A System for Stereo-Video Measurement of Sub-Tidal Organisms

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Abstract

The *in situ* estimation of the length of marine biological specimens or features by Scuba divers is complicated by the magnifying properties of water and the underwater environment. In this paper we describe the development and preliminary testing of an underwater stereo-video system which is designed to make accurate and precise measurements of the lengths of marine subjects. The results of 640 measurements of 16 plastic silhouettes of fish are presented. The initial results demonstrate the ability of the system to make accurate and repeatable measurements of length when the orientation of the subject to the stereo-video cameras is less than 75 degrees.

Introduction

In situ visual estimates of the size or length of marine organisms are frequently made by ecologists aided by self contained underwater breathing apparatus (SCUBA). Size or length data have been collected in this manner particularly for reef fish (Jones and Chase, 1975; Harmelin-Vivien and Bouchon-Navaro, 1981; Russ, 1985; McCormick and Choat, 1987; Bellwood and Alcala, 1988; Kulibicki, 1989; Samoilys, 1989; Francour, 1994). These estimates of size or length may be used to assess the biomass or population size structure of selected species, to detect seasonal changes in these variables or for detecting environmental impacts. Visual estimates have advantages over other sampling techniques in that they are rapid and non-destructive.

However, making accurate and precise visual estimates of the length of objects underwater is extremely difficult and requires the observers to be well trained and experienced (English et al., 1994). The estimation of the length of an object underwater is complicated by the magnification of water. In water objects are magnified by a factor of 1.3 and objects appear to be closer to the observer than the actual range. Researchers using SCUBA are not efficient workers when performance underwater is compared to similar activities in the air (Hollien and Rothman, 1975). Additionally, the sampling bias and errors resulting from the detrimental physiological effects related to SCUBA diving (Baddeley, 1965; Baddeley et al., 1968) must be of concern.

Where data from visual size or length estimates have been published few authors attempt to state the precision or accuracy of their data. Problems with long-term studies occur when different observers may be involved in making estimates of size or length of marine organisms at different spatial and time scales. Even though calibration procedures are used by some researchers (GBRMPA, 1979; Bell et al., 1985) inter-observer variability still poses a major bias. If the data collected are to be used to compare the size estimates recorded for different times, places or species then it is important that the level of precision and accuracy is stated to allow realistic interpretation of the comparisons.

These visual estimates, particularly of the length of reef fish, often lack precision and accuracy. Due to observer error and biases it is probable that many studies lack statistical power to detect small changes in the length of the organisms being studied (English et al., 1994; Fairweather, 1991). To overcome the problem of subjectivity in visual estimates and enhance accuracy and precision, an impersonal system of measurement is needed. Clearly, any impersonal system of measurement must be technology based, but within the limits imposed by the underwater environment and finite resources of research organisations.

Klimley and Brown (1983) described the use of stereophotography for estimating the size and dispersion of free swimming sharks. The system was viable underwater, convenient to use for measurement and could be developed or purchased at a reasonable cost. Since this project there have been rapid technological improvements in video cameras which improves the potential of such a system. The objective of this research is the development of a stereo-video system which can accurately and precisely determine the size or length of objects underwater.

What is Photogrammetry?

Principles

Photogrammetry is essentially the science of quantitative analysis of measurements from photographs. Photogrammetry pre-dates photography, as da Vinci and Desargues developed the principles of perspective and projective geometry in the 14th and 16th centuries. The first actual applications of photogrammetry for qualitative mapping occurred with the early photographic processes, but production line mapping systems were not introduced until the 1930s (Slama, 1980).

Quantitative photogrammetry is primarily derived from pairs of photographs. If two photographs image a common area of view, in much the same way as binocular vision operates for mammals and other animals, the perception of depth is possible. Also known as stereophotogrammetry, the use of stereo photographs is the basis for most photogrammetric recording and mapping, as it allows both position and height to be measured. Traditionally, a human operator is required to interpret the features imaged on the stereophotographs and delineate, in three dimensions, the desired detail of the object or terrain.

