How to make a robot" in 2009. The total time to make ACM-E1 was limited to 5 hours and 47 participants took the lecture. On the other hand, the second lecture was held as a series of 8 classes for freshman in Tokyo Tech., including laser cutting of the main mechanical parts, soldering of the micro controller. 23 students attended the lecture.

In this section, we report about the first lecture in RSJ seminar. Assembling practice consisted of (1)soldering a control circuit, (2)assembling the mechanical parts, (3)connecting multi-units and (4)maneuvering experiment. As for (1), each participant made an interfacing board using universal circuit board to connect micro controller, potentiometer and RC servo motor. We prepared printed instructions with many photos, and each participants did the soldering with his/her comfortable speed.

Fig. 11. Primary school students enjoy controlling Gyotaro

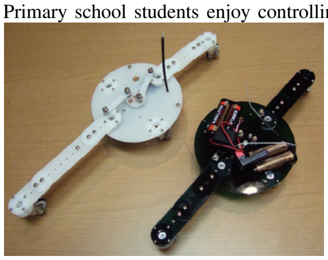

Fig. 12. The robot won the 1st place (right) and the 2nd place (left)

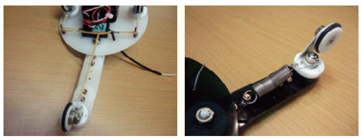

Fig. 13. Modification of the elastic elements

Since required time to finish all practice largely depended on the experience of soldering and assembling. The earliest participant finished within an hour, while the latest participant needed two hours. However, ACM-E1 could connect whenever new unit assembled. Connecting each unit naturally enhanced to communicate with each participants. Fig.15 shows that ACM-E1 gradually grew up as time advances. When the robot consisted of four units, the locomotion velocity was very slow. However as the number of units increased, ACM-E1 demonstrated smoother locomotion. Unfortunately, we could not connect all units due to time limitation, however, we successfully developed ACM-E1 with 24 units.

At the end of the seminar, many participants felt a sense of accomplishment and unity because we successfully made a hyper-redundant snake-like robot collaborating with all participants, suggesting ACM-E1 could successfully provide a valuable educational experience with the participants.

VI. Conclusion

In this paper, we presented biologically inspired educational robots based on gliding locomotion, which utilizes the reaction force difference between two orthogonal directions. The fish-like educational robot "Gyotaro-IIIa" has only one actuated degree of freedom, but we can control its moving speed and direction. The snake-like educational robot "ACM-E1" can be a hyper-redundant robot with an arbitrary number of units. By using these robots, the authors carried out lectures for primary, junior high, high school and university students.

We plan to commercialize these robot, and we can offer more detailed information for external educational organization. If you have interest, please contact us.

Fig. 14. Overview of the competition

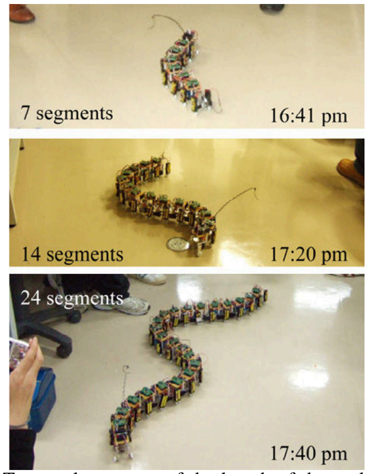

Fig. 15. Temporal sequence of the length of the snake-like robot

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