

Weight Estimation of the Sea Cucumber (*Stichopus japonicas*) using Vision-based Volume Measurement

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Abstract – Growth analysis and selection of sea cucumbers (*Stichopus japonicas*) is typically performed through length or weight measurements. However, because sea cucumbers continuously change shape depending on the external environment, weight measurement has been the preferred approach. Weight measurements require extensive time and labor, moreover it is often difficult to accurately weigh sea cucumbers because of their wet surface. The present study measured sea cucumber features, including the body length, width, and thickness, by using a vision system and regression analysis to generate R^2 values that were used to develop a weight estimation algorithm. The R^2 value between the actual volume and weight of the sea cucumbers was 0.999, which was relatively high. Evaluation of the performance of this algorithm using cross-validation showed that the root mean square error and worst-case prediction error were 1.434 g and ± 5.879 g, respectively. In addition, the present study confirmed that the proposed weight estimation algorithm and single slide rail device for weight measurement can measure weights at approximately 4,500 sea cucumbers per hour.

Keywords: Sea cucumber, Weight, Volume, Vision system

1. Introduction

The lengths and weights of marine animals are typically measured to determine growth and to select individuals. Weight measurements by scale are the most popular approach [1]. The weight measurement method requires frequent calibrations — i.e., taring the scale — and often hinders accurate and rapid measurement because of the webbed surface of the measured object.

To improve these methods, previous studies measured the lengths [2-5] and areas [6-7] of fish in two-dimensional images generated by a computer vision system; fish selection and weight estimation were then conducted. Lee et al. (2001) performed three-dimensional measurements and restructured a two-dimensional cross-section photography scan into a three-dimensional surface using charge coupled device (CCD) cameras and a multi-line laser [8-9]. In addition, it is possible to calculate the area of an oyster body using the cubic splines method [10] to estimate weight. However, unlike other marine animals, the sea cucumber (*Stichopus japonicas*) changes its shape into a football-like [11] or globular structure when it shrinks [12]; moreover, its shape is irregular when it is fully extended. Thus, it is difficult to apply the existing method of weight estimation by measuring the body length (BL), body width

(BW), thickness (T), and view area [13]. In Japan, the body size of the sea cucumber is measured after the administration of *l*-menthol anesthesia. However, because this method cannot be easily applied at practical sites, Yamana and Hamano derived a regression equation that uses a digital still camera to measure the BL and BW of the sea cucumber at any given time; it then converts the BL and BW to the image that is equivalent to its anesthetized condition [14]. Yingst formulated the size index (SI) = $BL \times BW$ to determine body size of the sea cucumber [15]. Moreover, Mitsukuri proposed an equation that facilitates calculation of the sea cucumber's body size using its square length and width [16]. However, the above calculation methods are inaccurate because they include no information on the thickness of the sea cucumber; rather, they are simply based on observations of shape changes in which the animal gradually becomes slender, during its extension. Body volume of the animal seems to be relatively stable during body extension; however, the influence of water storage in its respiratory tree remains to be clarified [14].

Existing measurement methods using sea cucumber volume or weight are impractical when a large quantity of farm-raised sea cucumbers are to be measured, particularly in a short time period; a substantial amount of time and labor are required for accurate measurements. Therefore, to generalize their ever-changing shapes, quickly and accurately analyze their growth or select them at any given time, a technology that automatically estimates sea cucumber weight is required.

The purpose of this study was to develop an algorithm that estimates sea cucumber weight by measuring its

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features, which include *BL*, *BW*, *T*, and volume, using the image processing technology of vision system. To simply perform the measurement of the sea cucumber — instead of using the existing method of measuring its *BL* and *BW* — it was assumed that the early shape of the sea cucumber in air is a half oblate ellipsoid. Therefore, the volume of the sea cucumber was measured using the *BL*, *BW*, and *T*, which were measured at the time of sample, and by using the volume equation for a modified ellipsoid. Accordingly, regression analyses of the calculated and actual volumes of sea cucumbers were performed for optimization. For optimal design of the weight estimation algorithm, regression analysis was conducted on each feature of the sea cucumbers against the weight, and the R^2 value and regression equation were examined. To confirm the validity and performance of the final weight estimation algorithm, replicates were performed using the single slider rail, which was produced in a laboratory-sized system for the present study.

