A comparison of the accuracy and precision of measurements from single and stereo-video systems.

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ABSTRACT

Underwater tests using plastic silhouettes of fish were used to compare the accuracy and precision of measurements made with a single video camera system to those made from two stereo-video systems (one using digital camcorders, the other using Hi8 camcorders). Test measurements made across a variety ranges and angles of silhouette orientation in the fields of view showed the length estimates from both the digital and Hi8 stereo-video systems were substantially more accurate and precise than those obtained by the single video camera system, and had the great advantage that the position (range and bearing) and orientation of a fish target could be measured directly. Measurements made with stereo-video were much less restricted by range and subject orientation than those made with single video. The data resulting from these trials are used to propose a set of guidelines to optimise the accuracy and precision of underwater measurements of fish length using single and stereo-video systems.

INTRODUCTION

Conventional still photography and video imagery have been widely adapted in the aquatic sciences for non invasively counting and measuring organisms underwater (Boland and Lewbel 1986; Hamner *et al.* 1987, 1988; Vrana and Schwartz 1989; Naiberg *et al*. 1993; Petrell *et al*. 1997). For example stereo-photography has been used *in situ* to measure the recruitment, growth and mortality of coral colonies (Done 1981), the length of free-swimming sharks (Klimley and Brown 1983) and dolphins (Brager and Chong 1999). Stereo-videography has been used for measuring aquacultured salmon (Petrell *et al*. 1997) and reef fish (Harvey *et al*. 2001, a, b). Recent, rapid technological improvements in video cameras have improved the utility and accuracy of measurements with such systems (Harvey and Shortis 1996, 1998), complementing the advantages of predictable precision of measurements, opportunity for motion sequence capture, and the enhancement and archival storage of digital images. Video techniques can be readily adapted for use by SCUBA divers (Harvey *et al.* 2001 a, b; Shortis *et al*. 2000) or mounted on remotely operated vehicles and submersible platforms (Baldwin and Newton 1982; Li *et al.* 1996; Pitcher *et al*. 1999) to capture images at depths beyond those accessible by SCUBA divers.

Accurate and precise information on the length frequency or biomass of wild and cultured fish populations is fundamental to the management of harvesting. Monitoring of length and age permit estimates of recruitment to fished populations, fishing intensity and rates of recovery from fishing or other disturbances (eg. McCormick and Choat 1987). Accurate morphometric measurements of cultured fin-fish can be used to determine fish condition, size variations and growth rates (Petrell *et al*. 1997).

Single video camera systems have been used to measure the length frequency distribution of fish assemblages in shallow (Willis *et al*. 2000; Willis and Babcock 2000) and deepwater (Love *et al*. 2000; Yoklavich *et al*. 2000). The advantages of stereo-videography for surveys of fish length frequency and density have been demonstrated by Harvey *et al*. (2001 a, b) for reef fish assemblages. The use of stereo-video technology was superior to conventional underwater visual surveys, which have relied on the experience and subjective choices by SCUBA divers to count and estimate the range, bearing and lengths of fish within strip transects or circular point counts. Stereo-videography has also successfully been used *in situ* to measure the length of cultured fin fishes (Naiberg *et al*. 1993; Savage *et al*. 1994; Steeves *et al*. 1998), to predict the weight of individual fish and the mean biomass of the fish in a sea cage or pond (Petrell *et al*. 1997).

Harvey and Shortis (1996) reported the accuracy and precision of measurements made with a stereo-video system constructed from two 3 CCD (Charged Coupled Device) Hi8 camcorders. The image quality of readily available digital video cameras has superseded both Super8 and Hi8 video cameras, but the cost of digital video is almost twice that of current Hi8 cameras. Consequently, it is important to determine whether the extra cost of using digital video cameras produces improvements in the accuracy and precision in stereo-video measurements. Stereo-videography, with the additional costs of a second camcorder and housing, and specialist stereo-photo comparator software, needs to be justified, given the recent uses of single video camera systems for the measurement of fish length (Love *et al*. 2000; Willis *et al*. 2000; Willis and Babcock 2000).

Consequently, this paper aims to:

1. Compare the accuracy and precision of *in situ* measurements of fish length made with a single video camera system to those made from two stereo-video systems (one using digital camcorders, the other using Hi8 camcorders) over a variety of ranges and angles.
2. Determine the effect of differences in the location and orientation of fish within the field of view of the stereo-video system on the precision and accuracy of stereo-video length measurements.
3. Develop a set of guidelines that maximise the accuracy and precision of *in situ* non-invasive measurements of fish length using single and stereo-video systems.

METHODS

All trials occurred in an indoor SCUBA diving pool at the Sorrento Quay Dive Shop, Hillarys, Perth, Western Australia on the 16th of May 2000. Horizontal water visibility was estimated at 8 m using a fibreglass tape measure.

Single video camera

To enable measurement from a single video camera system, scale bars 30 cm wide and 20 cm high were placed on the bottom of the pool at 1 metre intervals in a straight line (Figure 1). The corners of the scale bar were marked with white tape as reference points for scaling during manual computer measurement from images. A plastic, fish-shaped silhouette of 45.8 cm length between the snout and the caudal fork of the tail (fork length) was filmed beside scale bars at distances of 1, 2, 3, 4 and 5 m. At each metre interval, the silhouette was moved through a series of ten degree rotations (measured with a protractor) from zero (parallel to the scale bar) through to 90 degrees (perpendicular to the scale bar). Additional scale bars were set up 0.5 m and 1 m to the left of the scale bars at 2, 3, 4 and 5 m to investigate potential errors associated with increasing the horizontal distance between the point of scaling and the subject in the same two dimensional plane. A Sony TRV900 E digital camcorder in an underwater housing was used to record the images.

Stereo-video

Trials on the accuracy and precision of measurements from both the Hi8 and Digital stereo-video systems were conducted in the same manner as for the single video system. Additional measurements were made of the distance from the centre of the camera lenses to the silhouette to determine the accuracy of range measurements. To investigate the effect of increasing the angle of a silhouette, relative to the centre of the cameras (in both the x (height) and y (width) dimensions) had on the accuracy and precision of *in situ* length estimates, 28 plastic silhouettes of fish were spaced throughout the pool and recorded with the digital stereo-video system (Figure 2). These silhouettes ranged in fork length from 120.1 mm to 880.5 mm and were placed at distances between 3 m and 7.7 m from the centre of the two camera lenses.

SYSTEM DESIGN

Stereo-video System

The stereo-video systems used in this experiment were designed to make size estimates of marine flora and fauna at distances of 1.4 to 10 m, depending on water visibility. The system and the calibration procedure are described in detail in Harvey and Shortis (1996, 1998). In brief, two video cameras are mounted in underwater housings and fixed to a base bar separated by a distance of 1.4 m. Each camera is inwardly converged at 8 degrees to gain an optimised field of view. A Light Emitting Device (LED) indicator is mounted in a housing 1.4 m in front of the cameras, above a control plate (Figure 2). The LED is visible in images recorded by both cameras and can be switched on and off manually by the operator at appropriate times, or automatically switches on every five seconds. The LED serves as a simple means of synchronising the left and right camera images from which measurements are made. It is important that the grabbed images are synchronised as this avoids any motion parallax associated with movement of the cameras or the object of interest, as motion parallax degrades the accuracy of any subsequent measurements. Harvey and Shortis (1996, 1998) used a single LED. In the system described here, a circular array of 25 LEDs was built into a unit in an underwater housing (Figure 2). When the unit is switched on, individual LEDs flash on in a clockwise sequence. Each LED lights up for less than 1/25th of a second, which is faster than the recording rate of individual frames (24 frames per second) on the PAL camcorders. The colour of the LEDs in the circular sequence alternates from red to green to orange with the colour differentiation aiding the identification of the position of individual LEDs, and the synchronisation of images. This system allows more accurate synchronisation of images than the single LED used by Harvey and Shortis (1996, 1998).

