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The accuracy and precision of underwater measurements of length and maximum body depth of southern bluefin tuna (*Thunnus maccoyii*) with a stereo–video camera system

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Abstract

The accuracy and precision of in situ stereo–video measurements of the snout to fork length (SNFL) (range 830–1412 mm) and maximum body depth (MBD) (range 228–365 mm) of free-swimming southern bluefin tuna (SBT) (*Thunnus maccoyii*) were tested by filming live fish in sea cages immediately prior to harvest. Stereo–video measurements of the SNFL of 54 fish produced an average error of 1.72 mm (relative error of 0.16%), while an average error of 1.37 mm (relative error of 0.51%) was recorded for measurements of MBD from 47 fish.

A procedure was developed to maximise the accuracy and precision of measurements of the SNFL and MBD from a single SBT over sequential images to avoid the underestimation of SNFL and overestimation of MBD due to sinusoidal changes in body form associated with fast swimming.

The results demonstrate the potential of stereo–video systems to non-destructively make counts and measurements of tuna and other fish in both wild fisheries and mariculture situations, without the need to capture and handle them.

Keywords: Stereo–video measurement; Tuna; Underwater; Accuracy; Precision

1. Introduction

Southern bluefin tuna (SBT) (*Thunnus maccoyii*) are a highly migratory pelagic species found between latitudes 30–50°S. They are long-lived (up to about 40 years), slow-growing and late-maturing (8–12 years or older) relative to other tunas (Robins et al., 2000). The species has supported valuable commercial fisheries by Japanese and Australian fleets, and to a lesser extent those of Taiwan, New Zealand, Indonesia and Korea, but global catches have fallen steadily, from a high of 80,000 t in the early 1960s, due to over exploitation. The fish is marketed almost exclusively on the Japanese sashimi and sushi market, where it is one

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of the most valuable fish supplied to the restaurant industry.

SBT are now managed under the Commission for the Conservation of SBT (CCSBT) by a global catch quota of 11,750 t shared between Japan (6065 t), Australia (5265 t) and New Zealand (420 t). However, significant catches by three countries outside the CCSBT, and a rise in the Japanese catch through “experimental fishing” not endorsed by the CCSBT, raised the world catch to 19,200 t in 1998 (Robins et al., 2000).

Since the Australian quota was capped in 1988–1989, the Australian surface fishery for juvenile and sub-adult SBT has shifted in operation from direct marketing of wild-caught fish toward the transport, holding and fattening of fish after capture. These “farming” operations increased from 3% of the Australian total allowable catch (TAC) in 1991–1992 to over 95% in the 1999/2000 fishing season with all cage fattening operations occurring at Port Lincoln, South Australia. The product has risen in value from to AUS$ 12 million to ∼AUS$ 264 million in 2001 (South Australian Fisheries and Aquaculture Production Figures from 1997/1998 to 2000/2001, South Australian Research and Development Institute (SARDI)). Schools of SBT are captured by purse-seine in the Great Australian Bight during the austral summer with the catch transferred into towing cages for transport back to more sheltered waters near Port Lincoln. The SBT are then transferred into moored grow-out cages, fattened for several months on a diet of baitfish (predominantly pilchards *Sardinops* spp.) and harvested for the Japanese markets between 3 and 8 months later in May–September.

Before the development of the cage fattening industry, scientific data on the length frequency, weight and age of SBT were readily collected in the Australian fishery by measurement of freshly caught, dead whole fish aboard the fishing vessels. This process did not unduly interfere with the fishing activity. With the emphasis now on returning wild-caught SBT to Port Lincoln alive for transfer into grow-out cages there are fewer opportunities for scientists to collect length frequency and weight data without fishery-independent sampling. The monetary value of each fish makes farmers reluctant to stress fish by physically removing them from the water while these data are collected.

The importance of the collection of more numerous, precise and accurate data on length or age, without the need to physically handle live fish, has been identified as an urgent necessity for fisheries and aquaculture managers (Robins et al., 2000), and would be advantageous as an objective baseline for both fisheries and aquaculture managers.

Currently, the catch quotas are monitored by counting all the individuals transferred from towing cages to grow-out cages. Transfers are made by joining towing and grow-out cages and opening square mesh gates to allow fish to pass from one cage to another. Manual counts and recordings of the SBT swimming through the gates are made from an underwater video attached to the side of the gate. To estimate the catch weight, a sample of forty fish is caught by handline from within the tow cage prior to transfer and their lengths and weights are measured. The total number of SBT counted during a transfer is multiplied by the average weight of the SBT sampled to derive a total biomass per tow cage. The length or weight measurements from these 40 fish are also used to estimate the length distribution of the farm caught fish in the scientific stock assessments. Ideally, all fish entering grow-out cages should be counted and measured during transfers.