2. Material and Methods

2.1 Experimental animals: Sea cucumbeber

In January 2014, 350 sea cucumbers (weight range: 0.23–92.56 g) were collected by divers from the southern coast of Korea. The depth of the sampling location did not exceed 11m and the seawater temperature at the time of sampling was 13.8 °C. The sea cucumbers were transferred to the nearby laboratory of the Aquaculture Management Division and maintained in a tank, which was equipped with flowing 100 μm filtered seawater at ambient temperature (14 °C). All animals were starved for 24 h before the experiment to minimize the effect of excretion on weight.

2.2 Measurement of actual volume and weight

Actual volumes and weights of sea cucumber measurements were obtained using a density meter (Shinko Denshi Co., Ltd., DME-220) and digital balance (A&D Co., Ltd., ER-180A), respectively, after blotting the water on the external surface of the animals using a paper towel. The average of the actual volumes and weights were obtained after 20 replicate measurements. Using Archimedes' theory, the actual volumes were measured by applying to Eq. (1) the weights of the sea cucumbers in air and in distilled water, and the water density of the distilled water. The water density in this study was considered as 1, because the density of pure water is 0.997 g/cm³ at room temperature (25 °C) [10].

$$Actual\ volume = \frac{weight\ in\ air[g] - weight\ in\ water[g]}{density\ of\ water[g/cm^3]} \quad (1)$$

2.3 Image processing to measure *BL*, *BW* and *T*

Fig. 1 shows an image-processing flowchart for measuring the *BL*, *BW*, and *T* of the sea cucumber based on the vision system.

As shown in Fig. 1(a), preprocessing involved capturing images of the sea cucumber, which were projected by the backlights of the CCD cameras installed at the bottom and sides of a tank to measure the sea cucumber features. The brightness information of the black-and-white images was then converted to an 8-bit gray scale. At that point because the *BL*, *BW*, and *T* should be measured after removing the sea cucumber thorns [14], 8-bit gray scale-based images were converted to 9×9 matrix structure images by performing a closing calculation using morphological image processing to partially remove the thorns in the images [21]. Finally, in the binarization process and based on the 60 level, the pixel brightness was converted to a range between 0 and 255 to improve clarity of the edge lines in the 8-bit projected bottom and side images. The base coordinate system was then configured to each output image. As shown in Fig. 1(b), to measure the *BL*, *BW*, and *T* of the sea cucumber after preprocessing, the closed curve was detected from the projected bottom and side images; the center point and angles of the closed curve area were then extracted, whereby a base coordinate system was drawn.