Differences in the accuracy and precision of measurement were compared between a pair of Sony TRV516 Hi8 camcorders (single CCD) and a pair of Sony TRV900 E digital camcorders (3 CCDs). The TRV516 camcorders had a ¼ inch CCD with the lenses fitted with a 0.5 times wide angle converter providing a focal length of 3.1 mm in water. The TRV900 E camcorders had a ¼ inch CCD fitted with a 0.7 times wide-angle converter giving a focal length of 3.6 mm in water. Although the two optical systems were not identical, the slight difference in focal length was the only significant difference, so the analogue and digital camcorders were sufficiently similar to allow a valid comparison of results.

IMAGE ANALYSIS

Single video

Length estimates of images of the silhouettes were made from the single camera system using EHP, an image analysis package. Images were grabbed from the digital camera using DV Raptor© and converted into 32 bit TGA. Images were imported into EHP and calibrated from the appropriate scale bar, with measurements made of the fork length of a silhouette to the nearest millimetre. Five repeat measurements of the length of the silhouette were made at each distance from the centre of the camera. For each repeat the image was reimported into EHP, and calibrated again before measurement of the silhouette.

Stereo-video system

Images were manually synchronised and grabbed in a TIFF format using DV Raptor© for digital video imagery, and Buz© by Iomega© for the Hi8 imagery. Paired synchronised images were then imported into a stereo-photo comparator, Vision Measurement System (VMS). The computer interface for stereo measurement is shown in Figure 2. 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. Measurements were made by locating the feature of interest (in this case the head or tail fork of the silhouette) 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 (Figure 2) shows 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 is logged with the measurement. 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. A detailed description of the measurement process may be found in Harvey and Shortis (1996). Although there have been substantial improvements in the measurement interface since Harvey and Shortis (1996), the fundamental measurement process and theory are the same. As with the single camera system, each set of images was loaded into the stereo photo-comparator five times to allow five independent sets of repeat measurements.

ANALYSIS OF DATA

Accuracy was defined as the nearness of a measurement to the actual value being measured, while precision referred to the closeness of repeated measurements of the same subject to one another (Zar 1984). Estimates of accuracy and precision were derived for the fork length data generated from the single video camera and for the fork length and range data gathered from both the digital and Hi8 stereo-video systems. The accuracy was calculated by subtracting the known length or distance from the observed measurement made from the single and stereo-video systems. Negative values represented under-estimates and positive numbers represented over-estimates. The coefficient of variation (CV) was calculated by dividing the standard deviation of the estimate by the mean value of the estimate, and expressed as a percentage. CV is a useful measure of precision widely used in field research (eg. Thresher and Gunn 1986). The standard error (SE) of the measurements was also calculated.

RESULTS

Single video

At ranges from 1-5 m the single video measurements were reasonably accurate (mean error = 13.62 mm) and very precise (SE = 1.97 mm, mean CV = 1.00%) provided that the measured silhouette was:

1. beside the scale bar from which the image was calibrated and;
2. perpendicular to the camera.

As the angle of the rotation of the silhouette relative to the camera increased, there was a substantial degradation of the measurement error (Figure 3), and the precision of single video measurements deteriorated as the angle of the silhouette increased (0° CV = 0.71%, 50° CV = 1.60%, 90° CV = 2.14%). If all measurements at all angles of rotation are considered (Table 1), the single video system had a mean error of 86.84 mm (SE = 12.77 mm).

Changes in the position of the silhouette relative to the point of scaling had a major affect on the accuracy, but not on the precision of measurements of the length of the silhouette (Figure 4). It is notable that large positive errors result when a silhouette was in front of a scale bar from which the image is calibrated. If a fish is closer to the camera than the scale bar used to calibrate a measurement, the fish will occupy a proportionally larger area than it would if it were located beside the scale bar.

Consequently even if the horizontal distances on the scale bar and the length of the fish are similar, the fish will be measured as being longer than the horizontal distance on the scale bar. Conversely, if the fish is behind the scale bar the measured length will be shorter than the true length of the fish. For example, if a scale bar is placed 3 m from the camera, and a fish is measured at a distance 1 m from the camera using the 3 m scale bar to calibrate the image, over-estimates of the fork length of the fish in the order of 240% could be expected. Similarly, if a scale bar were located at 2 m from the camera and a fish was to be measured at 5 m, under estimates in the length of up to 76% could be expected. The overall trend of decreasing error with distance is evident in Figure 4. Local variations for data points at the same distance can be explained by minor variations in the image calibration from the same scale bar. Standard errors and CV of the fish length remained consistent at all combinations of range.

As the distance to the silhouette parallel to the scale bar increased both the precision and accuracy of length measurements deteriorated (Figure 5). Once more, the magnitude of the error is greatest at distances closer to the camera because the proportional error is greater. At the most distant ranges from the cameras, the relative error in the scale determination is comparatively small.

Stereo-video length estimates

Measurements of the length of a silhouette perpendicular to the digital stereo-video system at ranges between 2 - 9 m were more accurate (mean error = 1.26 mm) and precise (SE = 3.49 mm, CV = 5.07 %) than those made with the Hi8 stereo-video system (mean error = 7.60 mm, SE = 6.60 mm, CV = 9.50 %). As range increased the accuracy and precision of measurements made with both systems worsened, but this trend was more pronounced for the Hi8 stereo-video data (Figure 6).

Stereo-video range estimates

Measurements of range with the digital stereo-video system produced more accurate and precise estimates (mean error = 6.38 cm, SE = 0.99 cm, CV = 0.87 %) than those made with the Hi8 stereo-video system (mean error = 31.08 cm, SE = 3.11 cm, CV = 1.08 %) (Figure 7).

OPTIMISING MEASUREMENT ACCURACY AND PRECISION

The effect of increasing the angle of rotation of the silhouette on the accuracy and precision of stereo-video length estimates

As the angle of rotation of the silhouette relative to the camera systems increased from 0 degrees (silhouette perpendicular to the camera systems) to 90 degrees, both the accuracy and precision of measurements made by both the stereo-video systems deteriorated (Figure 8). If the silhouette was rotated at angles between 60 degrees and 90 degrees, the accuracy and precision of length measurements worsened rapidly. At the extreme rotation angles it became difficult to distinguish the edges of either the head or the tail of the silhouette in both the left and the right images. In some cases, the body of the silhouette obscured the head or the tail making measurement of the fork length of the fish impossible (Harvey and Shortis 1996).

The effect of increasing the angle of the position of the silhouette in the stereo-video field of view

The accuracy (mean error = -0.71 mm) and precision (SE = 0.45 mm, CV = 0.95 %, n=68) of length estimates made in a variety of different positions throughout the field of view of the digital stereo-video system were comparable with those made directly in front of the system. If measurements were taken across the complete field of view of the digital stereo-video system, the accuracy and precision at the edges of the field of view were similar to those at the middle field of view (Figure 9). Similarly, there did not appear to be any difference in the accuracy and precision of measurements when silhouettes were recorded higher in field of view (Figure 10).

