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Note

A digital stereo-video camera system for three-dimensional monitoring of free-swimming Pacific bluefin tuna, *Thunnus orientalis*, cultured in a net cage

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Abstract – We used a digital stereo-video camera system for three-dimensional monitoring of cultured Pacific bluefin tuna, *Thunnus orientalis*, swimming freely in a net cage. We estimated the fork length and length frequency distribution of individual fish using the direct linear transformation (DLT) method. Information obtained from stereo images is useful for managing the growth of tuna during rearing. Our aim was to develop a simple method involving a combination of DLT and commercial image-processing software to enable aquaculturists to obtain three-dimensional measurements of fish. In this study, we used a stereo-video camera system to evaluate the precision and validity of fish size estimates determined from repeated measurements. Of the total assessed individuals swimming within a distance of <5.5 m from the camera system, estimates for 99% (106/107) were found to be valid, with an error ratio (standard error/mean) of <5%. Therefore, we believe that our proposed simple method for monitoring free-swimming fish could be very useful for aquaculture management.

Key words: Three-dimensional monitoring / Pacific bluefin tuna / Stereo-camera / Aquaculture / Direct linear transformation (DLT) method

1 Introduction

For fish cultured in net cages, managers of fisheries industries need information about fish size and length frequency distribution to manage the growth of fish during rearing. This information can be obtained from stereo images.

In recent years, fish size measurement techniques using stereo-video cameras have been developed (Harvey et al. 2002, 2003; Costa et al. 2006). Harvey et al. (2003) also used this method to measure fork length of southern bluefin tuna in a net cage. Furthermore, Costa (2009) developed a stereo-video camera system, with an artificial neural network tool, for counting tuna stock during their transfer to aquaculture cages. A method of stereo-video analysis has also been used for marine and fisheries research projects in the open sea (Watson et al. 2005, 2007; Williams et al. 2010).

The direct linear transformation (DLT) method (Adbel-Aziz and Karara 1971; Hartley and Zisserman 2004; Ikegami et al. 1991) is widely applicable to monitoring in various situations, and has been used for underwater 3-D monitoring research (Takahashi et al. 2006; Wang et al. 2008). We are trying to develop and improve the DLT method of three-dimensional fish size measurements of free-swimming tuna by using a commercial image-processing software program (Move-tr/3D, Library Co.) in an aquaculture net cage.

Takahashi et al. (2006) investigated the validity of underwater monitoring using the DLT method, and reported that the distance between two objects can be estimated with sufficient precision without using non-linear distortion compensation parameters; although an estimate of the 3-D world coordinate position of a certain object is improved by including non linear distortion compensation. Therefore, we used the DLT method without non-linear distortion compensation parameters for recording fish fork lengths.

As soon as the recording of stereo-video images under the sea began, calibration procedures were performed using a 3-D cubic calibration target. It was then possible to calculate three-dimensional positions of each point in all images using the equations of DLT parameters determined in our method. Such a method can, therefore, be used practically by aquaculturists to monitor the growth of tuna during rearing.

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The purpose of this study was to develop the monitoring method that could be operated by aquaculturists for the cultured Pacific bluefin tuna, *Thunnus orientalis*, using a stereo-video camera system, particularly focusing on the fork length and length distribution. We evaluated the validity of the fish size estimates from images recorded using a stereo-video camera system, in order to confirm the potential of our simple method of monitoring non-captured fish in aquaculture for growth management purposes and for investigating wild species in the ocean.

2 Materials and methods

We monitored Pacific bluefin tuna cultured in a net cage (diameter: 30 m, maintained by TAFCO Co.) located off Kashiwa-jima island, Kochi prefecture, Japan (Lat. 32° 46.76 N, Long. 132° 37.83 E). The monitoring research was conducted on February 7 and July 27, 2010, using a digital stereo-video camera system set up under the sea by three ropes from a boat fixed to a net cage. The stereo-video camera system comprises two digital video cameras (HDC-SD100, Panasonic) in underwater housings mounted on a stainless steel frame; the two cameras are spaced 30 cm apart, forming a stereo pair. The stereo-video images of free-swimming tuna in the aquaculture net cage were recorded at 29.97 frames per second (fps) for 5 min at depths of 2, 4, 6, 8, 10, and 12 m. Light intensities were simultaneously measured at 0, 2, and 12 m with Pendant light loggers (Hobo, Onset Co.) to check whether the underwater illumination was sufficient for monitoring.