The most familiar aspects of modern day photogrammetry are maps and charts of the Earth. Aerial photography and stereophotogrammetric analysis are used to produce the vast majority of topographic maps, street directories and tourist maps in use today. Modern systems use computer based capture and presentation systems which integrate the information into a CAD or geographic information system (GIS). Most of the maps and charts produced from such systems are at medium (1:5,000 to 1:50,000) or small scale (1:100,000 and smaller). Smaller scale maps, such as those used in an atlas, are generally derived from compilations of photogrammetric products. All such maps and charts are cartographically designed, analysed and enhanced to aid in the presentation of spatial features, and the relationships between features, to the map user.

Photogrammetry is also in use for archaeological and architectural recording, biological measurement, industrial metrology and engineering surveillance, just to name a few of the many “close-range” applications (Karara, 1989). In many cases a large scale map or a chart is produced, for example a line plot and sections of a building facade undergoing restoration, for analysis and interpretation of an architect. The majority of these applications do not require a high level of precision nor reliability and also use stereophotogrammetric techniques.

Industrial and engineering applications of close-range photogrammetry have very different requirements. First, stringent levels of precision and reliability are likely, especially in the aerospace and manufacturing industries. This requirement necessitates additional camera stations beyond the two photographs of a stereo pair. Multiple photographs from a variety of different perspectives constitutes a photogrammetric network, and the improvement in precision and reliability is proportional to the square root of the number of camera stations. Secondly, the output of the process is often only coordinates of signalised points on the object. Individual locations to be measured are marked with a target or other unambiguous signal to uniquely identify the point and enhance the accuracy of measurement. Such points may be placed to identify key dimensions of the object, or to characterise a surface at a known sampling density. The coordinate set is then subjected to post-analysis, generally by the client for whom the measurement task was undertaken.

Photogrammetry has been used specifically for various types of biological recording and analysis, generally using stereo photographs. Film-based stereo-photogrammetric analysis has been used to make many types of biological measurements; the shoulder heights of animals (Ruther, 1982) and the demography of under-water plants (Kaczynski and Szmeja, 1988) being just two examples. When this type of measurement process is applied to the human form it is known as biostereometrics. This science has been applied to a wide variety of measurement tasks in medicine and bio-engineering using film, X-ray and video photography over a number of decades (Herron, 1974; Baumann and Herron, 1988).

Image Recording, Measurement and Processing

Traditionally, images of the object to be measured are exposed from two or more different view points and recorded on film or glass plate negatives. The image locations are then measured using manual or semi-automated devices such as photogrammetric comparators or stereoplotters. A comparator is effectively a very precise x-y digitiser with the facility to record the measured locations in computer readable form. Stereoplotters are typically analogue devices which use an opto-mechanical system to view and measure image locations on the photographs.

The image locations are connected to the corresponding points on the object under the assumption that the camera lens provides a perfect central projection and the focal plane of the camera is perfectly flat. In other words, the image point, the perspective centre and the object point should be collinear. As no lens system is perfect, small errors in the otherwise ideal central projection have to be accepted, or models of variations such as lens distortions and image plane unflatness are applied to correct the collinearity. Some cameras are specifically designed for photogrammetric measurement to have insignificant departures from a perfect central projection. The camera lens must have minimal distortions and there must be a vacuum or platen system to flatten the film or glass plate against the focal plane. This is typical of the so-called “metric” cameras, used in aerial mapping systems to produce medium and small scale maps of the earth.

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 collinearity model can be compensated. The calibration process can be characterised as a procedure of taking multiple photographs of a test object with some particular attention to the placement and attitude of the camera. If the test object is also the object to be measured, then the process is known as “self-calibration”.

The object photographed is then re-created in three dimensions using the principle of collinearity. The observer, combined with the mathematical algorithm, can be considered to be a 3D digitiser which can locate any point which is visible on the surface of the object. Natural and man-made features can be located or delineated to produce regular or free-from descriptors of the surface, limited only by the image resolution. After some post-measurement analysis and processing, simple paper plots or complex CAD/CAM models can be generated from the image measurements in order to visualise the shape of the object, the surface detail of the object or both.