Developing guidelines to maximise the accuracy and precision of length measurements

Single camera measurements

For single camera measurements the error and precision deteriorated when the silhouette was rotated to an angle of more than 70 degrees to the camera (Figure 3). If measurements were made only from silhouettes that were at angles less than 70 degrees to the camera, there were substantial improvements in the accuracy and precision (Table 1).

Stereo-video measurements

Figure 6 clearly shows that for the digital stereo-video system the accuracy of the measurements started to degrade at a range of 7 m and beyond. Given that the maximum visibility (the distance at which the unaided human eye could clearly define the edges of objects) was 8 m during these trials, only images within a range of 85% of the maximum visibility should be measured. This ensures that the silhouettes or fish could be clearly seen, facilitating accurate and precise measurements. For the

Hi8 stereo-video cameras the accuracy and precision of measurements decreased rapidly at a range of 6 m and beyond, indicating that the maximum range at which subjects could be measured should be approximately 75% of the maximum visibility. The difference in the recommended range ratios at which subjects can be measured by the Hi8 and digital cameras is most probably due to the poorer image quality of the Hi8 video cameras.

Figure 8 indicates that mean errors deteriorate markedly when the subject to be measured is rotated 60 degrees or more away from the camera systems. If the object is orientated at greater than 60 degrees rotation or more away from the cameras, or if the object can not be clearly seen, measurement should not be attempted. Although the angle of rotation is not known accurately prior to the measurement, the visual check of being able to see both the snout and tail clearly can be applied, and measurements exceeding the criterion discarded once the angle is known.

Optimum number of repeated measurements

One of the most significant advantages of stereo-video technology is the ability to make repeat measurements of the length of a particular object (Harvey *et al*. 2001a). Taking the mean of a set of repeated measurements can substantially improve the accuracy and precision of stereo-video measurements. A total of five repeat measurements were made of 44 silhouettes with both systems (Figure 11). For the digital stereo-video system the optimum number of repeat measurements was three, after which there were no large gains in either the accuracy or the precision of measurements. For the Hi8 stereo-video system there were still substantial improvements in the precision after five repeat measurements (Figure 11).

Optimum size of the zoom measurement window

When making measurements with the stereo-photo comparator VMS, it is possible to adjust the number of pixels that are displayed in the variable zoom window (Figure 2). The number of pixels can be set from 10 x 10 up to 128 x 128, with a corresponding decrease in the level of detail in the zoom window. To determine the optimum number of pixels, measurements were made of a single silhouette over a range of distances, and with different combinations of zoom window sizes. In general, more accurate and precise measurements were made using a zoom window with a lower pixel count (30 x 30) than a larger count (128 x 128) (Figure 12). If the number of pixels set was too low, it became difficult to manually select the position of features of interest for measurement.

Summary of rules for optimising single and stereo-video measurements

Measurements of fish length should not be attempted with a single video camera if:

1. the fish is oriented at an angle equal to or greater than 70 degrees to the camera;
2. the fish is in front of, or behind the point of scaling;
3. the fish is more than 1m to the left or right of the point of scaling, and in the same plane parallel to the scaling point relative to the camera.

Measurements of fish length should not be attempted with a stereo-video camera if:

1. the fish is oriented at an angle equal to or greater than 60 degrees to the camera system;
2. the fish to be measured is at a range greater than 85% of the maximum horizontal visibility for digital stereo-video systems and 75% for Hi8 stereo-video systems.

If these guidelines are applied to the selection of images recorded by the single camera, digital and Hi8 stereo-video systems used in these trials, there are substantial improvements in both the accuracy and precision of length estimates (Table 1).

DISCUSSION

The ability to be able to make accurate and precise non-invasive measurements of fish length is important to managers of wild and aquacultured fish stocks. It has been demonstrated that the accuracy (mean error = 13.62 mm) and precision (SE = 1.41 mm) of single video measurements are similar to those reported by Willis *et al*. (2000) and Willis and Babcock (2000) (mean error = 16.9 mm, SE = 2.4 mm). The single camera system used by Willis and Babcock (2000) was mounted 115 cm above, and looking vertically down onto, a triangular base used to calibrate the images. Our measurements were made horizontally and over a much greater range of distances. The fish measured by Willis and Babcock (2000) were most likely swimming into the camera field of view above the calibration base. It is therefore likely that their field measurements significantly over-estimated the true length of the fish in the field of view. Our study has shown that measuring a fish that is closer to the single camera system than the point of scaling will result in significant over-estimates in length measurements.

This issue might be partially overcome by using paired, parallel laser dots as scaling points (Love *et al*. 2000; Yoklavich *et al*. 2000). The distance between the laser dots reflecting off the body of a fish provide a constant scaling regardless of distance, provided the fish traverses the beams. However, we have shown that as the angle of rotation of the fish increases, the accuracy of such measurement system is severely compromised. A rotation greater than 70 degrees increases the measurement error above 10% of the body length. Accurate measurements using laser dots are also restricted to the particular fish on which the lasers dots are displayed. Measuring fish that are in front of or behind that fish, or 50 cm or greater to the left or right of the fish used for scaling an image, will result in substantial degradations in accuracy and precision. Thus, laser measuring systems based on single cameras are limited to measurements of single fish in any one image and, depending on the requirements for measurement accuracy, are limited to measuring fish that are perpendicular to the camera system. Furthermore, it is only possible to make measurements of distance with a triangulating laser system (Caimi and Bessios 1994)

Both the digital and Hi8 stereo-video systems were substantially more accurate and precise in their length measurements than the single camera system and had the added advantage that measurements of the range of a fish, and the angle relative to a central point between the camera lens, could be made. These range and angle measurements are essential if line transect theory (Burnham 1980; Buckland *et al*. 1993**)** is to be applied to surveys of reef fish. Additionally, it was possible to accurately measure the length of a silhouette over a greater range of rotation with improved accuracy compared to the single video camera. If guidelines are applied to the selection of fish to be measured in images, significant improvements in measurement accuracy and precision can be achieved.

The digital stereo-video system had significantly better accuracy and precision in both range and length measurements when compared to the Hi8 stereo-video system for two principal reasons. Firstly, the digital systems had the advantage of a 19% longer focal length, and this fundamental characteristic enhanced accuracy and precision. Secondly, the images captured from the digital camcorders had superior resolution and colour fidelity (see Figure 13). Significant differences in image quality and noise are apparent in the main images of Figure 13 and are highlighted in the magnified segments inset at the bottom. One inset shows a coded target (used in the calibration procedure to automatically recognise the orientation of the calibration frame) and the visually clearer image from the digital camera is evident. The pair of insets for each image demonstrates the image noise in a relatively uniform area of the image on the black cloth. The left inset of the pair shows exaggerated noise and the right inset of each pair shows histogram-equalised noise. Whilst the digital image shows slightly higher noise levels, probably due to poorer low light sensitivity, the noise from the digital camera is clearly more random. The noise from the Hi8 camera is less random probably due to the analog tape recording, which tends to smear the image and the associated noise (Shortis *et al.* 1993), and an apparent correlation of intensity between adjacent horizontal lines that is possibly caused by the architecture of the interline CCD array (Shortis and Beyer, 1996). The reliability and quality of digital tape recording preserves the randomness of the noise produced by the combination of the CCD sensor and optical components of the camera. This allows the manual point and click measurements by operators to be substantially more accurate and precise, especially at greater ranges in the field of view. The accuracy and precision of the digital stereo-video system compares very favourably with the published measurements from other systems.