At the beginning of the recording of the stereo-video images, calibration procedures were performed using a 3-D cubic calibration target of 60 cm length. This made it possible to calculate the 3-D positions of each recorded point in all the images using the equations of DLT parameters determined with the least squares method. The DLT equations are basically expressed as follows (Hartley and Zisserman 2004):

$$u = \frac{L_1X + L_2Y + L_3Z + L_4}{L_9X + L_{10}Y + L_{11}Z + 1} \quad (1)$$

$$v = \frac{L_5X + L_6Y + L_7Z + L_8}{L_9X + L_{10}Y + L_{11}Z + 1} \quad (2)$$

where u and v are the x-y positions of a certain point in the 2-D camera coordinate system, and X, Y, and Z are the positions in the 3-D world/camera coordinate system, respectively. L_1-L_{11} indicate the DLT parameters of each camera.

To calculate the 3-D coordinate positions from the two 2-D stereo-images recorded simultaneously by the two side cameras, the DLT method was used, consisting of two equations including 11 DLT parameters of each camera. To achieve this, it is necessary to know the 3-D positions of more than six calibration points (or so-called control points) in the world coordinate system, without using the camera constant parameters such as the focal distance of the lens, camera distance, and angles of the camera axis.

In this research project, we analyzed the images using commercial image-processing software (Move-tr/3D, Library Co.). From eight control points, we determined the DLT parameters and evaluated the accuracy of calibration. We could, therefore, use the DLT method to calculate the 3-D position of each point from two stereo camera images. The three-dimensional positions of the snouts and tail forks of individual tuna could then be calculated from the stereo images.

Based on the continuous time series data in 20 frames (29.97 fps) of the fork lengths of the same individuals, mean values, standard errors (SE), and error ratios (SE/mean) were calculated to evaluate the precision and accuracy of the calculated fork lengths of tuna individuals recorded during the trials in February and July.

We considered these estimates were appropriate since the error ratios were within the level of precision requested by the aquaculturists, and so went on to determine the length frequency distributions of the cultured tuna. Furthermore, we compared our results with the estimated fork length distributions and fork lengths of tuna captured and directly measured by aquaculturists as test samples, in order to confirm the validity of our estimated tuna fork lengths in these terms.

3 Results

3.1 Calibration of images recorded by a stereo-video camera

Based on the calibration results on known 3-D coordinate positions of eight control points of a 60-cm cubic 3-D calibration target at a distance of 2.5–3.1 m from the camera system, 11 DLT parameters of both cameras and the precision and accuracy of estimated 3-D positions could be determined. The mean and standard deviation (SD) of errors between calculated and known 3-D coordinate positions of eight control points of the 60-cm target in the calibration experiments in February and July were determined to be 0.84 cm (<2%) ± 0.56 cm and 0.46 cm (<1%) ± 0.34 cm, respectively. Since the 3-D positions could be estimated using the DLT method within the 5% error precision required by the aquaculturists, the precision and accuracy of the calculated positions were found to be sufficient to provide fish size estimate information for managers of fisheries and aquaculture industries.

3.2 Stereo monitoring of tuna fork lengths

The measurement interface and results of the 3-D stereo-video images of tuna recorded by right and left side cameras on February 7 are shown in the upper photographs of Figure 1. The positions of the snouts (1, 2 and 3) and tail forks (4, 5 and 6) were marked in three individual tuna. Using the DLT method, these positions could be calculated in the three-dimensional coordinate system. These 3-D positions are shown in the lower parts of Figure 1. The lower left and middle side figures indicate a front and top view of the 3-D coordinate positions.