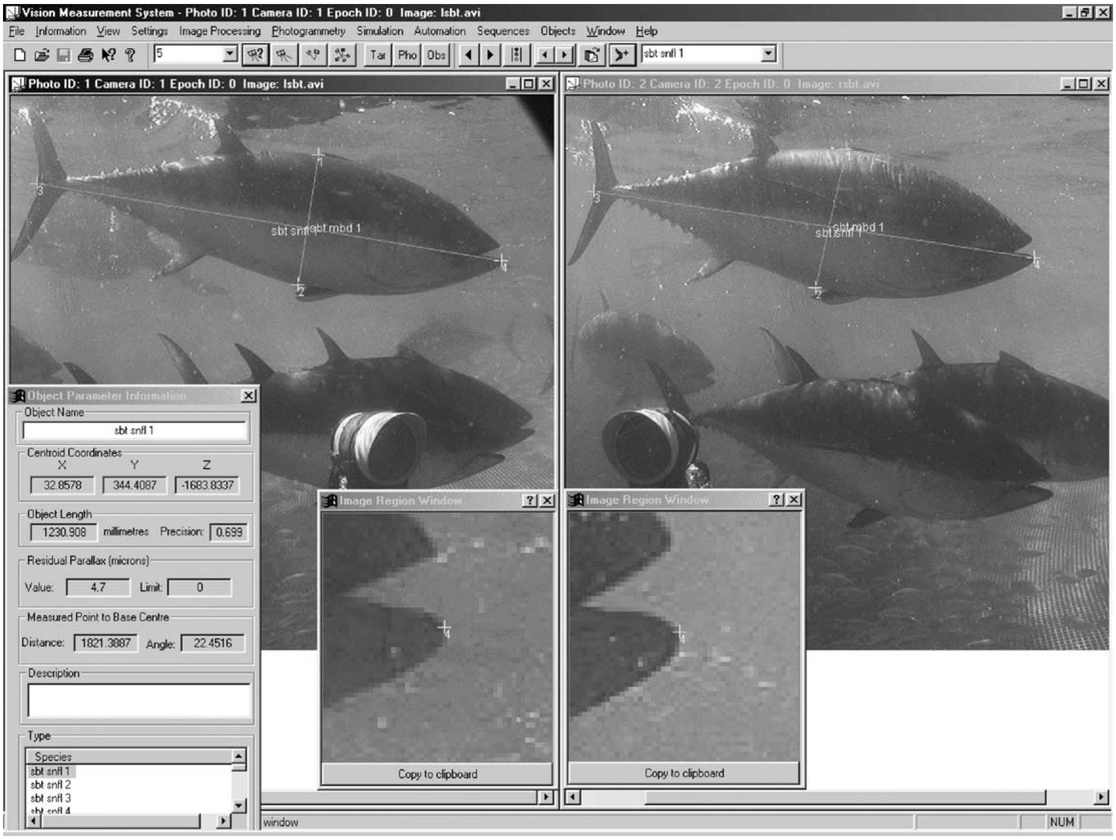
Underwater stereo–video is a research tool that is capable of making accurate, precise, non-invasive measurements of fish length (Naiberg et al., 1993; Harvey and Shortis, 1996; Li et al., 1996; Petrell et al., 1997; Steeves et al., 1998; Harvey et al., 2001a,b, 2002a) and may have many benefits for managers of wild stock and for aquaculturalists (Harvey et al., 2002b).

The objectives of this study were to determine a set of guidelines for making measurements of SBT and validate the accuracy and precision of stereo–video measurements of the snout to fork length (SNFL) and maximum body depth (MBD) of live SBT under field conditions. Additionally, the photogrammetric calibration stability of the camera system was tested in order to develop field guidelines for calibration.

2. Materials and methods

2.1. The stereo–video system

The stereo–video system comprised two Sony TRV 900 E PAL digital video camcorders in underwater housings mounted on a steel frame as a stereo pair.



Object Name: sbt snfl 1

Centroid Coordinates: X 32.8578, Y 344.4087, Z -1683.8337

Object Length: 1230.908 millimetres Precision: 0.699

Residual Parallax (microns): Value: 4.7 Limit: 0

Measured Point to Base Centre: Distance: 1821.3887 Angle: 22.4516

Description:

Type: Species

sbt snfl 1
sbt snfl 2
sbt snfl 3
sbt snfl 4

Fig. 1. The measurement interface of VMS. The LED synchronisation light can be seen above the zoom measurement boxes.

These cameras do not have the facility for master-slave synchronisation, so a light emitting device (LED) was mounted in a housing 1 m in front of the cameras (Fig. 1). The LED is visible in images recorded by both cameras and can be switched on and off manually by the operator at appropriate times. The LED serves as a simple means of overcoming motion parallax by synchronising the left and right camera images from which measurements are made. Motion parallax decreases the accuracy of any subsequent measurements.

2.2. Calibration of the stereo–video

The video cameras used for close-range applications are typically "non-metric" or "semi-metric". In general, this means that these cameras have significant departures from a perfect central projection. The departures must be modelled in a calibration process so that the error in the central projection model can be compensated. In particular, the calibration procedure addressed the internal characteristics of the cameras (principal points, focal lengths, radial and decentring distortions in the lenses, and orthogonality and affinity terms) and the relative orientation of the two cameras to one another (distance between the two cameras, angles of convergence, and the tilt and roll of the cameras).