The system used by Petrell *et al.* (1997) could measure the fork length of anaesthetised Chinook Salmon to within ±3.0%, giving estimates within 97.0 to103.0 cm for a fish of 100 cm fork length. The digital stereo-video system described here, using standard, off the shelf digital camcorders, produced a mean accuracy of 0.22mm. (±0.05%). If the same 100 cm salmon was measured using the digital stereo-video system described here, a 95% confidence limit would produce estimates within the range 99.32 to 100.68 cm.

For the assessment of wild fish stocks remote stereo-video systems can be deployed to greater depths for longer periods of time than divers (Francour *et al*. 1999), and often record greater biodiversity of fish life than other conventional stock assessment techniques (Cappo *et al*. 2000). The demonstrated accuracy and precision of the stereo-video system, combined with the reliability embodied in the measurement guidelines given above, provides an increased incentive to pursue this technique and deploy remote stereo-video systems in preference to remote single cameras.

CONCLUSION

Stereo-video systems (Harvey and Shortis 1996; Li *et al*. 1996; Petrell *et al*. 1997; Steeves *et al*. 1998) have much utility for managers of wild and cultured fin-fish as a data collection tool. Accurate information on the length frequency, width and height of fish, and the distance between individual fishes can be collected in a cost-effective and harmless manner. Additionally, if the camera system is located in a fixed position it is possible to determine the swimming speed of fish by determining the x, y, z location of a fish at time *A* and calculating the distance the fish has travelled at time *B*. Further innovation is needed to measure the three dimensional volume of fish. This measure will be a more useful indicator of fish condition and size frequency than measurements of length. The accuracy, precision and versatility of single video camera systems is limited in comparison to stereo-video. One of the significant drawbacks of stereo-videography is the time required to post process imagery. Progress is needed in the field of automating the recognition (Culverhouse *et al*. 1996; Ellis *et al*. 1997; Zion *et al*. 1999) and measurement of fish (Shortis *et al*. 1998) from stereo-video imagery.

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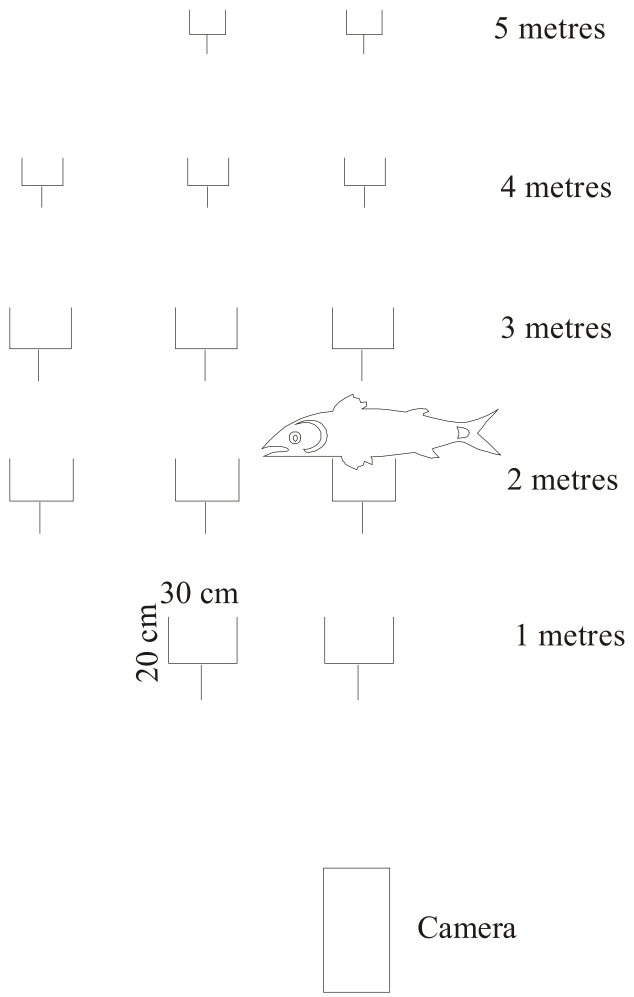


Figure 1. The layout of the scale bars used to determine the effects of changing the distance of the subject to be measured relative to the unit used to scale the image.

