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Hybrid Dual Actuator Unit: A Design of a Variable Stiffness Actuator based on an Adjustable Moment Arm Mechanism

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Abstract—**For tasks requiring robot-environment interaction, stiffness control is important to ensure both stable contact motion and collision safety. The variable stiffness approach has been used to address this problem. We propose a hybrid dual actuator unit (HDAU) which is a novel variable stiffness unit design. The HDAU is composed of a hybrid control module based on an adjustable moment arm mechanism and a drive module with two motors. By controlling the relative motion of gears in the hybrid control module, position and stiffness can be simultaneously controlled for the same joint. The HDAU provides a wide range of joint stiffness due to nonlinearity obtained from the adjustable moment arm. The joint stiffness can be kept constant independent of the passive deflection angle of the output shaft. Furthermore, stable interaction can also be achieved because the joint stiffness is indirectly adjusted by position control of the hybrid control module. The characteristics of the HDAU are analyzed in this study. We show by experiment that the HDAU can provide a wide range of stiffness variation and rapid response for stiffness change.**

I. Introduction

In interactions between a robot and the environment, stiffness (or compliance) control is very important to ensure both stable contact and operational safety. Therefore, various research efforts have been directed toward the development of variable stiffness actuation devices [1]-[9]. Variable stiffness can be obtained from the stiffness control of a conventional robot composed of rigid joints and a force/torque sensor. The current of a motor installed at each joint is regulated to provide proper joint stiffness depending on sensor feedback. However, this approach suffers from limited system bandwidth due to the time delay associated with sensing, control, and communication [10]. Furthermore, the sensitivity of a force/torque sensor increases as the desired stiffness decreases, so instability often occurs and thus the minimum stiffness is limited [11] .

To address these problems, a variable stiffness approach based on a mechanical system has been proposed by many researchers. In this approach, joint stiffness is adjusted using passive elements such as springs so that high bandwidth and stable contact motion can be achieved. Furthermore, the control problem is simplified since interaction control is conducted using position control rather than torque control.

Although several types of variable stiffness mechanism have been proposed, the methods for implementing variable stiffness can be classified into two approaches. The first approach uses agonist/antagonist actuation inspired by the musculoskeletal system [1]-[3]. Two actuators are connected in parallel through a nonlinear spring, and the torque and velocity are simultaneously controlled by controlling the position difference between the two actuators. The variable stiffness actuator (VSA) [1] is the representative example for this approach. The second approach uses a variable stiffness mechanism composed of a main actuator and an auxiliary actuator [4], [5]. Position or velocity is controlled by a main actuator, whereas the stiffness is regulated by an auxiliary actuator with the variable stiffness mechanism. The variable stiffness joint (VS-joint) [5] is a good example of this approach.

A wide range of joint stiffness is required to execute a variety of tasks, and thus most variable stiffness actuator designs are focused on how to improve the stiffness range. Consequently, the feature of nonlinear stiffness is mainly used since it can achieve a wide range of stiffness. However, joint stiffness changes nonlinearly during contact motion, so the controller should adjust it by solving a series of nonlinear equations, or by finding an adequate value from a look-up table.

To address this problem, we propose a hybrid dual actuator unit (HDAU) which is a novel variable stiffness unit design based on the adjustable length of a moment arm mechanism. The HDAU consists of a hybrid control module and a drive module. In the hybrid control module, a modified planetary gear train with a rack-and-pinion mechanism is adopted to exploit the adjustable moment arm mechanism. The HDAU controls both position and stiffness of the output shaft simultaneously, depending on the angular position of the ring gear and carrier. The hybrid control module is connected to the drive module via gear trains so that the torque of each motor installed at the drive module is independently transmitted to the ring gear and carrier.

The HDAU features a wide range of joint stiffness

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irrespective of the external torques exerted on the output shaft. Maintaining constant joint stiffness for the same control parameter means that the output torque and the passive deflection angle are in a linear relationship, which is a more convenient way to control the contact force during contact motion. Furthermore, the compliance provided by the hybrid control module can improve the dynamic characteristics of the actuator unit.