2.3. Analysis of stereo–video images

Streams of video images are frame-grabbed in Audio Video Interleaved (AVI) format using a DV Raptor© frame grabber. Two AVI files containing images from the left and right cameras are then imported into Vision Measurement System (VMS), a stereo–photo comparator developed by Dr. Mark Shortis and Dr. Stuart Robson (Shortis and Robson, 2001). Paired images within the AVIs are synchronised using the LEDs and measurements of the SBT recorded. The computer interface for stereo measurement is shown in Fig. 1. The left and right overviews are the larger images in the left and right of the screen, while the variable zoom windows in which measurements are actually made are the two smaller viewing boxes at the bottom of the image. Measurements were made by locating the feature of interest (in this case the snout or tail fork of the SBT) in the overview box using simple cursor positioning and mouse clicks, then in the zoom windows to precisely locate the point of interest and make the measurement. The object parameter information box (Fig. 1) displays numerical data on the object being measured and provides an interface for logging comments on a particular measurement into a data file, where all numerical measurement data are stored. The two pairs of image space coordinates are converted into coordinates in three-dimensional object space (x, y and z) and an estimator of the quality (root mean square residual, also known as residual parallax) of the measurement and a precision of the measurement is logged. As length measurements are of particular interest, the three-dimensional distances between consecutive point measurements are computed automatically. The range from the point of interest to the central point between the camera lenses and the angle of the point of interest relative to the camera centres are also automatically computed. These values can be used to limit the measurements to a particular volume or transect relative to the cameras, if required by the sampling regime.

Optimal measurements are recorded when the body of the SBT is approximately parallel to the focal planes of the stereo pair of cameras. In this orientation, the snout and tail of the SBT are seen most clearly in profile, maximising the definition of the silhouette of the body against the background. Previous trials (Harvey and Shortis, 1996; Harvey et al., 2002b) have demonstrated that the length of a fish can be measured accurately providing the fish is orientated between 0° and 60° relative to the stereo–video system.

A detailed description of the design, calibration and measurement procedure used for the stereo–video system may be found in Harvey and Shortis (1996, 1998), Shortis and Harvey (1998) and Harvey et al. (2002b). Information on the availability of software and hardware design can be accessed through Shortis and Robson (2001).

2.4. *Measuring the accuracy and precision of stereo–video measurements of SBT*

Field trials took place in research cages maintained by SARDI at Port Lincoln in May 2001. The accuracy and precision of the stereo–video system was determined from in situ measurements of SBT made with the stereo–video system. The SNFL and MBD of the same fish were measured by vernier calipers after the fish had been harvested and compared to the stereo–video measurements. The individual SBT were captured by hand by a skin diver in a holding net and transferred for measuring and processing to a support vessel. The individual SBT were filmed by a second skin diver with the stereo–video prior to and during capture. During the measuring and recording of the SNFL and MBD on the support vessel a scribe also recorded the actual time and time code recorded on the videotape for each SBT. As only one SBT was being recorded, caught and processed at a time it was possible to relate measurements of the SNFL and MBD with the calipers to the records on a video tape for comparison.

2.5. *Calibration stability of the stereo–video system*

The stereo–video system was initially calibrated in a freshwater swimming pool at the Port Lincoln Leisure Centre on 21 May 2001. The calibration process entails capturing 30–40 images of a calibration frame. The frame is an open cuboid, assembled from aluminium rods and snap-in joiners, with approximately 80 known locations marked on the rods with targets. The critical calibration parameters derived from the process are shown in Table 1. The calibration of the stereo–camera system is subject to prevailing conditions, because the interfaces between the external water and the ports of the waterproof housings are effectively part of the optical path to the lens of each camera. Previous experimental testing has shown that there is little change in calibration if the environment is consistent (Shortis et al., 2000), however it could be

Table 1
Critical parameters resulting from the calibration of the stereo–video system in freshwater and in saltwater on 22 May 2001 and 24 May 2001

Parameter	Camera 1	Camera 2
Calibration in saltwater 21 May 2001		
Focal length (mm)	3.596	3.636
1/2 distance between cameras (cm)	−37.32	37.32
Convergence angle (°)	−7.851	7.033
Calibration in saltwater 22 May 2001		
Focal length (mm)	3.614	3.651
1/2 distance between cameras (cm)	−37.15	37.15
Convergence angle (°)	−7.827	7.166
Calibration in saltwater 22 May 2001		
Focal length (mm)	3.615	3.662
1/2 distance between cameras (cm)	−37.02	37.02
Convergence angle (°)	−7.778	7.045

expected that changes in water temperature, pressure or salinity may effect the calibration of the system. To address the issue of the validity of calibrating a system in freshwater but making measurements in saltwater, an additional two calibrations were made with the stereo–video system in the SBT cage on the 22 and 24 May 2001 (Table 1).

2.6. *The development of guidelines for making measurements of SBT with a stereo–video*

2.6.1. *The effects of swimming motion*

Observations of SBT swimming behaviour noted that tail flex and muscle contractions associated with swimming could possibly alter the measurable SNFL and MBD of an individual. To determine the effects of swimming motion on the accuracy of measurements, and to help determine the optimal number of images to process for a single fish, measurements of a fast swimming SBT were made from each of ten sequential frames.

2.6.2. *Repeated measurements*

One of the advantages of stereo–video measurement is that images are stored either on tape or as a digital computer file making it possible to make numerous repeat measurements of a fish during the analysis of recorded images. Taking the mean of this set of measurements will result in greater accuracy and precision than using a single measurement (see Harvey et al., 2001a). To determine the optimal number of repeat measurements for field measurements of SBT, 10 repeated measurements of the SNFL and MBD were taken from images recorded of 10 SBT.