Photogrammetry has a number of advantages as a general measurement system. First, it is a non contact, remote sensing technique and minimal direct information is required from the object to be measured. This technique can be potentially adapted for use in conjunction with Remote Operated Vehicles and Submersibles to assist scientific explorations investigating sub-tidal environments at depths beyond those accessible by researchers aided by SCUBA (Turner, 1992). Photogrammetry can assess objects of almost any size or orientation. The precision of the object measurement can be adjusted by varying the geometry of the photography, in particular the separation of the camera stations, the distance to the object and the focal lengths of the cameras used to suit a wide range of applications. Lastly, photographic records can be kept in archival storage for re-measurement if re-assessment is required.

Like all measurement tools, photogrammetry also has its disadvantages. These include the cost of the equipment, vulnerability to malfunction resulting in down time, and the time required to process data. The technique is limited by the quality and resolution of the photography, and can be impractical in situations where very convoluted objects are to be measured or where there are many foreground obstructions.

New Developments in Photogrammetry

Currently, conventional still film has advantages over video images in terms of resolution and dynamic range. However, perhaps the most pressing problem for film-based still photography in the biological sciences is that film resources are finite and have quite large sampling intervals, which is often inadequate in dynamic situations. This is particularly relevant for counts of reef fish where the subjects are usually moving, in some cases quite rapidly. The sampling interval that would arise between winding a still camera onto the next frame may result in subjects not being recorded. Additionally, when operated by a researcher using SCUBA the use of full face dive mask containing an underwater microphone linked to the video camera permits audio observations made by operators to be recorded on top of visual records (Byers, 1976; Erwin, 1976). Conventional still film must be photographically processed, and after processing cannot easily be altered in exposure, contrast or balance, unlike digital images. In addition, the measurement of the photographic images requires specialist skills and expensive photogrammetric equipment.

Automation of the measurement process has been the subject of research during the last several years. Digital image based systems are only now becoming widespread due to advances in machine vision technology, but more importantly because they are relatively inexpensive and can be used by non-specialists. Digital systems use either conventional film which is then scanned (Shortis, 1988) or camcorder or CCD type cameras to capture the digital image directly (Fraser and Shortis, 1995). Although such systems still have limitations imposed by the relatively low resolution of sensors and large storage requirements of digital images, digital photogrammetry has been rapidly accepted and has found many applications in the areas of manufacturing, industrial inspection and biological measurement (Gruen 1992).

The clear advantages of direct video recording are the ability to capture motion sequences at a high sample rate and the possibility of digital image processing and analysis to enhance the imagery. Early testing quickly showed that the principles of stereo-photogrammetry could be combined with video technology to allow the measurement of the sizes of the subjects and their distance from the camera (Wong and Wei-Hsin, 1986; Boland and Lewbel, 1986).

System Design

Camera System

This stereo-video system was designed to make size estimates of large mobile reef fish at distances of between 2 and 10 meters depending upon water visibility. The stereo-video system uses two Sony VX1E Hi 8 video cameras. The cameras have a sensor resolution of 795 (horizontal) by 596 (vertical) pixels. The cameras are mounted in water proof housings on a neutral buoyancy frame. The base separation of the cameras was dictated primarily by the ability of the diver to manipulate the frame underwater. A larger frame would improve the overall measurement precision due to an increase in the base separation of the cameras, but would be more difficult to manoeuvre underwater. The compromise adopted was a base separation of 1.4 metres.