The remainder of this paper is organized as follows: Section II describes the concept of an adjustable moment arm mechanism. Section III describes the hybrid control module. The prototype and experimental results are shown in Section IV. Finally, Section V gives our conclusions.

II. Variable Stiffness Mechanism

The link of a conventional robot is rigidly connected to a motor so as to provide high stiffness for improved position accuracy. This rigidity of the robot, however, is disadvantageous to controlling the contact force since the contact motion requires compliance. Therefore, a flexible joint mechanism, including a compliant element inserted between a link and a motor, has been proposed by some researchers. The VSA depicted in Fig. 1 is similar to a flexible joint mechanism, but the main difference is that its stiffness is adjusted by a variable stiffness mechanism (VSM). Joint stiffness k_j varies with control parameter α, which depends on the system. The passive deflection angle θ_δ, which represents the difference in angles of the position frame and the output frame, becomes nonzero when an external torque is applied to the output shaft. Since the features of the VSA mainly depend on the VSM, the characteristics of the VSM should be carefully considered according to specific applications.

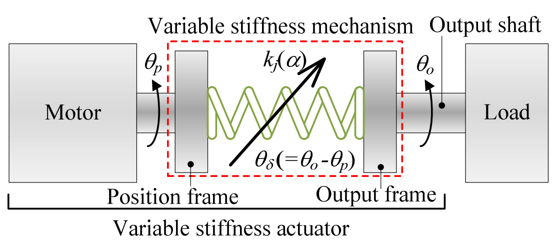

Fig. 1. Conceptual diagram of variable stiffness actuator.

A. Desired characteristics of VSM

Two types of desired characteristics of the VSM are shown in Fig. 2. To provide a wide range of joint stiffness, the joint stiffness k_j should vary nonlinearly with control parameter α as shown in Fig. 2(a). On the other hand, the joint stiffness should be constantly maintained when α is fixed even though the passive deflection angle θ_δ varies, as shown in Fig. 2(b). This θ_δ-k_j relationship helps make the control algorithm simple, but most VSAs are focused only on the α-k_j relationship.

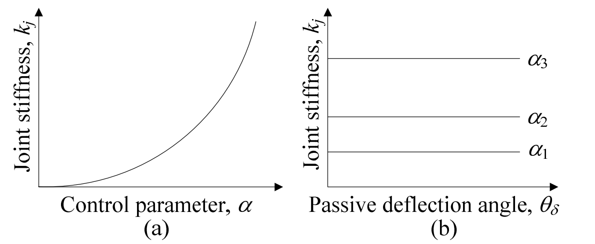

Fig. 2. Desired characteristics of variable stiffness mechanism. (a) α-k_j relationship, and (b) θ_δ-k_j relationship.

B. Principle of variable stiffness mechanism

The proposed VSM is capable of providing a joint stiffness independent of θ_δ as shown in Fig. 3. The VSM consists of a position frame, an output shaft fixed to a guide link, and two spring blocks. The linear compression spring installed at each spring block restricts the rotation of the output shaft relative to the position frame by pushing the guide link at both sides. The rotation angle of the position frame θ_p and the adjustable moment arm r are the control parameters associated with position control and stiffness control, respectively.

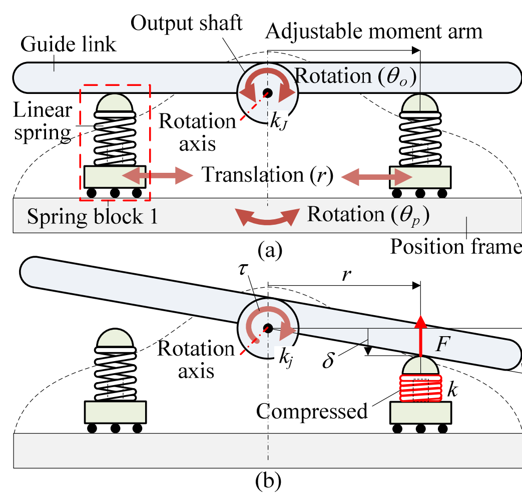

Fig. 3. Principle of variable stiffness mechanism based on adjustable moment arm: (a) initial state, and (b) rotated state.