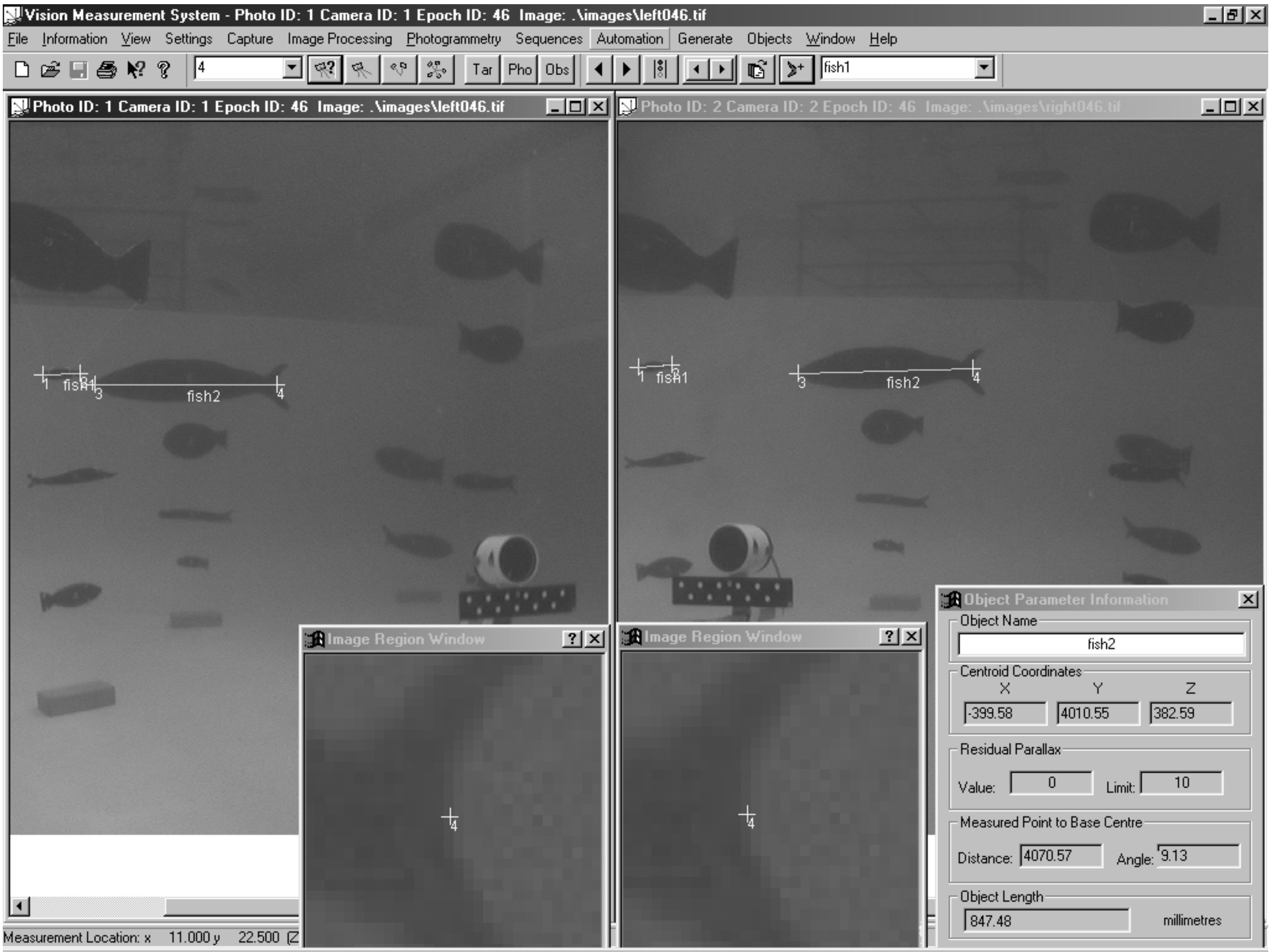


Figure 2. The computer measurement interface (VMS). The LED synchronisation unit and the control plate are visible in the lower centre of each of the larger images. The two smaller windows at the bottom centre are the variable zoom windows. The object parameter information window is located in the lower right of the image and displays the xyz coordinates, the distance, angle of the measurement and length of fish 2.

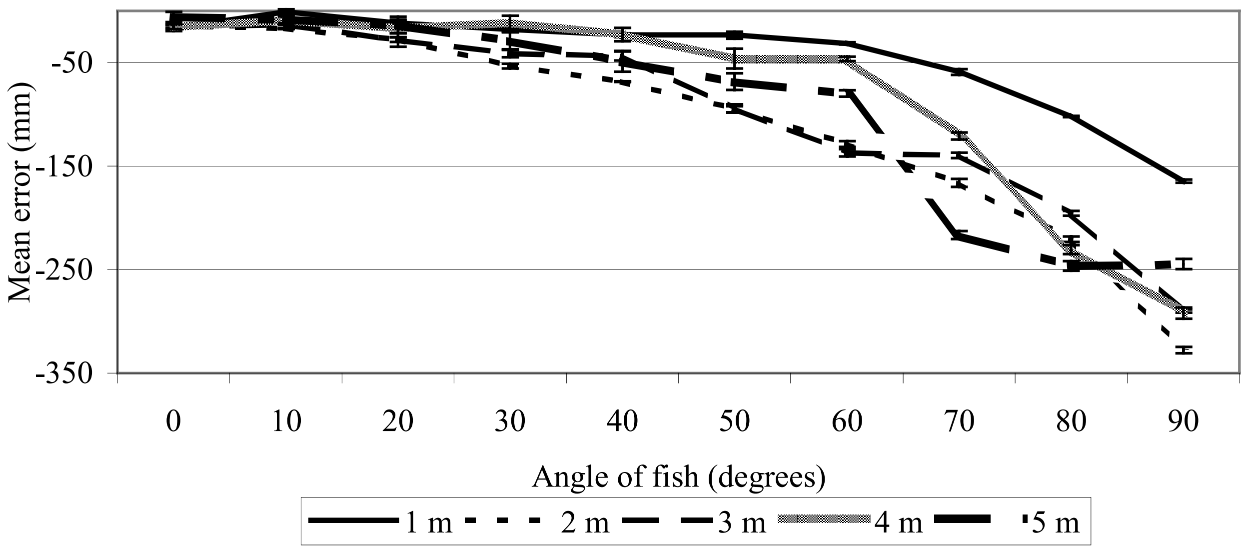


Figure 3. The effect of increasing angle of the silhouette on the accuracy and precision of single video camera measurements. Error bars indicate ±2 standard errors.

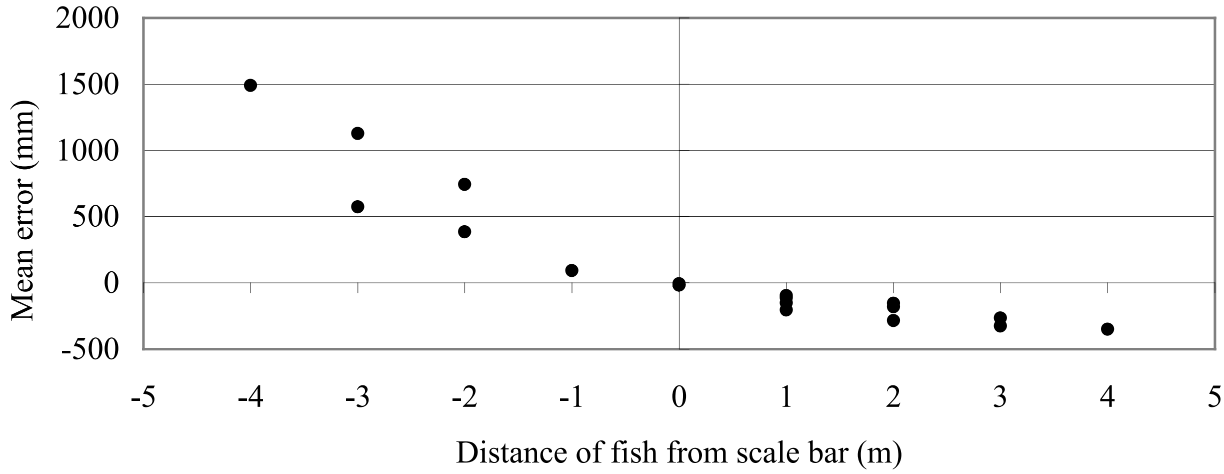


Figure 4. The affect of the position of the silhouette relative to the point of scaling on the accuracy of measurements of the length of a silhouette. Negative distances indicate that the plastic silhouette was in front of the scale bar. Fewer measurements were made when the silhouette was in front of the scale bar because the silhouette often blocked the view of the scale bar.

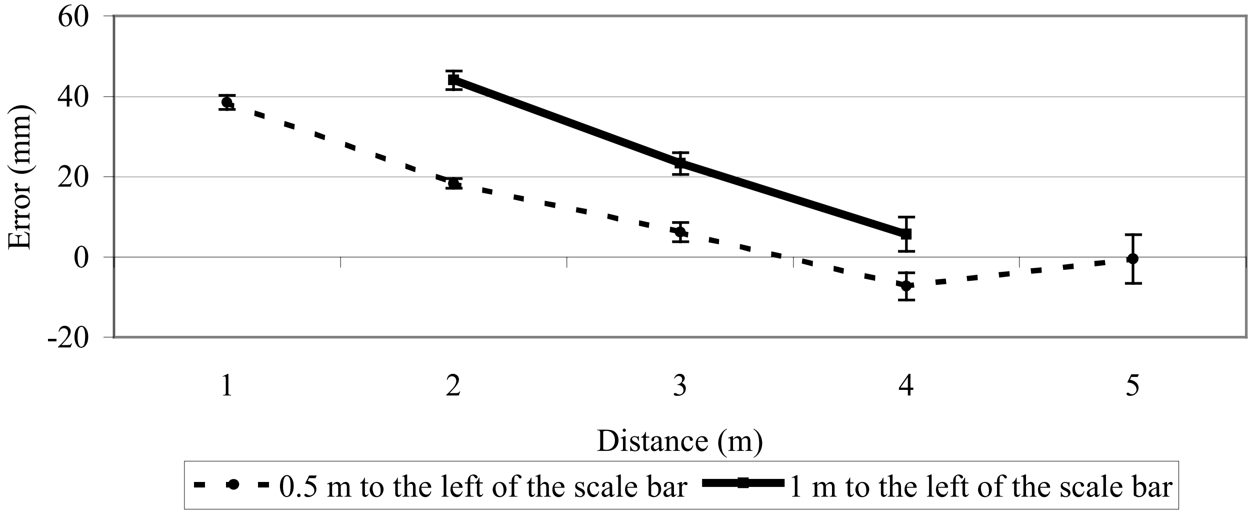


Figure 5. The effect of increasing the perpendicular distance of the silhouette from a scale bar on the accuracy and precision of measurements from a single camera system. Error bars indicate ±1 standard error.