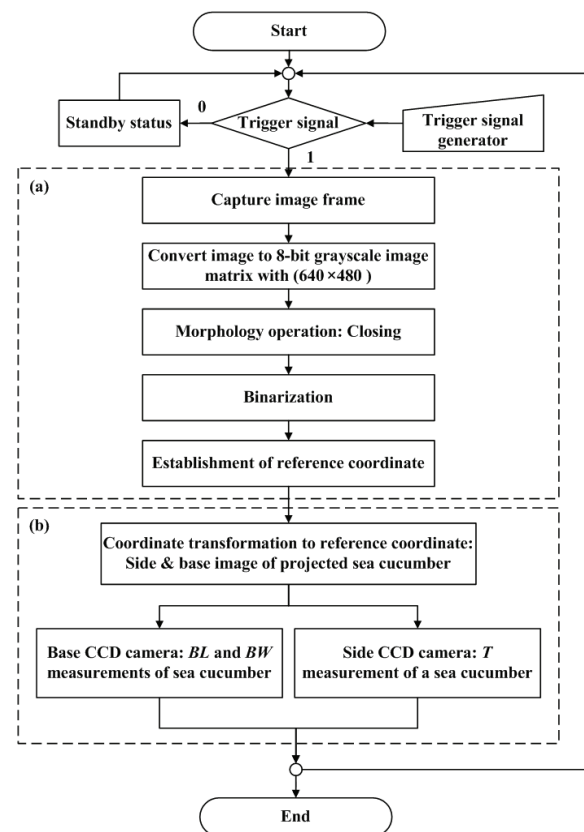


Fig. 1. Image processing flowchart: (a) preprocessing; (b) measuring process.

Fig. 2 shows images captured while measuring the BL of the sea cucumber. The BL of the sea cucumber was measured from the estimated centerline in the projected bottom image. The measurement process was as follows:

- 1) As shown in Fig. 2(a), the circular and linear patterns were extracted from the bottom image of the sea cucumber, which was projected on the x - y plane; the bottom image was scanned from the outside to the center point of the area. Then, 100 edge points were extracted.
- 2) Of the extracted edge points, as shown in Fig. 2(b), the left coordinate (x_0, y_0) and right coordinate (x_9, y_9) , which were the farthest from the area's center point, were selected.
- 3) The x coordinate area of the selected two points, $x_0 - x_9$, was divided by eight to obtain a straight-line equation ($x = x_1, x_2 \dots x_8$). Then, as shown in Fig. 2(c), the center coordinates $(x_1, y_2), \dots (x_8, y_8)$ of the edge points, where brightness was considerably different on the straight

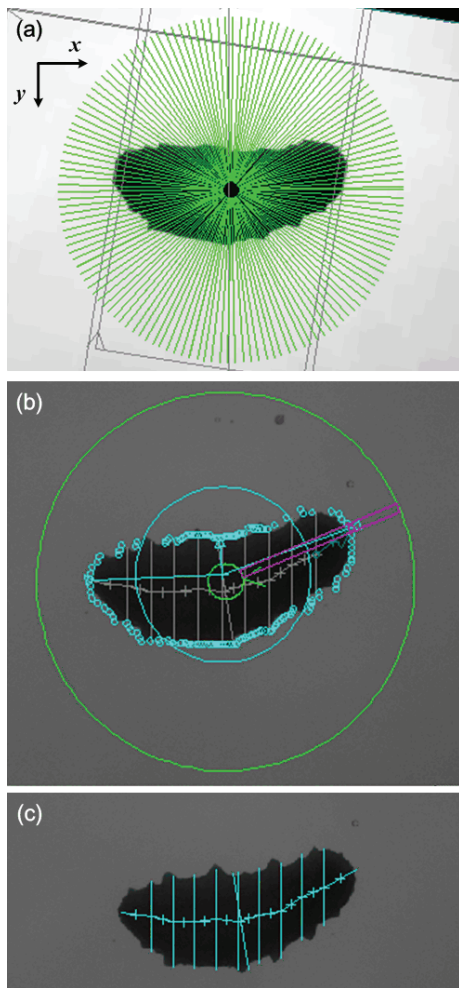


Fig. 2. Process of measuring sea cucumber BL : (a) detection of edge points; (b) detection of the left and right coordinates that are the farthest from the center point; (c) connection of the detected coordinates.

- line, were detected.
- 4) The BL of the sea cucumber was measured by applying each detected coordinate to Eq. (2).

$$BL = \sum_{i=0}^9 \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \quad (2)$$

Fig. 3 shows the image captured in the sea cucumber BW measurement process which was as follows:

- 1) As shown in Fig. 3, in reference to the center point angle in the bottom image, in which the sea cucumber was projected on the x - y plane, the straight-line equation passing the center of gravity was detected.
- 2) The two edge points, whose brightness levels were substantially different on the straight-line were detected to measure the sea cucumber BW .
- 3) The distance between the coordinates of the two edge points was then designated as the BW .