Assume that the output shaft passively rotates by θ_δ due to an external torque τ, and that the spring blocks are placed away from the rotation axis by a distance r. Since $\tan\theta_\delta$ can be approximated as θ_δ for a small θ_δ, the deflection of the compressed spring δ is represented by

$$\delta = r\tan\theta_\delta \approx r\theta_\delta \qquad (1)$$

Then, the spring force F is given by

$$F = k\delta \approx kr\theta_\delta \qquad (2)$$

where k is the spring constant of the linear spring. Therefore, the joint stiffness k_j is given by

$$k_j = \tau / \theta_\delta \approx kr^2 \qquad (3)$$

because $\tau = kr^2\theta_\delta$. On the other hand, the position of the output shaft θ_o determined by both θ_p and θ_δ is represented by

$$\theta_o = \theta_p + \theta_\delta = \theta_p + \tau / k_j \tag{4}$$

Equation (3) indicates that the joint stiffness is proportional to r^2 and is also independent of the passive deflection angle θ_δ. This means that the desired characteristics described in Section II-A can be satisfied using the proposed mechanism.

III. Hybrid Control Module

A. Structure of hybrid control module

The hybrid control module, which is a mechanical structure for implementing the VSM based on an adjustable moment arm, consists of two spring blocks and an adjustable moment arm mechanism as shown in Fig. 4(a). The spring block consists of a linear compression spring, a linear motion block, and a roller follower. A modified planetary gear train with a rack-pinion mechanism is adopted in the adjustable moment arm mechanism.

Figure 4(b) shows the internal structure of the hybrid control module. By replacing the sun gear with dual rack gears, the dual rack-pinion mechanism and the planetary gear train are combined into a single structure. The planet gears were used for the roles of the planet gears and pinion gears at the same time. The two rack gears with their own spring blocks were symmetrically connected to the carrier through a linear motion guide system. Two internal ring gears were connected to the ring gear and the carrier, respectively, and they meshed with the driving gears attached to the motor shafts. Therefore, two motors included in the drive module, described in Section IV-A, were connected independently to internal ring gears 1 and 2, and their torques transmit to the ring gear and the carrier through power transmission paths 1 and 2, respectively, as shown in Fig. 4(b). From the combined motion of the carrier and ring gear, the spring blocks move inward (or outward) and rotate CW (or CCW). For compact design, the carrier parts consisting of the carrier, the internal connector, and internal ring gear 2 are nested in the ring gear parts consisting of the ring gear, the outer connector, and internal ring gear 1.

The internal motions of the hybrid control module are illustrated in Fig. 5. If the ring gear rotates CW while the carrier maintains its initial position, the planet gears rotate CW due to the relative motion of the ring gear and the carrier (II), as shown in Fig. 5(a). As a result, the spring blocks move outward (III). On the other hand, if both the ring gear and the carrier rotate by the same angle in the same direction (i), then the spring blocks rotate around the center of the mechanism without any translation (ii), as shown in Fig. 5(b).