2.6.3. *Statistical analysis*

Four measures of error were used to summarise the accuracy of estimates of SNFL and MBD for each SBT. If the "estimated" (stereo–video) SBT length was O and the "observed" (caliper) length was T, these four measures are

Error	$E = O - T$
Relative error (%)	$\mathrm{RE} = (O - T)/T = E/T$
Absolute error	$\mathrm{AE} = \text{absolute}\lvert O - T\rvert = \lvert E\rvert$
Relative absolute error (%)	$\mathrm{RAE} = \text{absolute}\lvert O - T\rvert/T = \lvert E\rvert/T = \lvert\mathrm{RE}\rvert$

The four measures provide different information. The error E will be positive or negative according to whether the observed length is an overestimate or an underestimate. A mean of E close to zero can imply either estimates are accurate, or that cancellation of under and overestimates has occurred. The absolute error AE avoids such cancellation when a mean is taken, but does not give indication of the direction of estimation errors. The relative errors RE and RAE (expressed as percentage) are derived here to show the consistency of estimates across the full range of true dimensions (Harvey et al., 2001a).

3. Results

3.1. *The accuracy and precision of stereo–video measurements of SBT*

The tuna filmed with the stereo–video system ranged between 830 and 1412 mm SNFL, and 228–365 mm MBD. Of the 81 SBT harvested, it was possible to make 54 measurements of the SNFL (mean error = 1.72 mm, ±1 S.D. = 8.1 mm, ±1 S.E. = 1.11 mm) and 47 measurements of MBD (mean error = 1.37 mm, ±1 S.D. = 5.06 mm, ±1 S.E. = 0.74 mm) of identifiable individuals from the stereo–video imagery. A dense cloud of baitfish present in the holding net, or the movements of the harvest diver, obscured SBT in the remaining images,

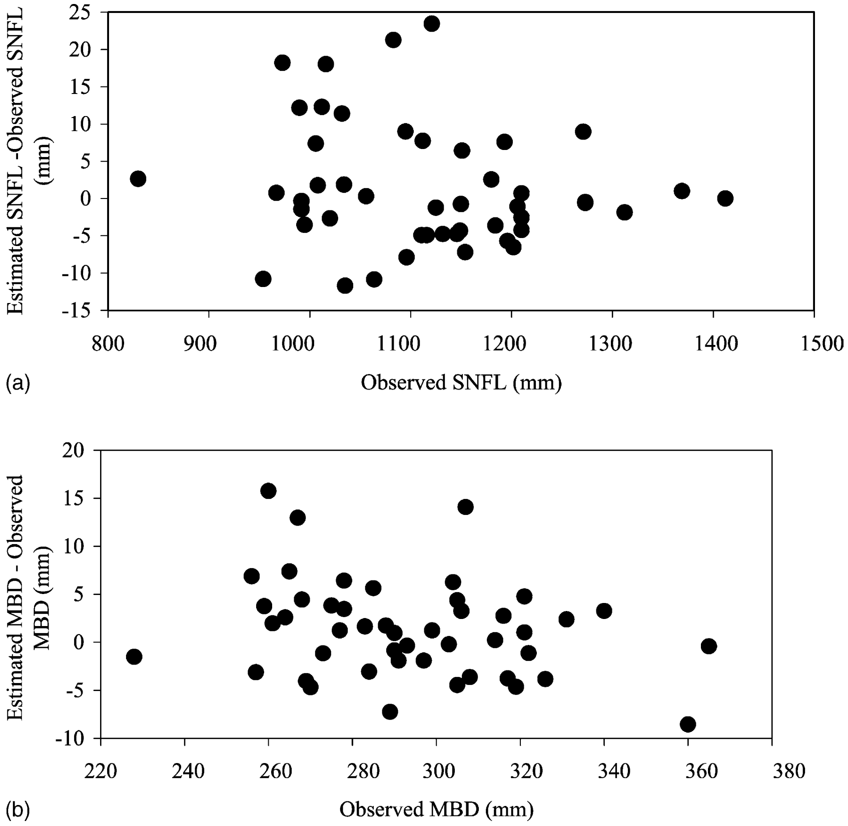


Fig. 2. (a) Relationship of the difference between the SNFL estimated by underwater stereo–video and the SNFL measured on deck with calipers (estimated SNFL − observed SNFL) plotted against the observed SNFL measured on deck with calipers. (b) Relationship of the difference between MBD estimated by underwater stereo–video and the MBD measured on deck with calipers (estimated MBD − observed MBD) plotted against the MBD measured on deck with calipers.

preventing measurement. Plots of the differences between stereo–video and caliper measurements indicate that, on average, estimates from stereo–video were slightly higher than measurements made of the same fish after death (Fig. 2a and b). A mean relative error of 0.16% was recorded for SNFL and 0.51% for MBD. The mean errors, absolute mean errors, mean relative errors and absolute relative errors demonstrate that the stereo–video system can make both accurate and precise measurements of the SNFL and MBD of SBT (Table 2).