Fig. 4 shows the image captured in the process of measuring the sea cucumber T . Fig. 5 shows the thickness errors according to measurement points observed while moving a 10 mm regular hexahedron standardized specimen along the y -axis. The measurement point was at the area center point of the sea cucumber's bottom image.

As shown in Fig. 5, measuring thickness using CCD cameras, in general, led to variations because of the perspective between the point of the measured specimen and the CCD camera installed at the side. Hence, an additional modification process was required for this study. To minimize variations when measuring T , the linear regression analysis between the location of the sea

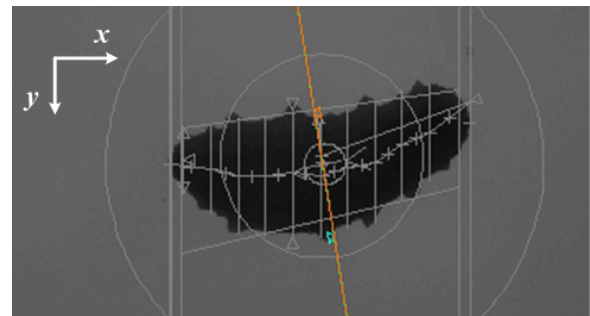


Fig. 3. Measurement of sea cucumber BW .

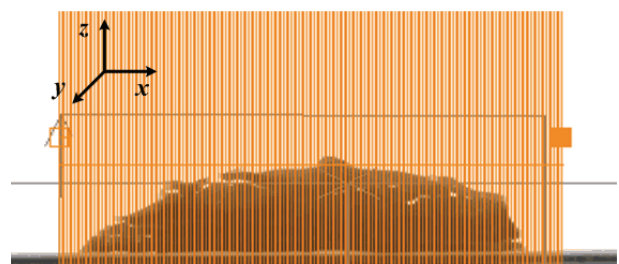


Fig. 4. Measurement of the sea cucumber T .

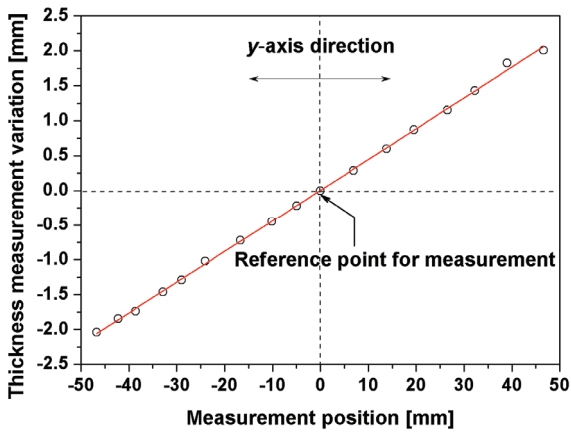


Fig. 5. Variations in thickness according to measurement points.

cucumber and the measured T was performed. The revision equation was derived, as shown in Eq. (3), where t is the measured thickness of the sea cucumber; y is the location of the sea cucumber; and α and β are regression coefficients, which were 0.044 and 0.009, respectively.

$$T = t - (\alpha \cdot y + \beta) \quad (3)$$

The process of measuring sea cucumber T was as follows:

- 1) As shown in Fig. 4, 100 edge points were detected in the side image. The sea cucumber was projected in the x - z plane by scanning the image from white to black in the direction of the center of gravity using the straight-line pattern.
- 2) Of the detected 100 edge points, the farthest edge point from the x - y plane and center of gravity — i.e., the location of the sea cucumber from the bottom image of the sea cucumber projected on the x - y plane — were simultaneously detected.
- 3) The sea cucumber T was measured by the distance between the detected edge point and x - y plane, and it was calibrated as shown in Eq. (3).