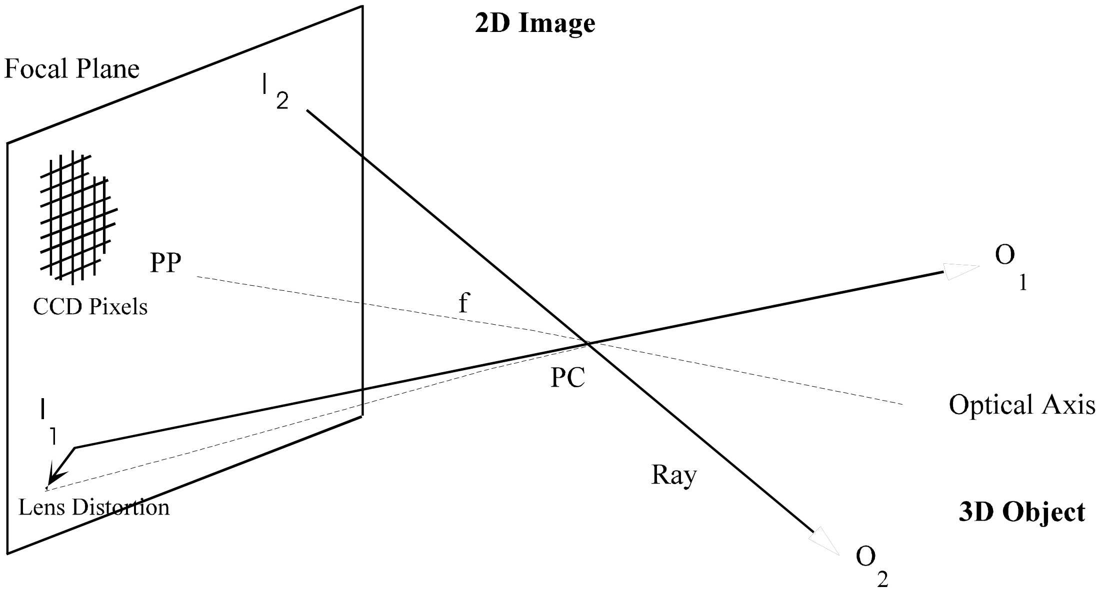
The focal lengths are set at 10 mm or 5mm to obtain fields of view of 2.5 or 5 metres at a range of 5 metres. Each camera is inwardly converged at 8.5 degrees to gain an optimised field of view. Like the base separation, these design issues are adopted as a compromise between competing considerations. For example, shorter focal lengths increase the field of view, but decrease the measurement precision. Similarly, a more acute convergence would improve the measurement precision, but decreases the useable field of view and increases the apparent perspective distortion.

A Light Emitting Device (LED) is mounted above a calibration plate 2.5 metres from the centre of the camera base bar. The LED, which can be seen in the images recorded by both cameras, can be switched on and off manually by the operator at appropriate times and serves as a means of synchronising the left and right images from which measurements will be made. It is important that the grabbed images are synchronised. This avoids motion parallax, from movement of the cameras or the object of interest, which would decrease the accuracy of any subsequent measurement. The calibration plate is used to verify the stability of the camera relative orientation. Periodic measurement of the points of the calibration plate can be made to detect any variability between full calibrations of the system, as discussed below.

The paired video images are converted from analogue video signal to digital computer file using an IBM PC compatible frame grabber. The files are saved at a geometric resolution of 736 by 580 pixels and a radiometric resolution of 256 grey scales in a Microsoft Windows bit map (bmp) format. Once in digital format on the PC the images can be adjusted for brightness and/or contrast if necessary, and image locations can be measured within the frames. However, before any length estimations can be made, the system must be calibrated.

System Calibration

Calibration of the system is necessary for two reasons. First, the interior orientation of the cameras must be defined to determine the internal geometric characteristics of the cameras. Sometimes known simply as camera calibration, the required characteristics of the cameras include the principal distance (or focal length at a particular focus setting), the principal point (intersection of the optical axis of the lens with the focal plane), lens distortions and any bias in the spacing of the pixels on the CCD sensor (see figure 1). Second, the relative orientation of the two cameras with respect to one another must be known. This effectively defines the separation of the perspective centres of the two lenses, the pointing angles of the two optical axes of the cameras and the rotations of the two CCD sensors (see figure 2). The parameters of the relative orientation are selectable, but here it is convenient to opt for six rotation angles and the base separation.



PP = Principal Point f = focal length or principal distance PC = Perspective Centre

Figure 1. Principle of camera calibration.

The calibration is accomplished using a purpose built frame (see figure 2). The frame is an open cuboid constructed from light weight aluminium. It is black in colour and has 56 white, circular targets riveted to the surface. The targets provide high contrast, unambiguous points which allow a simultaneous, self-calibration of both cameras. Video footage is captured during two or four circuits of the frame by the diver, the first circuit with the camera base in the “normal” horizontal position, and the following circuits with the camera base vertical and in other orientations. The rotation of the base is necessary to de-couple some of the parameters of the self-calibration. Note that accurate information for the positions of the targets on the frame is not required, as coordinates of the targets are derived as part of the self-calibration procedure. Hence it is immaterial if the frame distorts or is dis-assembled between calibrations.