When the sign of the difference between stereo–video and caliper measurements of SNFL was removed, a mean absolute error of 6.06 mm and relative absolute error of 0.56% was recorded for the stereo–video. Similarly for MBD, a mean absolute

Table 2
Errors associated with stereo–video estimates of the SNFL and MBD of SBT

	Error (mm)	Absolute error (mm)	Relative error	Relative absolute error
SNFL				
Mean	1.72	6.06	0.16%	0.56%
1 S.D.	8.13	5.62	0.76%	0.54%
1 S.E.	1.11	0.77	0.10%	0.07%
Sample size	54	54	54	54
MBD				
Mean	1.37	3.93	0.51%	1.37%
1 S.D.	5.06	3.43	1.78%	1.24%
1 S.E.	0.74	0.50	0.26%	0.18%
Sample size	47	47	47	47

error of 3.93 mm and relative absolute error of 1.37% were recorded for the stereo–video system.

3.2. *Calibration stability of the stereo–video system*

Differences in the critical parameters displayed in Table 1 are readily apparent, however, a comprehensive analysis requires that the significance of the changes is investigated. Statistical significances of difference values were computed using the following formula:

$$\text{Significance} = \frac{|\text{parameter}_n - \text{parameter}_{n-1}|}{\sqrt{\text{variance}_n + \text{variance}_{n-1}}}$$

where the variance is the square of the standard deviation, provided by the least squares estimation solution for the camera calibrations. The significance value effectively gives a weighted, dimensionless estimator of the significance of the change in the parameter. These values can be statistically tested against a distribution such as the Student's *t*. For a 95% confidence level and high magnitudes of degrees of freedom, the critical value is approximately 2. For a camera calibration based on 20 photographs and 90 targets, the degrees of freedom were approximately 2500.

The significances of the changes to the camera calibration parameters for the stereo–video system are shown in Table 3. It is evident that there were some quite significant changes, indicating that the prevailing conditions may have some effect on the calibration. However, the average figure for significance of parameter changes from fresh to salt water is only slightly larger than that for the two calibrations in salt water. These results are in accord with previous research investigations, which invariably showed a very strong correlation between changes in the camera calibration parameters and the removal of the video cameras from the housings in order to change videotapes and batteries. Whilst the change from salt to fresh water may have an influence, the magnitude of that influence requires more investigation under controlled conditions.

The significance of the changes in the camera relative orientation parameters, comprising the base separation and the three orientation angles, are shown in Table 3. Here again the results agreed with previous research studies, which also showed that when the camera housings are fixed to the base bar then there was no significant change. Hence, in this particular situation, the relative orientation of the camera was very stable, whilst the camera calibration parameters are changing due to the combined effects of removal of the cameras from the housings and the absorption of the changes in the prevailing conditions.

However, the most indicative test of stability of the stereo–video system is the reliability of distance measurements under varying conditions. Whilst the calibration and orientation parameters will respond to changes in the prevailing conditions, it is the measurements of the lengths of objects in the water that are paramount. Accordingly, 12 distances between targets on rigid members of the calibration frame were computed, based on the coordinates produced from the camera calibrations. The lengths were spread evenly between the lateral and longitudinal directions, and between the upper and lower levels of the calibration cube. The shortest, average and longest lengths included in the sample were 261, 328 and 460 mm, respectively. The precisions of the lengths, again as determined from the camera calibrations, varied between 0.17 and 0.33 mm (Table 4).

The results shown in Table 4 indicate that there were no significant changes to lengths on the calibration cube. There is clearly a consistent change from fresh water to salt water in terms of the mean change in length, however, the magnitude is approximately 0.07%. Further, the two calibrations in salt water show no overall scale change at all. Although this testing is not based on an independent, external reference, nevertheless the results indicate a very reliable system, despite the changes in the camera calibration parameters as discussed above.

3.3. *Guidelines for making measurements of SBT with a stereo–video*

3.3.1. *The effects of swimming motion*

The cycles of muscle contraction and relaxation on alternate sides of the fish caused a sinusoidal oscillation of stereo–video estimates of both SNFL and MBD in sequential frames (Fig. 3a and b). The amplitude of the variation in estimates was about 4 mm for SNFL and 3 mm for MBD on a fish of 1273 mm SNFL and 326 mm MBD.

Table 3
Significance (Student's t statistics) of change to camera calibration and relative orientation parameters for the stereo–video system

		Pool on 21 May to salt water on 22 May 2001	Salt water 22 May to salt water 24 May 2001
Calibration parameter			
Camera 1	Principal point X location	1.49	4.32
	Principal point Y location	3.45	2.33
	Focal length	7.22	0.55
	Radial lens distortion	5.11	0.64
	Decentring lens distortion	1.76	1.90
	Image affinity	3.19	1.17
Camera 2	Principal point X location	1.61	5.54
	Principal point Y location	0.17	0.08
	Focal length	6.30	4.38
	Radial lens distortion	5.17	3.09
	Decentring lens distortion	1.71	3.77
	Image affinity	3.15	2.16
Average		3.36	2.49
Relative orientation parameter			
Camera 1	Base separation	1.22	0.76
	Tilt	0.08	0.68
	Convergence	0.19	0.33
	Roll	0.04	0.24
Camera 2	Tilt	0.08	0.68
	Convergence	1.03	0.78
	Roll	0.60	0.33
Average		0.46	0.54