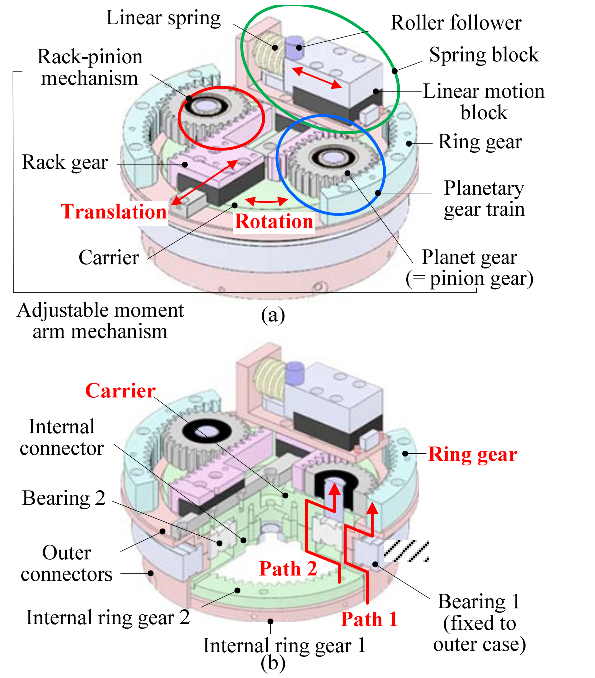

Fig. 4. Hybrid control module. (a) Front top view, and (b) partial cross-sectional view (one spring block is omitted).

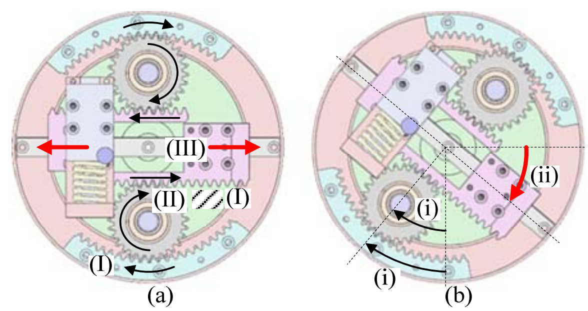

Fig. 5. Internal motions of hybrid control module. (a) Translation output, and (b) rotation output (one spring block is omitted).

B. Control of hybrid control module

Figure 6 shows the simplified hybrid control module. r_i, r_c, r_r, and r_p are the initial length of the moment arm, the radius of the carrier, the radius of ring gear, and the radius of planet gear, respectively. Assume that the carrier and ring gear rotate θ_c and θ_r, respectively, and θ_r is larger than θ_c. Because the carrier acts as the position frame of the VSM as explained in Section II-B, θ_c is equal to θ_p from Eq. (4). Therefore, the position of the output shaft θ_o is given by

$$\theta_o = \theta_c + \frac{\tau}{k_j} \tag{5}$$

where τ is the external torque and the k_j is the joint stiffness. If there is no external torque, the last term on the right side of Eq. (5) disappears.

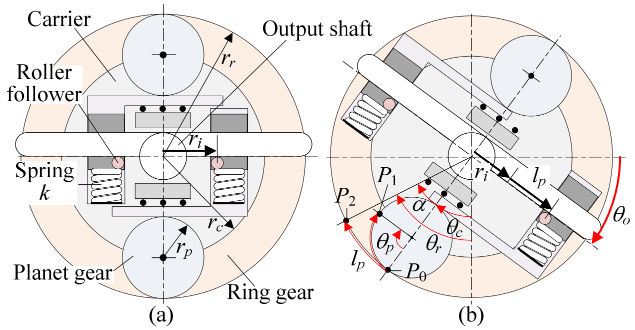

Fig. 6. Control of hybrid control module. (a) Initial state, and (b) simultaneous position and stiffness control.

To calculate the joint stiffness, the internal motions of gears in the hybrid control module must be investigated. First, we replace θ_r with $(\theta_c + \alpha)$. The motion of the hybrid control module can then be divided into two steps: the first step is pure rotation of the hybrid control module by θ_c, and the second step is the pure translation of the spring block in proportion to α. To satisfy the geometric constraints, the translation of the spring block l_p is equal to the length of arc P_0P_1 $(= r_p\theta_p)$ and the length of arc P_0P_2 $(= r_r\alpha)$. Since $\alpha = \theta_r - \theta_c$, l_p can be obtained by

$$l_p = r_p\theta_p = r_r\alpha = r_r(\theta_r - \theta_c) \tag{6}$$

By replacing r from Eq. (3) with $(r_i + l_p)$, the joint stiffness of the hybrid control module is represented by

$$k_j = k(r_i + r_r(\theta_r - \theta_c))^2 \tag{7}$$

within the boundary condition for θ_c and θ_r given by

$$r_{\min} < r_i + r_r(\theta_r - \theta_c) < r_{\max}$$
$$\text{or} \quad \frac{r_{\min} - r_i}{r_r} < \theta_r - \theta_c < \frac{r_{\max} - r_i}{r_r} \tag{8}$$