The sea cucumber shrinks to a half oblate ellipsoid at its maximum as it is handled in the air. Thus, assuming that the early shape of the sea cucumber is a half oblate ellipsoid, as shown in Figs. 2, 3, and 4, the BL , BW , and T were simultaneously measured using the vision system. They were then calculated using Eq. (4), which is a modified ellipsoid equation. The actual volume (A_v) and calculated volume (C_v) were compared and verified through linear regression analysis using Eq. (5), where α and β are regression coefficients.

$$C_v [\text{cm}^3] = \frac{\pi}{6} \cdot BL \cdot BW \cdot T \quad (4)$$

$$A_v [\text{cm}^3] = \alpha \cdot C_v + \beta \quad (5)$$

2.4 Regression analysis for designing a sea cucumber weight estimation algorithm

For design optimization of the sea cucumber weight estimation algorithm, regression analyses on the measured BL , BW , T , and A_v , and on the C_v were performed based on the assumption that the sea cucumber form is a half oblate ellipsoid. The R^2 and regression equation were then obtained. The power curve regression model was used for the regression analyses of the BL s, BW s, and T s against the weights; the linear regression model was used for the actual sea cucumber volumes against the weights.

2.5 Experimental systems

We produced a vision system-based device (size: 600×500×1300 mm) for measuring sea cucumber features, BL s, BW s, T s, and volumes, as shown in Fig. 6. The vision system (PV-200, Panasonic) and CCD cameras were installed at the bottom and sides, respectively, to capture two-dimensional images of the bottom and sides of the sea cucumber. These images were projected on the two-dimensional plane. In the opposite direction of each CCD camera, a 30 W infrared backlight was installed to generate a silhouette of the sea cucumber. A data collection device (National Instruments, cDAQ-9174) was installed to collect the visual information required to measure the BL , BW , and T and to calculate the volume, based on LabVIEW software (version: LabVIEW 2013, National Instruments).

Fig. 7 shows the single slide rail system for measuring sea cucumber weights that we produced in a laboratory

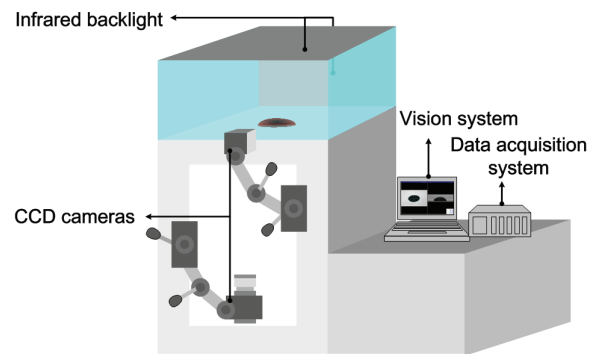


Fig. 6. Device for measuring sea cucumber features.

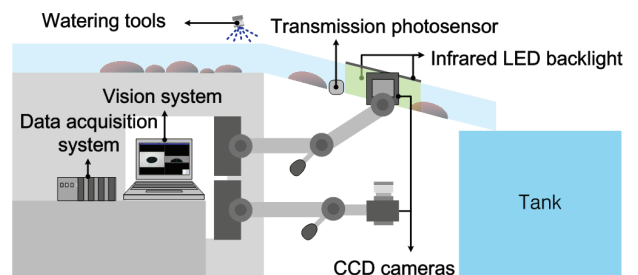


Fig. 7. Single slide rail device for measuring sea cucumber weights.

size to verify the performance of the optimized sea cucumber weight estimation algorithm through repeated testing. The system components were the same as those of the sea cucumber feature measurement device, except for the addition of an installed photosensor (Autonics Co., LTD, BYS500-TDT) that generates trigger signals to automatically capture images. The weight of each sea cucumber whose respiratory tree was emptied of water in advance was measured by dropping it in the single side rail linked to the tank. At that point, the optimized algorithm for sea cucumber's weight estimation was used to continuously measure the weights of sea cucumbers moving in the rail.