Table 4
Significance of change to measured lengths for the stereo–video system

Parameter	Pool on 21 May to salt water on 22 May 2001	Pool on 21 May to salt water on 24 May 2001	Salt water 22 May to salt water 24 May 2001
Mean length change (mm)	−0.23	−0.23	0.00
Mean significance value (Student's t statistic)	1.24	1.09	0.60

3.3.2. Repeated measurements

The mean error and width of error bars stabilised after five repeated measurements for both SNFL and MBD (Fig. 4a and b). Subsequently, measurements of the SNFL and MBD of individual SBT comprised the average of five measurements made from five sequential images when the SBT appeared to be gliding in a reasonably straight line. Images were not selected for analysis if the fish was filmed when swimming very strongly or turning.

4. Discussion

This study has shown that stereo–video technology can be applied to make accurate, non-invasive measurements of the SNFL (mean error = 1.72 mm) and MBD (mean error = 1.37 mm) of SBT in situ. The implementation of a set of procedures for the calibration of the stereo–video system and measurement of SBT will ensure that the measurement accuracy and precision of the technology will be maintained.

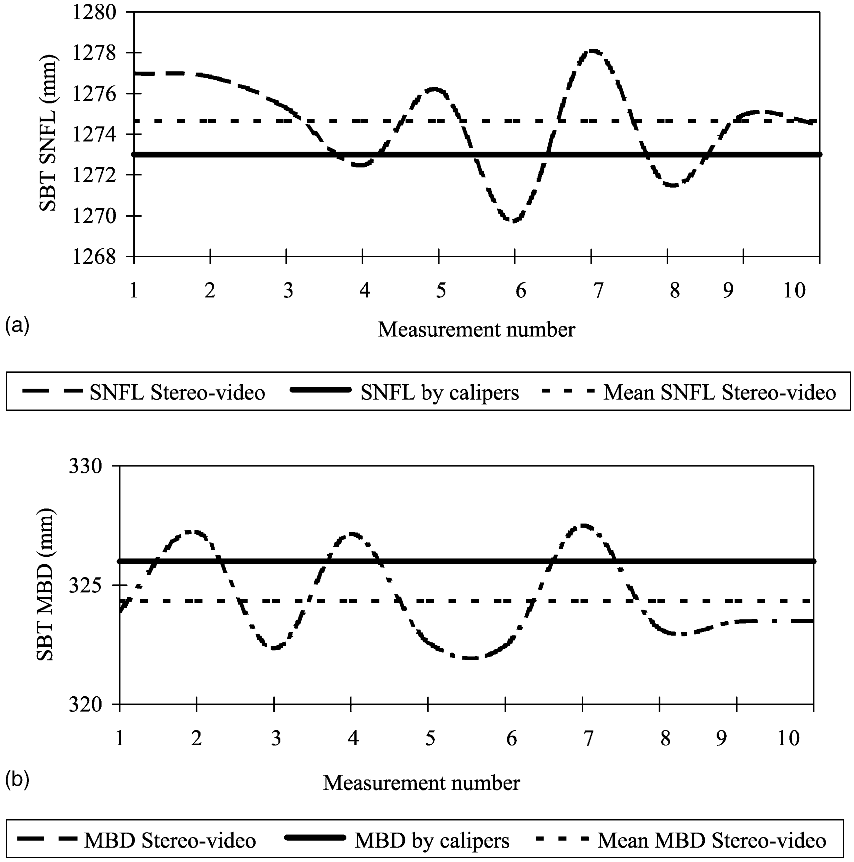


Fig. 3. (a) Change in stereo–video measurements of the SNFL of a rapidly swimming SBT in sequential video frames in comparison to the true SNFL of 1273 mm (determined by caliper measurements). The mean SNFL is the average of the 10 measurements. (b) Change in stereo–video measurements of the MBD of a rapidly swimming SBT in sequential video frames in comparison to true MBD of 326 mm (determined by caliper measurements). The mean MBD is the average of the 10 measurements.

Whilst the measurement accuracy and precision of the stereo–video system was acceptable, it is predicted that substantial improvements will be achievable. The video cameras used were off-the-shelf consumer models limited to 720 × 576 pixel resolution. The use of high resolution, progressive scan digital cameras recording directly to computer drive rather than tape will substantially enhance measurement accuracy and precision. It will also facilitate the development of a fully automated system eliminating the major weakness in the system—operator error associated with defining the edges of points of interest (in this case the snout and fork of the tail of a tuna) with a computer mouse. This bias arises from a combination of the discrete sampling of the CCD array, the optical transfer function of the lens elements and refractive surfaces in the imaging devices. The edge of the silhouette is spread across multiple pixels in the image and the manual measurement tends to favour the apparent edge of the silhouette in the digital image.