Similarly, we could estimate the 3-D positions of snouts and tail forks of tuna individuals recorded in both trials, and

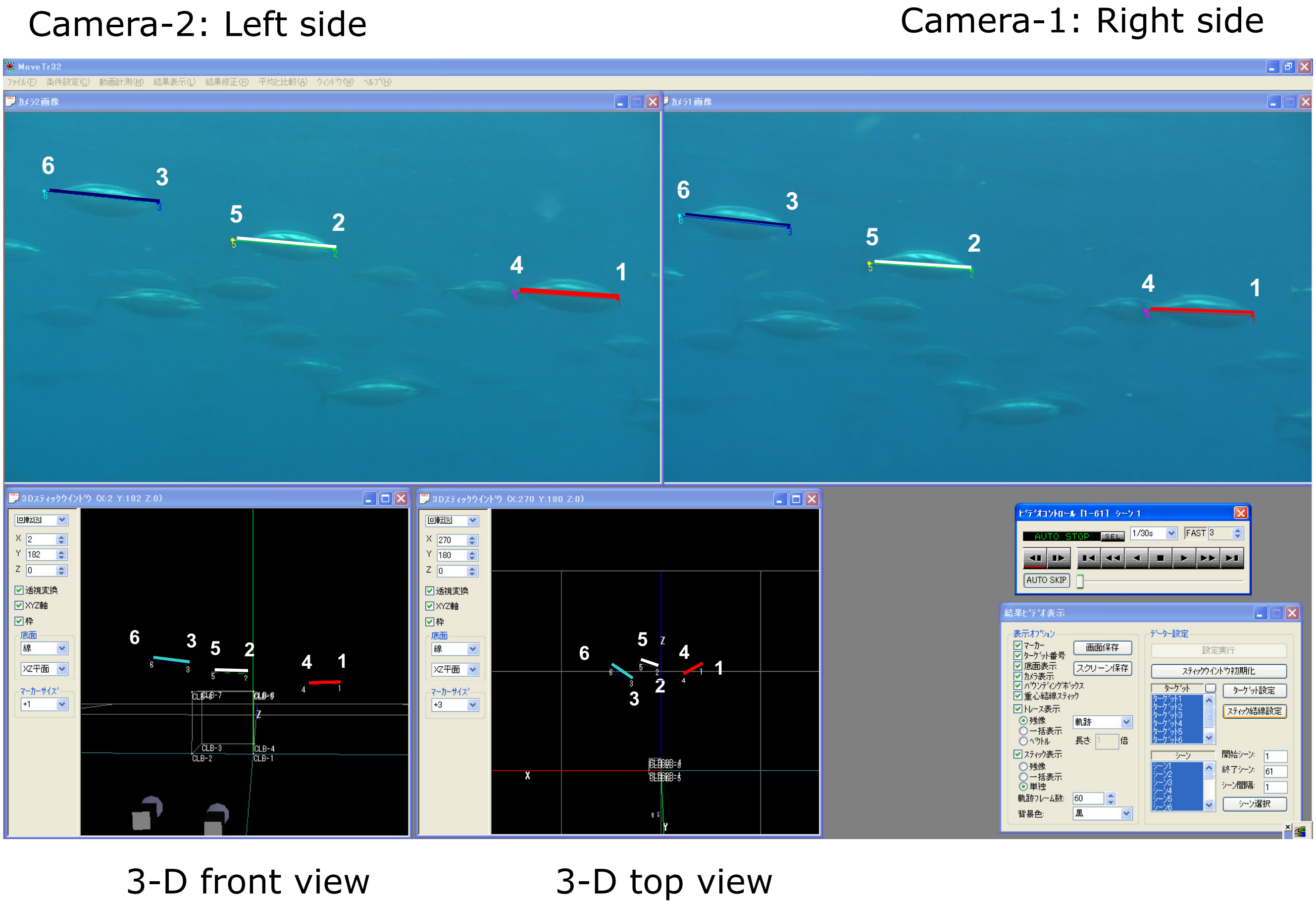

Fig. 1. Measurement interface of the Move/tr-3D software. Stereo images of tuna recorded by right and left side cameras on February 7, 2010 are shown in the upper figures. The lower left and middle side figures show a front view and a top view of their 3-D positions, respectively.

thus estimate the fork lengths of 46 and 77 (total = 123) individuals in February and July, respectively.