3. Results and Discussion

3.1 Repeatability of measurement

The inspection or measurement method of a certain object based on images leads to respective inspection or measurement errors depending on the brightness of lighting and external environments. Therefore, the repeatability of the designed algorithm for sea cucumber features was measured to verify its reliability. After selecting standardized regular hexahedron specimens with a regular surface (dimensions: 10×10×10 mm), their lengths, widths, and heights were simultaneously measured 300 times within an interval of a second under the same measurement conditions.

Fig. 8 shows the results of 300 measurements of the standardized regular hexahedron specimens. Table 1 indicates the mean, standard deviation, and coefficient of variation of the features. As a result, the means,

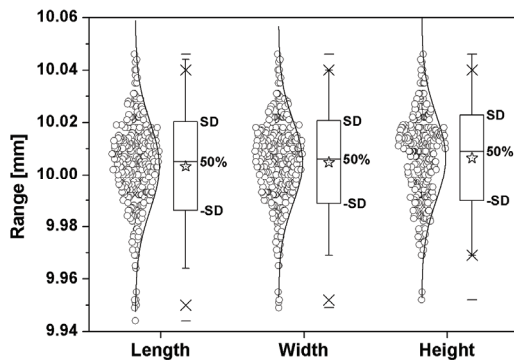


Fig. 8. Test results of repeated measurements of the standardized regular hexahedron specimens.

Table 1. Results of measurements: mean, standard deviation, and coefficient of variation

Features set	Mean [mm]	SD [mm]	CV [%]
Length	10.002	0.017	0.170
Width	10.003	0.016	0.160
Height	10.004	0.016	0.160

standard deviations, and coefficients of variation were within 10.004 mm, 0.017mm, and 0.170%, respectively, thereby confirming high repeatability.

3.2 Design of sea cucumber weight estimation algorithm

For optimized design of the sea cucumber weight estimation algorithm, regression analyses were performed on the *BLs*, *BWs*, *Ts*, actual volumes, and calculated volumes — where sea cucumber form was assumed to be a half oblate ellipsoid — against the sea cucumber weights.

Figs. 9 through 11 show the correlations of the *BL*, *BW*, and *T* against the weight. Each correlation was nonlinearly distributed. The power curve regression model was used to examine the regression equation and R^2 value, as shown in Table 2. Here, y denotes weight, x represents the measurement item, and α and β are regression coefficients. The test results confirmed that the R^2 values of the *BL*, *BW*, and *T* against the weight of the sea cucumber were all

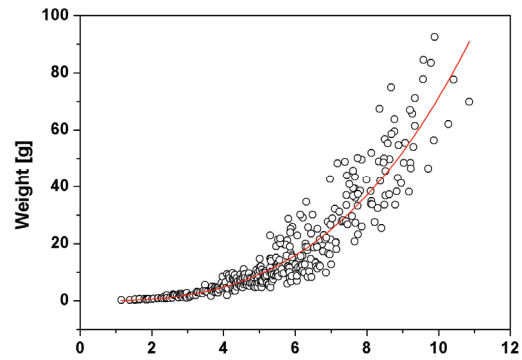


Fig. 9. Plot of power curve fit of weight compared with *BL* and weight.

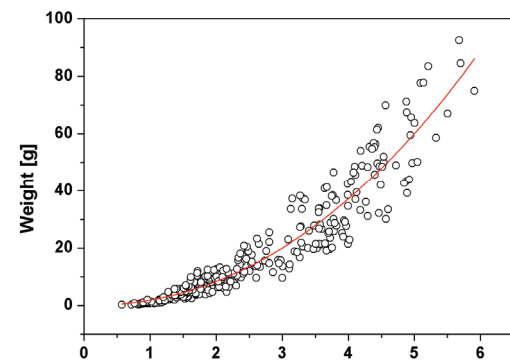


Fig. 10. Plot of power curve fit of weight compared with *BW* and weight.