It is interesting to note that the relative error in measuring MBD is greater than that for SNFL. The MBD is a measure of the deepest part of the fish body and is more subjective due to the lack of defined points to measure between (see Fig. 1). It is also apparent that fish movement will affect the measurement accuracy and precision. Fast swimming perceptibly affected stereo–video measurements of both fork length and MBD, with under- and overestimates occurring in

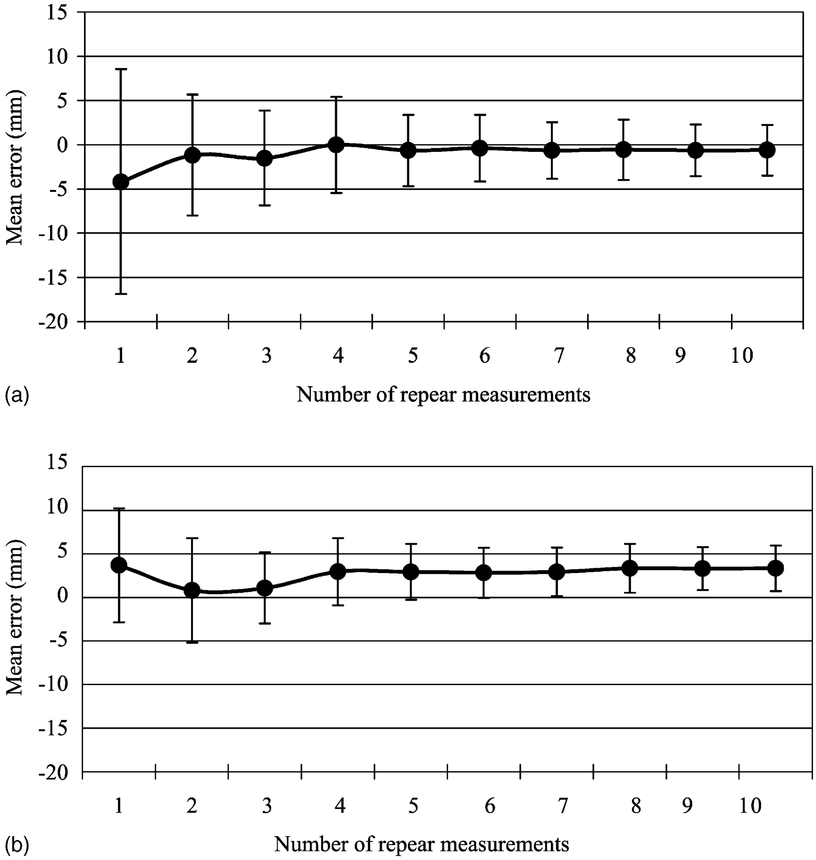


Fig. 4. (a) The mean error (±S.D.) of 10 repeated measurements of the SNFL from sequential images of 10 SBT. (b) The mean error (±S.D.) of 10 repeated measurements of the MBD from sequential images of 10 SBT.

a sinusoidal relationship as muscles on each side of the body contracted and relaxed. The underestimates are to be expected in powerful swimming strokes as the actual distance between the fork of the tail and the snout is shortened due to the curvature of the body. The overestimates are in accord with the general overestimation of lengths as shown in Table 2. The primary source of this overestimation is the manual "point and click" measurement of the key points on the silhouette. The discrete sampling by the CCD imager and the transfer function of the elements in the optical train combine to smear the edge across multiple pixels. Manual measurement is biased toward overestimation because of the tendency of the operator to define the edge as the visible termination of contiguous pixels associated with the fish body, rather than the mid-point of the transition between the fish body and the background of clear water.

The study has shown that accurate and precise measurements of SBT can be made with a stereo–video system using the following guidelines:

1. Measurements should be attempted only when the head and the tail of an SBT are oriented less than 60° away from the stereo–video, where they can be clearly seen in the images recorded by the left and right cameras.
2. Taking the average of five measurements of the same fish will optimise the precision of stereo–video measurements. Each of the five measurements should be made over five sequential frames to minimise the affect of the fish swimming motion.

3. Measurements should not be made when the swimming motion of a fish involves excessive tail flex during a power stroke or tight turn.

Overall the results indicate that the stereo–video system was photogrammetrically stable. Repeated calibrations of the stereo–video system showed the relative orientations of the cameras were very stable, even though the critical camera calibration parameters changed significantly. These changes were due mostly to removal and replacement of cameras in underwater housings between calibrations. To maximise measurement accuracy and precision, the calibration of a stereo–video system should always be made under working conditions.

The reported measurement accuracy and precision of the stereo–video system is very favourable to other systems (e.g. Petrell et al., 1997) and will improve as technological issues such as synchronisation of images, progressive scan and digital transmission are further developed over time. The system used by Petrell et al. (1997) to measure the fork length of anaesthetised chinook salmon had a precision of ±3.0%, giving estimates within 97.0–103.0 cm for a fish of 100 cm fork length. The digital stereo–video system described here had a mean accuracy of 1.72 mm (±0.76 mm). If the same 100 cm salmon was measured using the digital stereo–video system described here, a 95% confidence limit would produce estimates within 98.37 and 101.62 cm. Unlike Petrell et al. (1997), the accuracy and precision of measurements reported here incorporates changes in body length due to swimming and incorporates a range of fish lengths at orientations of the fish less than 60° to the plane of the cameras.