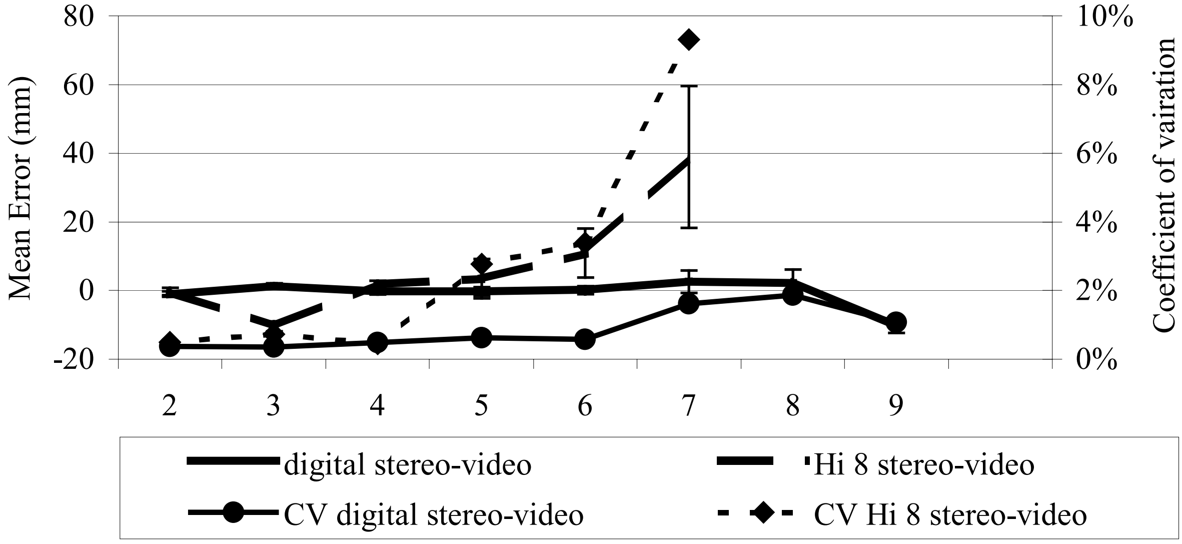


Figure 6. The accuracy and precision of length measurements with a digital stereo-video system and a Hi8 stereo-video system. Error bars indicate ±1 standard error.

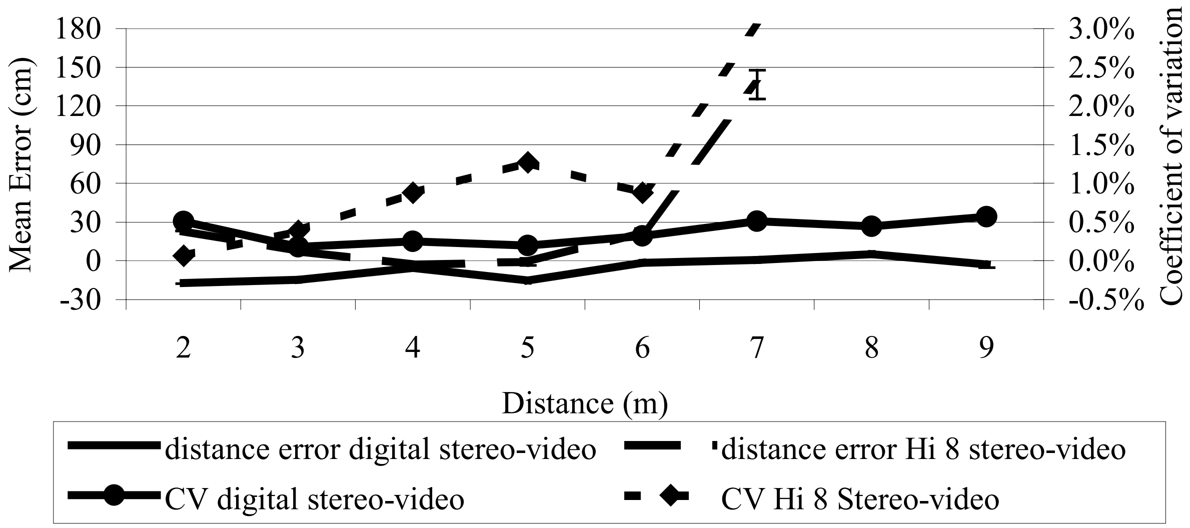
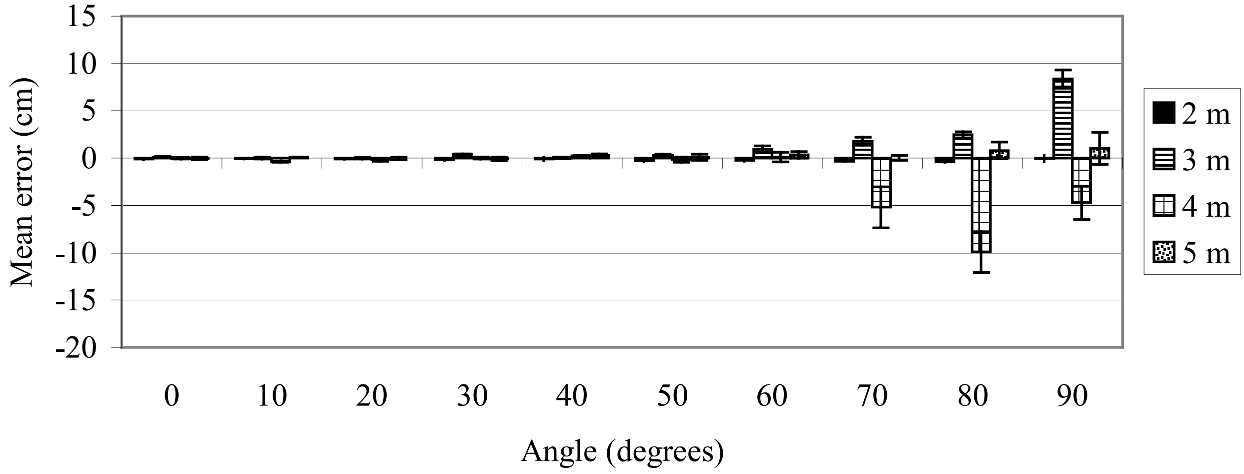


Figure 7. The accuracy and precision of distance measurements with a digital stereo-video system and a Hi8 stereo-video system. Error bars indicate ±1 standard error.