Simultaneous measurements were made of underwater light levels at depths of 0, 2, and 12 m during the monitoring experiments; the values in February and July ranged from 55 100 to 1 090 lux and from 44 090 to 510 lux, respectively. In both monitoring sessions, we confirmed that underwater illumination levels were sufficiently high that the maximum distance for distinguishing the snouts and tail forks of recorded tuna from a camera reached about 7 m. In these conditions, estimated width and height of recorded area by our stereo-video camera system ranged more than 5 m and 3 m in February and July, respectively.

3.3 Evaluation of the precision of fork lengths estimated from repeated measurements

To evaluate precision and accuracy of fish size estimation, error ratios of the same individuals were calculated in 20 sequential frames of the time series data for the individuals that had been measured in the February and July trials. Figure 2 shows two typical results of the time series data of fork lengths in two individual tuna (No. 1 and 2) swimming at distances of 3.3 and 3.5 m from the camera. The mean values and standard errors (SE) of No. 1 in February and No. 2 in July were calculated as 52.6 ± 0.6 cm and 71.1 ± 1.1 cm, so that the error ratios (SE/mean) were found to be 0.011 (~1%) and 0.016 (<2%), respectively.

The relationships between error ratios and recorded distances for fork length estimations of all 123 recorded tuna are shown (Fig. 3). The error ratio of estimated fish size was less than 5% for 66 of the 77 individuals (86%) measured in February, and 44 of the 46 individuals (96%) measured in July.

A problem arose during the February trial, concerning 11 fish (about 15%), which reached unallowably high error ratio values due to the unlimited target used for the tuna. Figure 3 (left) shows that error ratios increased at distances over 4.5 m from the camera system, and the estimates that exceeded the 5% error ratio were found at distances of >5.5 m for all cases except for one individual.

In this study, we tried to calculate the size of all recorded tuna in which we could distinguish the snouts and tail forks during monitoring. However, we determined that the maximum distance from camera system for appropriate and accurate fish size estimation was 5.5 m. Based on the results of both trials, we could accurately estimate sizes of 106 (62 + 44) out of the 107 tuna recorded at this distance, with error ratios less than 5%; this is 99% (106/107) of the target fish.