where $r_{\min}$ is the minimum length of the moment arm related to the radius of the roller follower, and $r_{\max}$ is the maximum length of the moment arm associated with the diameter of the ring gear. For example, assume k=1000 N/mm, r_i=10 mm, and r_r=40 mm. If the desired position and joint stiffness of the output shaft are 10° and 5x10^5 N·mm/rad, respectively, the desired angle of the carrier θ_c is 10° from Eq. (5), and the desired angle of the ring gear θ_r is 27.7° from Eq. (7).

IV. Experiments using HDAU

A. Prototype of HDAU

A prototype of the hybrid dual actuator unit (HDAU) based on the adjustable moment arm mechanism shown in Fig. 7 was constructed to experimentally examine its performance. This prototype consists of the hybrid control module and the drive module. Two die cast springs were used in the hybrid control module, and their spring constants are 190 kN/m. The minimum and the maximum length of the moment arm are 3 mm and 24 mm, respectively. The drive module contains two 60 W DC motors with their own gear reducers with a gear ratio of 33:1. The total gear ratio is 99:1 since the gear ratio of the driving gear to the internal ring gear is 3:1. Two encoders were installed at motors 1 and 2 and their resolution with the gear reducer is 1.8x10^{-3} °/pulse. One additional encoder with a resolution of 9.0 x10^{-3} °/pulse was externally attached to the output shaft to measure its actual position. Table 1 shows the specifications of the HDAU.

A DSP (TMS320F2812) was used for position control of the two motors using motor drivers (Maxon ADS50/10). A PID control scheme was adopted for accurate position control. Both motors were controlled at a sampling rate of 1 kHz. To investigate the characteristics of the HDAU, a force/torque sensor (JR3, IFS-90M31A50) was also installed.

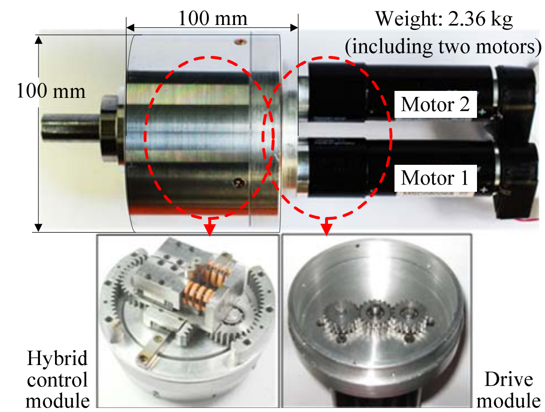

Fig. 7. Prototype of HDAU.

Table 1 Specifications of HDAU

Hybrid control module only	
Max. allowable torque	50 N·m
Size	100 mm (*D*) x 100 mm (*L*)
Weight	1.8 kg
Max. deflection	± 30°
Stiffness range	0.07 ~ 2.2 N·m/°
Including drive module (two 60 W dc motors)	
Max. continuous torque	8.5 N·m
Max. speed	360°/s
Size	100 mm (*D*) x 258 mm (*L*)
Weight	2.36 kg

B. Experiments

- Stiffness control

Among various performance measures, the stiffness range and response time required to vary the stiffness are the most important factors in evaluating the variable stiffness actuators. Figure 8 shows the experimental setup used to investigate their performance. The HDAU was attached to the horizontal frame, and the output link of 26.5 cm was connected to the output shaft of the HDAU. As the output link rotated due to the external force, the joint torque of the HDAU and the passive deflection angle of the output link were simultaneously measured by the force/torque sensor and the external encoder connected to the output shaft, respectively.

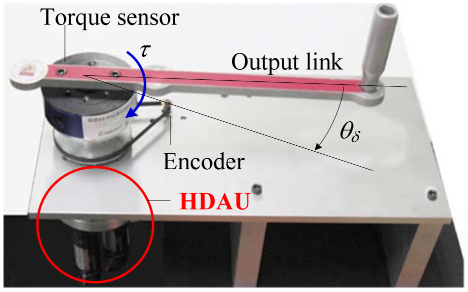

Fig. 8. Experimental setup using HDAU.