(a) Digital stereo-video



(b) Hi8 stereo-video

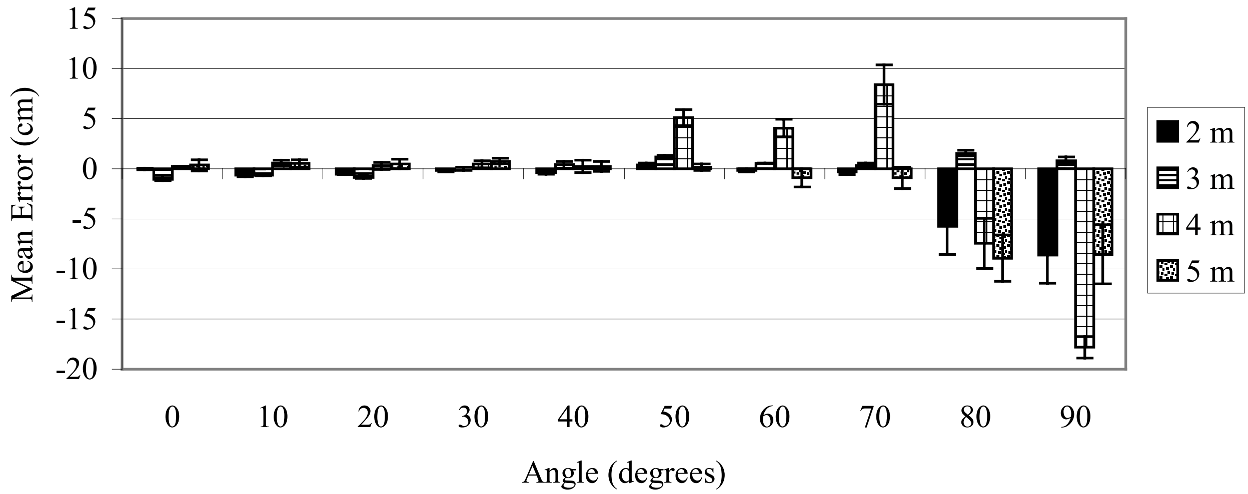


Figure 8. The effect of the increasing angle of the subject, relative to the camera system on the accuracy and precision of length estimates made with (a) a digital stereo-video and (b) a Hi8 stereo-video. Error bars indicate ±1 standard error.

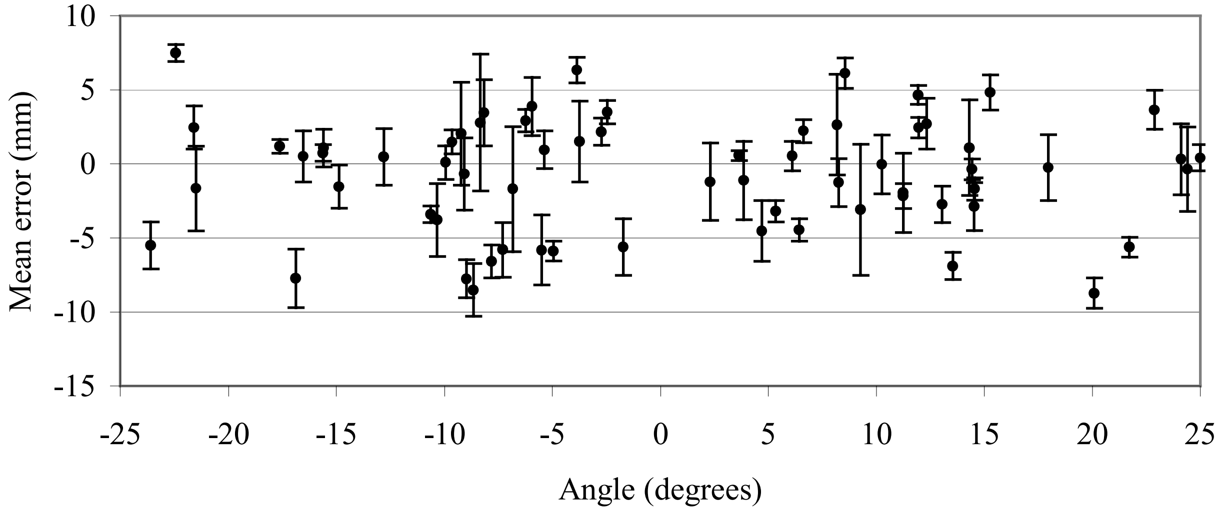


Figure 9. The effect of increasing the angle of the position of the silhouette in the width dimension of the field of view on the accuracy and precision of digital stereo-video measurements. Error bars indicate ±1 standard error.

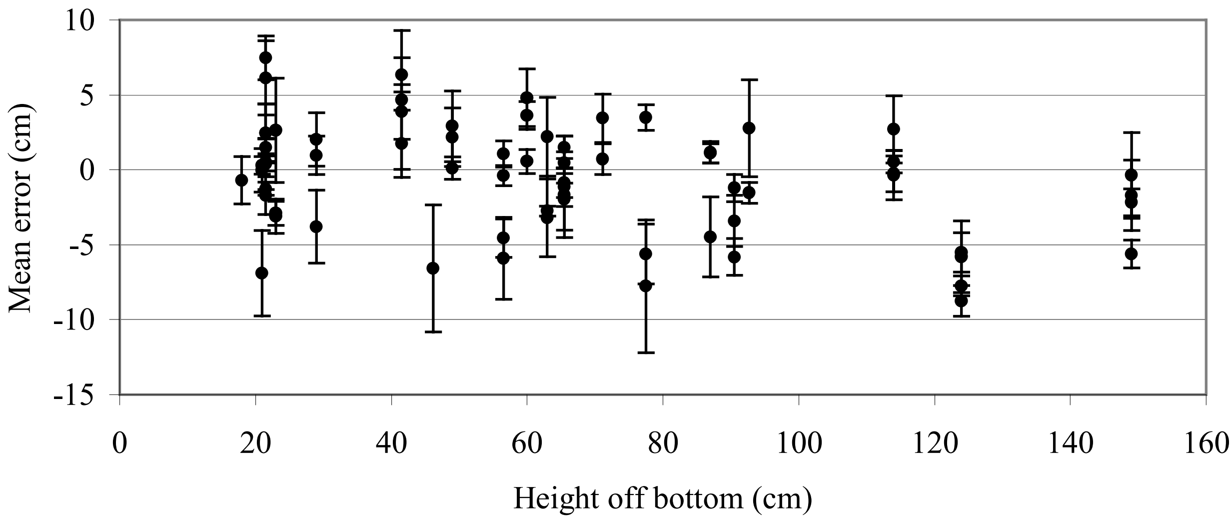


Figure 10. The effect of increasing the angle of the position of the silhouette in the height dimension of the field of view on the accuracy and precision of digital stereo-video measurements. Error bars indicate ±1 standard error.