Reliable and accurate catch monitoring is an essential component of SBT fishery management by the CCSBT. The data collected from the farms at Port Lincoln determine the reliability of the information on almost the entire Australian component of the global SBT catch. A number of concerns exist with the current process and particularly with the passive or active selection of the 40 fish for weight and length measurement, and with the small size of this sample in comparison to the thousands of fish in the cages. For example, it may be that smaller fish are more likely to take the hook at the surface in the cages. More importantly, the measured sample now represents only about 0.5% of the overall Australian catch. These and other, unknown factors have the potential to bias the precision and accuracy of the length frequency distributions estimated for the Australian catch in scientific stock assessments. The high cost of the current methodology and the possibility of fish being injured during, or dying from, the sampling process has been a concern for farm operators and consequently have been factors in limiting the sample size to 40 fish.

For many species of fish relationships between length and weight are already published. For fish like SBT, which tend to become thicker in girth as they grow, the probability of a relationship existing between combined factors such as SNFL, MBD and weight is high. The implications for the husbandry and management of grow-out fisheries industries are the ability to determine mean weight changes and food conversion ratios for a cage of fishes without the need to handle individual fish.

5. Conclusions

There are obvious benefits for fisheries, aquaculture and farm managers if SBT can be measured by underwater stereo–video without the trauma of capture and handling. The sample could include measurements of a high proportion of all the SBT comprising the Australian catch. The most significant disadvantages in the current use of the system is the delay in the availability of information to farm managers and fisheries and aquaculture management agencies, due to the manual post-processing of video images. Incremental automation of the measurement process is essential and achievable to avoid these delays. This will also overcome the greatest source of error, in the manual selection by an operator of the same features in images from the left and right cameras. A longer-term aim is fully automated, accurate counts of individual animals within a sea cage, requiring the additional tasks of robust feature matching and verification, under variable conditions of lighting and perspective, to ensure that every individual animal in the population sample is unambiguously identified. The development of these algorithms and techniques, over a 2–3-year period, will ensure that the length frequency distribution of fin fishes in a sea cage or transfer is accurate, precise and reliable.

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References

Harvey, E.S., Shortis, M., 1996. A system for stereo–video measurement of subtidal organisms. Mar. Tech. Soc. J. 29 (4), 10–22.

Harvey, E.S., Shortis, M., 1998. Calibration stability of and underwater stereo–video system: implications for measurement accuracy and precision. Mar. Tech. Soc. J. 32 (2), 3–17.

Harvey, E.S., Fletcher, D., Shortis, M., 2001a. A comparison of the precision and accuracy of estimates of reef-fish lengths made by divers and a stereo–video system. Fish. Bull. 99 (1), 63–71.

Harvey, E.S., Fletcher, D., Shortis, M., 2001b. Improving the statistical power of visual length estimates of reef fish: a comparison of estimates determined visually by divers with estimates produced by a stereo–video system. Fish. Bull. 99 (1), 72–80.

Harvey, E.S., Fletcher, D., Shortis, M.R., 2002a. Estimation of reef fish length by divers and by stereo–video. A first comparison of the accuracy and precision in the field on living fish under operational conditions. Fish. Res. 57 (3), 257–267.

Harvey, E.S., Shortis, M.R., Stadler, M., Cappo, M., 2002b. A comparison of the accuracy and precision of digital and analogue stereo–video systems. Mar. Tech. Soc. J. 36 (2), 38–49.

Li, R., Li, H., Zou, W., Smith, R.G., Curran, T.A., 1996. An underwater digital photogrammetric system for fishery goematics. Int. Arch. Photogr. Remote Sens. 31 (B5), 524–529.

Naiberg, A., Petrell, R.J., Savage, C.R., Neufeld, T., 1993. Non-invasive fish size assessment method for tanks and sea cages using stereo–video. In: Wang, J.K. (Ed.), Techniques for Modern Aquaculture. American Society for Agricultural Engineering, pp. 372–381.

Petrell, R.J., Shi, X., Ward, R.K., Naiberg, A., Savage, C.R., 1997. Determining fish size and swimming speed in cages and tanks using simple video techniques. Aquacult. Eng. 16, 63–84.

Robins, C., Polacheck, T., Preece, A., Caton, A., 2000. Southern bluefin tuna fishery. In: Caton, A., McLoughlin, K. (Eds.), Fishery Status Reports 1999: Resource Assessments of Australian Commonwealth Fisheries. Bureau of Rural Sciences, Canberra, Australia, pp. 159–168.

Shortis, M.R., Harvey, E.S., 1998. Design and calibration of an underwater stereo–video system for the monitoring of marine fauna populations. Int. Arch. Photogr. Remote Sens. 32 (5), 792–799.

Shortis, M.R., Robson, S., 2001. VMS Reference and User Guide. http://www.geomsoft.com.au.

Shortis, M.R., Miller, S., Harvey, E.S., Robson, S., 2000. An analysis of the calibration stability and measurement accuracy of an underwater stereo–video system used for shellfish surveys. Geomatics Res. Aus. 73, 1–24.

Steeves, G., Peterson, R., Clark, L., 1998. A quantitative stereoscopic video system for visually measuring the linear dimensions of free-swimming fish. In: Proceedings of the Oceans'98 Engineering for Sustainable use of the Oceans, 28 September–1 October 1998, Nice, France Piscataway. IEEE OES, NJ, pp. 1405–1408.