As explained in Section II, the joint stiffness of the HDAU can be adjusted by controlling the length of the moment arm. The relationship between the output torque and the passive deflection angle was measured for every 3 mm of r within the boundary condition, as shown in Fig. 9. The solid lines represent the measured data and the dotted lines represent the curve-fitted data using a linear function. Experimental results show that the joint torque of the HDAU is linearly proportional to the passive deflection angle. A small amount of hysteresis was observed when the external torque was applied or released. These problems seem to be related to the friction between the internal parts of the HDAU. Therefore, an adequate compensation method based on the rotational direction of the output link is needed to minimize these errors.

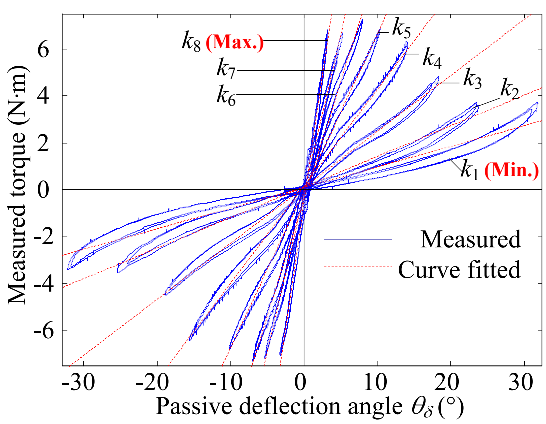

Fig. 9. Passive deflection angle-torque relationship.

Figure 10 shows the joint stiffness variation for different lengths of the moment arms. The measured data of the joint stiffness were approximated using a second-order polynomial and the theoretical joint stiffness was obtained using Eq. (3). The measured joint stiffness shows a good agreement with the theoretical joint stiffness, and the ratio of maximum stiffness (2.154 N·m/°) to minimum stiffness (0.068 N·m/°) is as high as 32.

The response time for stiffness variation can be examined by measuring the length of the moment arm, as shown in Fig. 11. About 140 ms is required from the minimum to the maximum stiffness, which is reasonably fast for practical applications.

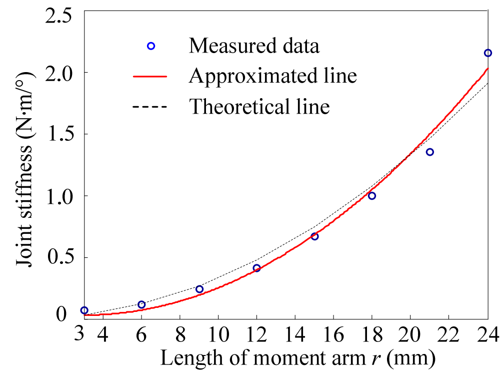

Fig. 10. Joint stiffness variation.

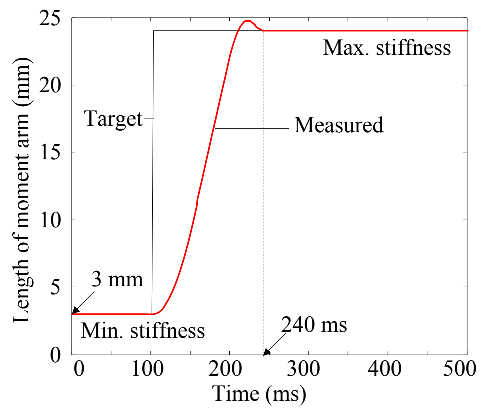

Fig. 11. Step response for stiffness variation.