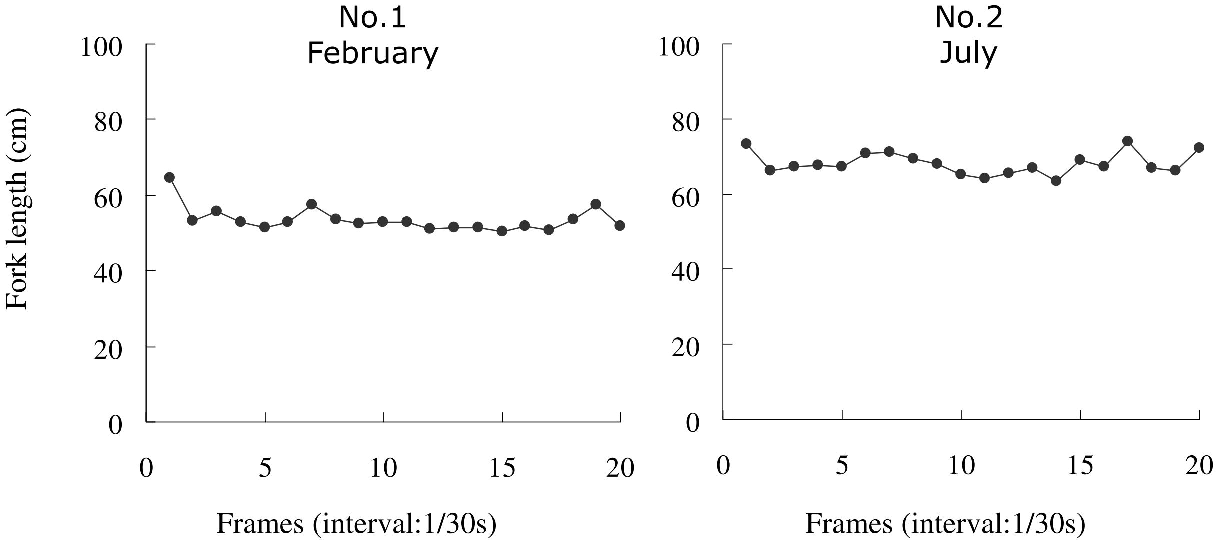

Fig. 2. Time series data of calculated fork length for a individual monitored tuna. Two typical results of fork lengths from 20 frames of the same individual recorded with 29.97 fps were shown. Tuna No.1 monitored on February 7 (left) and Tuna No. 2 (right) monitored on July 27, 2010.

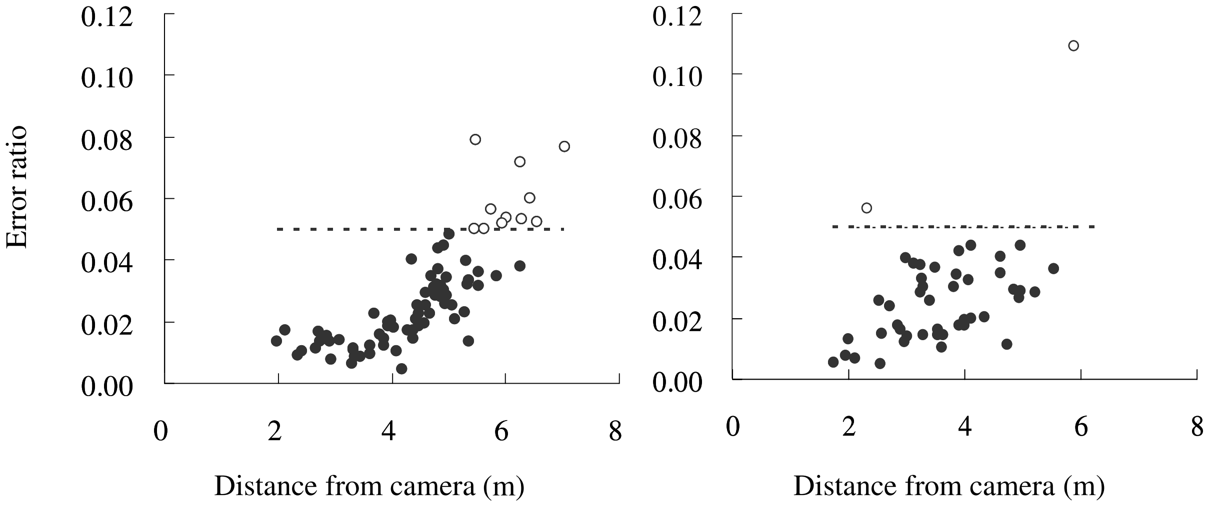

Fig. 3. Relationships between recorded distances from a camera and error ratios. Closed and open circles indicate error ratios of <5% and ≥5%, respectively. Results from February 7 (*n* = 77, left), results from July 27 (*n* = 46, right).

We suggest that the estimated mean fish size, obtained from the average of 20 sequential repeated measurements within 5.5 m of the camera and using our DLT method, provides useful fish size estimates within the required precision and accuracy to assist aquaculture management.

3.4 Relative frequency distributions of tuna fork lengths

Based on the mean values of sequential fork lengths of each tuna within the error ratio of <5%, relative frequency distributions of tuna fork lengths in both trials were obtained and are shown in Figure 4. The mean fork lengths and standard deviations (SD) of all tuna estimated within the error ratio of <5% on February 7 and July 27 were determined as 56.6 ± 6.4 cm and72.2 ± 6.7 cm (*n* = 66, *n* = 44), respectively.