Table 2. Equation fit result for sea cucumber weight compared to *BL*, *BW*, and *T*

Equation: $y = \alpha \cdot x^\beta$	<i>BL</i>	<i>BW</i>	<i>T</i>
α	0.081	1.876	4.135
β	2.945	2.154	2.694
R^2	0.871	0.904	0.925

>0.871, where the R^2 value between the T and weight was rather high (0.925).

However, Figs. 9, 10, and 11 suggest that the smaller size of the sea cucumber indicates a smaller weight deviation. Thus, the larger the size of the sea cucumber is, the bigger the weight deviation is, implying that a bigger error would occur in estimating the weight of a large sea cucumber. In addition, the weight against the BL , BW , and T was nonlinear; therefore, a more precise measurement technology would be required when classifying sea

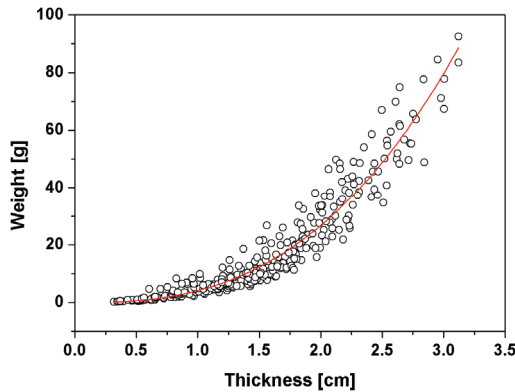


Fig. 11. Plot of power curve fit of weight compared with T and weight.

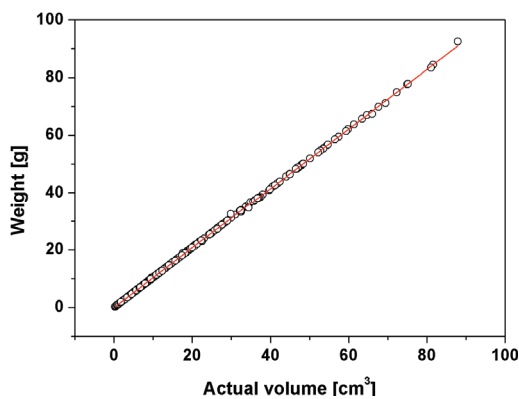


Fig. 12. Plot of linear fit of weight compared with A_v and weight.

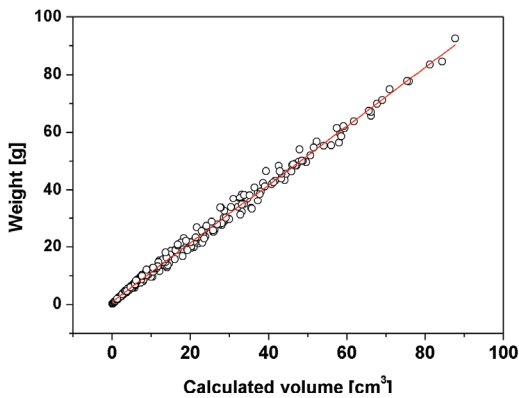


Fig. 13. Plot of linear fit of weight compared with C_v and weight.

cucumbers according to their weights.

Figs. 12 and 13 show the correlations between the actual volume and calculated volume where the sea cucumber was assumed to be a half oblate ellipsoid. Each correlation was linearly distributed. The regression equation and R^2 value were investigated using the linear regression model, as shown in Table 3.

The R^2 value between the actual volume and weight was 0.999, which was relatively very high. The R^2 value between the calculated volume and weight was 0.995, which was likewise high. The results of comparing each regression equation confirmed that the differences in the slope and y -intercept were approximately 0.017 and 0.944, respectively.

As shown in Fig. 14, we ran a linear regression analysis using Eq. (5) to compare and verify the correlation between the actual volumes and calculated volumes.

The coefficients of variation α and β were 0.984 and 0.912, respectively, where the R^2 value was 0.995. The regression analysis, where β was 0, showed α and R^2 were 1.010 and 0.997, respectively. Thus, the regression equation slope and R^2 between the actual volume and calculated volume were both close to 1. Moreover, the R^2 value was also high. Based on this finding, we confirmed that there was no significant difference between the actual volume and the calculated volume in experimental range.