- Position control

To investigate the performance of position control, the step responses for an amplitude of 90° were investigated for the minimum and the maximum joint stiffnesses. As shown in Fig. 12, the oscillatory response lasted about 2 s for the minimum joint stiffness, and disappeared within 0.5 s for the maximum joint stiffness. This experimental result demonstrates the behavior of the compliant actuator. If the link is rigidly connected to the motor shaft, the maximum velocity of the link is limited to the maximum motor speed. However, the link velocity can be higher than the motor speed in the specific region (Fig. 12-B) when the compliant element exists between the link and the motor, because the elastic energy stored in the compliant element is converted to kinetic energy.

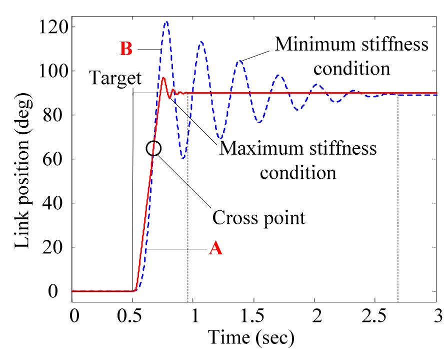

Fig. 12. Step response for position control.

- Playing darts

Figure 13 shows a demonstration of playing darts with the HDAU. A 32 cm link was installed at the output shaft of the HDAU. The diameter of a dart board was 20 cm and the distance to the board was 1.8 m. To ensure a long flight of the dart, both the speed and the angle of departure were carefully determined. Maintaining the same angle of departure, the dart was thrown at both the maximum and the minimum joint stiffness. The dart could reach the dart board with the minimum joint stiffness, as shown in Fig. 13(b). This is similar to the human motion of throwing. A person makes the arm compliant while increasing the speed of the hand as fast as possible at the point of the throw. This observation supports the suggestion that a compliant actuator can improve the performance of the dynamic motion of the system.

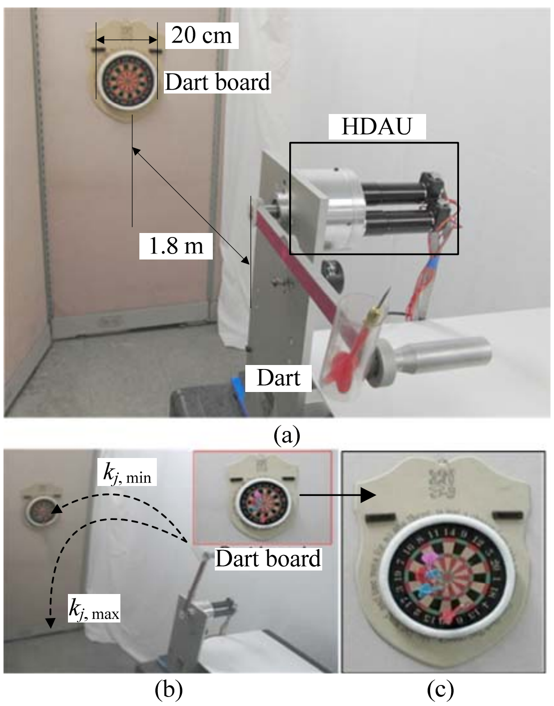

Fig. 13. Playing darts with the HDAU: (a) experimental setup, (b) throwing dart, and (c) enlarged dart board.

V. Conclusion

A variable stiffness unit called a hybrid dual actuator unit (HDAU) was proposed to enable position and stiffness control to be conducted simultaneously for the same joint. The characteristics of the HDAU were analyzed, and both the variable stiffness range and the response time were investigated through a series of experiments. The following conclusions are drawn from these results:

(1) The HDAU can control position and stiffness simultaneously for the same joint by exploiting the hybrid control module.

(2) The HDAU can provide stable interaction since joint stiffness is indirectly adjusted through position control of the ring gear and carrier.

(3) The HDAU is capable of generating variable stiffness in the range of 0.068 to 2.154 N·m/°. The response time required for stiffness variation is about 0.14 s, which is reasonably fast for practical applications.

(4) The HDAU can maintain the joint stiffness irrespective of the passive deflection angle of the output shaft. This feature is advantageous in controlling the contact force during contact motion.

The HDAU proposed in this study can be used for a variety of applications requiring stable contact motion and dynamic motion such as robot manipulators.

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