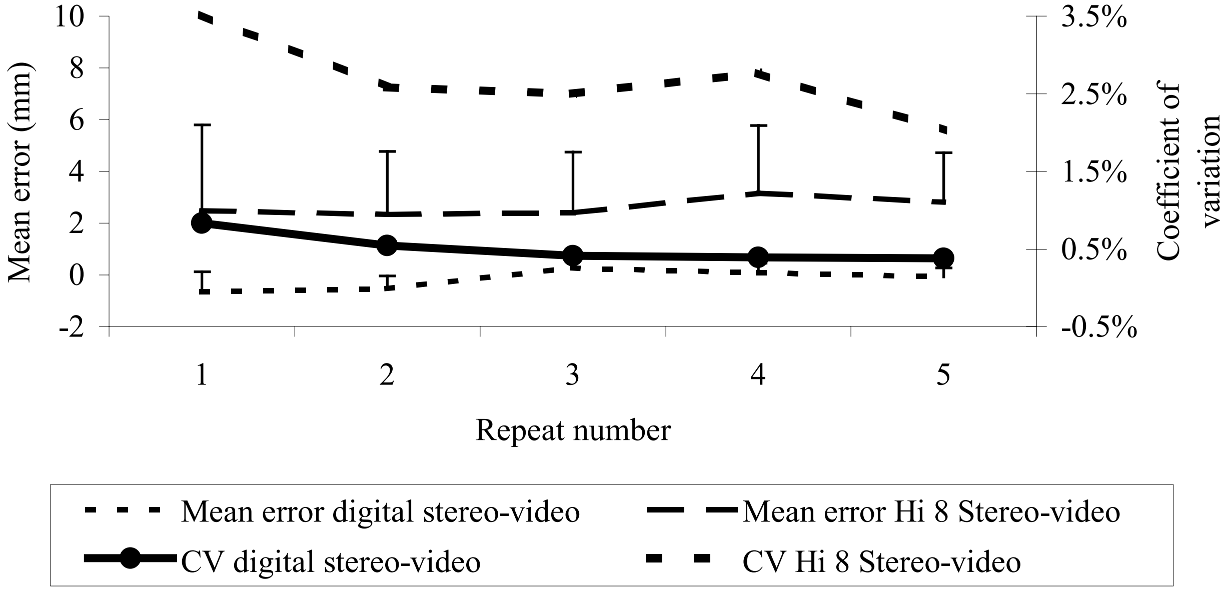


Figure 11. The effect of increasing the number of repeat measurements on optimising the accuracy and precision of measurements from digital and Hi8 stereo-video systems. Error bars indicate ±1 standard error.

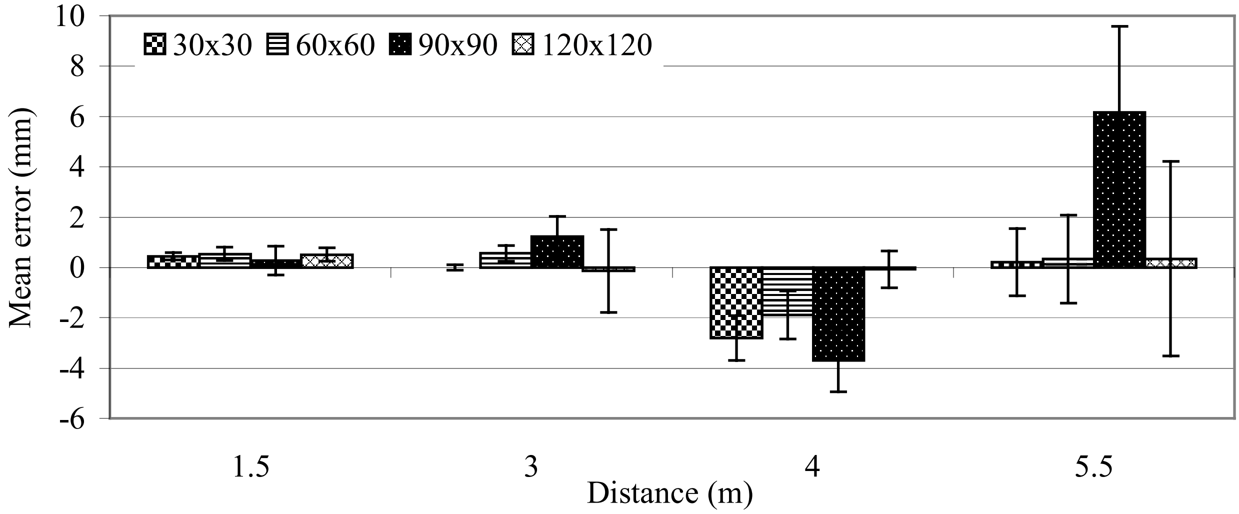


Figure 12. The effect of the ratio of pixels displayed in the variable zoom window on the accuracy and precision of length estimates. Error bars indicate ±1 standard error.

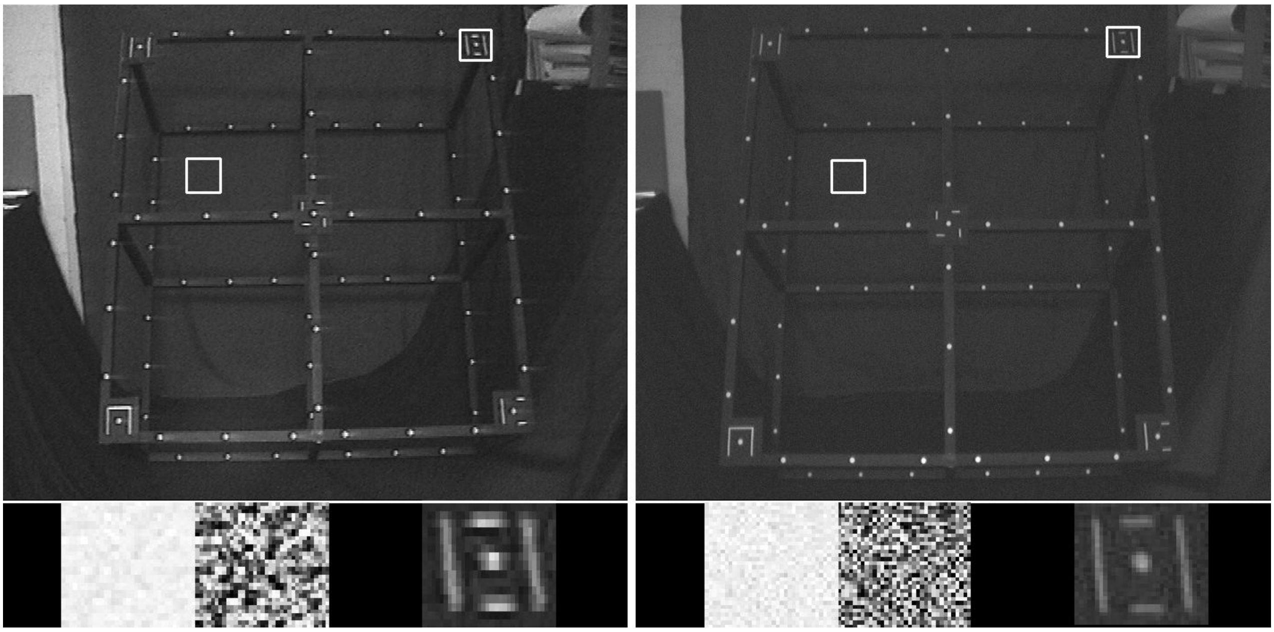


Figure 13. Comparison of images from the Hi8 (left) and digital (right) cameras. The inset images for each type of camera show enlarged sections of, from left to right, enhanced noise, histogram-equalised noise and a coded target. The noise and coded target regions used are indicated on the main images by the white outlines.

Table 1. Improvements in the accuracy and precision of length estimates made from Digital and Hi8 stereo-video systems and a single following the application of guidelines.

	Single camera		Digital stereo-video		Hi8 stereo-video	
	Before	After	Before	After	Before	After
Mean error (mm)	-86.84	-14.34	-1.26	-0.22	7.60	-0.98
Std deviation (mm)	90.34	7.19	23.17	1.73	42.77	5.25
Std error (mm)	12.77	1.86	3.49	0.37	6.60	1.12
Sample size	50	15	44	22	42	22
CV (%)	24.34%	1.62%	5.07%	0.38%	9.50%	1.15%