The mode of tuna length distribution in February was 54–56 cm and included 29% of the individuals. The range of the fish sizes spread from 44 to 74 cm. In November, the mode was 72–74 cm and included 18% of individuals. The range was 56–88 cm. These ranges are both considered widely spread; however, the higher peak of distribution was found in February, rather than July. These results indicated that the characteristics and tendencies of length frequency distributions are different during growth. Based on these results, our trial with the DLT method found this to be a very useful method. The growth of the same individual group in a same net cage can be continuously measured and easily operated by the aquaculture industry staff.

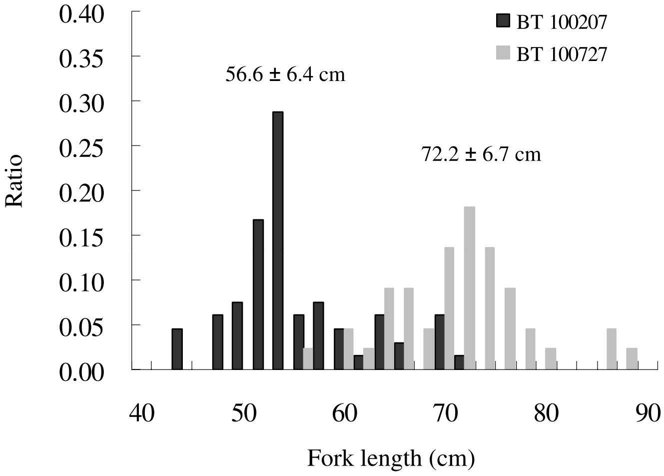

Fig. 4. Relative frequency distributions of fork length in cultured tuna on February 7 and July 27, 2010. Black and grey bars indicate the ratios in February and July, respectively, $n = 66$, $n = 44$).

4 Discussion

4.1 Validation of tuna length measurements

Although the individuals in the group on which we estimated the fork lengths could not be simultaneously captured during our stereo monitoring in the same way as they had in the research for evaluating the validity of fish size estimates (Harvey et al. 2003, Williams et al. 2010), they were regularly sampled and had their fork lengths directly measured by aquaculture industry staff (TAFCO Co.). Based on the measured results of the tuna samples captured on February 22 and July 25, the fork lengths ranged from 51 to 57 cm and from 70 to 81 cm, and the mean values and standard deviation were 54.8 ± 2.4 cm and 75.4 ± 3.5 cm, respectively. In spite of the slight differences in the dates of monitoring, the ranges of measured fork lengths of both captured samples were consistent with the ranges of our estimated size distributions. Therefore, the fish sizes estimated using our method were judged to be sufficiently valid.

Furthermore, Takahashi et al. (2006) reported the validity of length results between two certain positions, determined using the DLT method without compensating non-linear distortion, suggesting that our length results were appropriate. Although the distance from snouts to tail forks of fish is not constant (it fluctuates sinusoidally during swimming), we were able to estimate robust fish lengths by taking the mean of 20 sequential frames of data.

In addition, the variation in estimated length of the same individuals occurred due to the errors incurred by extracting the positions of the same fish points from two camera images by hand clicking. In the case of the transformation from slightly mismatched or different 2-D points of tuna snout or tail fork under low contrast conditions into the same position in the 3-D coordinate system, an overestimate occurred due to mismatches between the calculated positions in the z-axis coordinates and those of the fish body axis plane.

Nevertheless, we found that we could collect enough results of fork lengths of the tuna that swam within 5.5 m of the camera system, within 5% of error ratio (calculated from 20 sequential images including the errors mentioned), for management of cultured fish. Thus, 3-D analysis based on the camera coordinate system can obviously supply useful information, such as fish size distributions and their characteristics. The validity of the fish size estimates obtained using our stereo-video camera system was adequate within 5.5 m of the camera system. Therefore, this method is appropriate for monitoring tuna and other fish species in aquaculture and in the wild. We suggest that our simple method (as well as the method of Hsieh et al. (2011), although these authors describe image analysis made on the deck of tuna fishing vessels that uses neither stereo-images nor an under water monitoring system) of non-destructive stereo fish monitoring, which can be operated by aquaculturists using DLT method and commercial image-processing software, is sufficient to provide a helpful tool for aquaculture and fisheries management.

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