The results of performing the regression analyses of the BL , BW , T , A_v , and C_v against weight confirmed that the method of measuring the actual sea cucumber volume was effective in estimating sea cucumber weight. Therefore, using the regression equation between the actual volume and weight, as shown in Table 3 and Eqs. (4) and (5), and the algorithm — which estimates sea cucumber weight by measuring its volume (Eq. (6), where C_1 and C_2 denote

Table 3. Equation fit result for sea cucumber weight compared to A_v and C_v

Equation: $y = \alpha x + \beta$	A_v	C_v
α	1.036	1.019
β	0.013	0.957
R^2	0.999	0.995

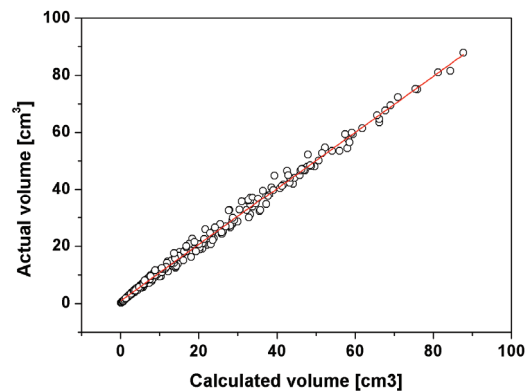


Fig. 14. Plot of linear fit of weight compared with C_v and A_v .

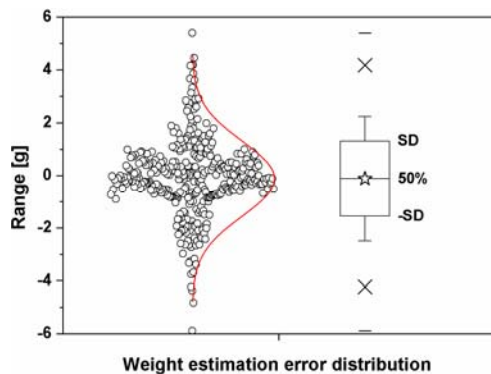


Fig. 15. Sea cucumber weight prediction error distribution, evaluated by leave-on out cross-validation.

the constants calculated with the regression coefficients between the actual volume and weight and between the actual and calculated volume)—the C_1 and C_2 of our experiments were determined to be 0.534 and 0.958, respectively.

$$\text{Weight}[g] = C_1 \cdot (BL \cdot BW \cdot T) + C_2 \quad (6)$$

The performance of this algorithm was evaluated through leave-one-out cross-validation [22, 23], moreover, as shown in Fig. 15, the root mean square error and weight estimation error spread were 1.434 g and ± 5.879 g, respectively. These findings prove that the accuracy of this algorithm improved compared to that of existing estimation methods that measure three-dimensional projected volume of the fish [24, 25]. It was confirmed that the developed weight estimation algorithm and single slide rail system for weight measurement can weigh approximately 4,500 sea cucumbers per hour.

4. Conclusion

Regression analysis between each feature and the weight of the sea cucumber to estimate weight showed that the correlation between the actual volume and weight of the sea cucumber was high. The proposed algorithm was shown to estimate the weight of sea cucumbers by measuring their volumes using the vision system. This method calculated the volume of the sea cucumber by assuming its early form as a half oblate ellipsoid; moreover, it proved to be more convenient than existing measurement methods in which the line laser and vision system were combined. Moreover, optimization was performed through linear regression analysis between the calculated and actual volume of the sea cucumber.

The developed sea cucumber weight estimation algorithm can rapidly and accurately measure the growth of sea cucumbers that are raised within the recently developed integrated multi-trophic aquaculture (IMTA) system; facilitates automated management. The proposed algorithm

shows potential applications to the selection of sea cucumbers.

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