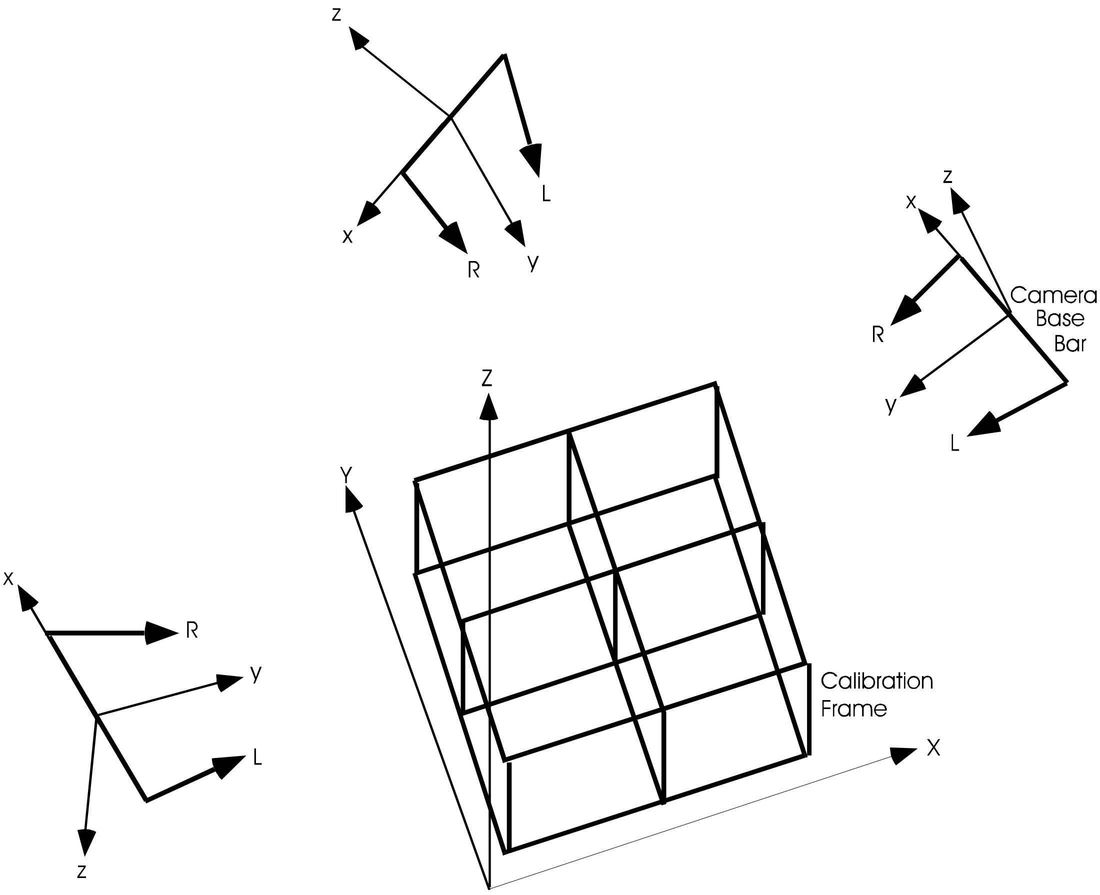


Figure 2. Calibration of the cameras and camera base bar using a calibration frame.

From the footage, 8 or 16 synchronised pairs of frames are gathered and the locations of the target images measured. The image data, approximate locations and orientations of the cameras, approximate camera calibration information and initial target coordinates are then processed by a self-calibrating multi-station bundle solution (Granshaw, 1980). Least squares estimation is used to model the statistical behaviour of the observed image coordinates and to detect and eliminate observation errors. The bundle solution provides estimates and precisions of the camera calibration parameters and the locations and orientations of the cameras at each synchronised pair of exposures.

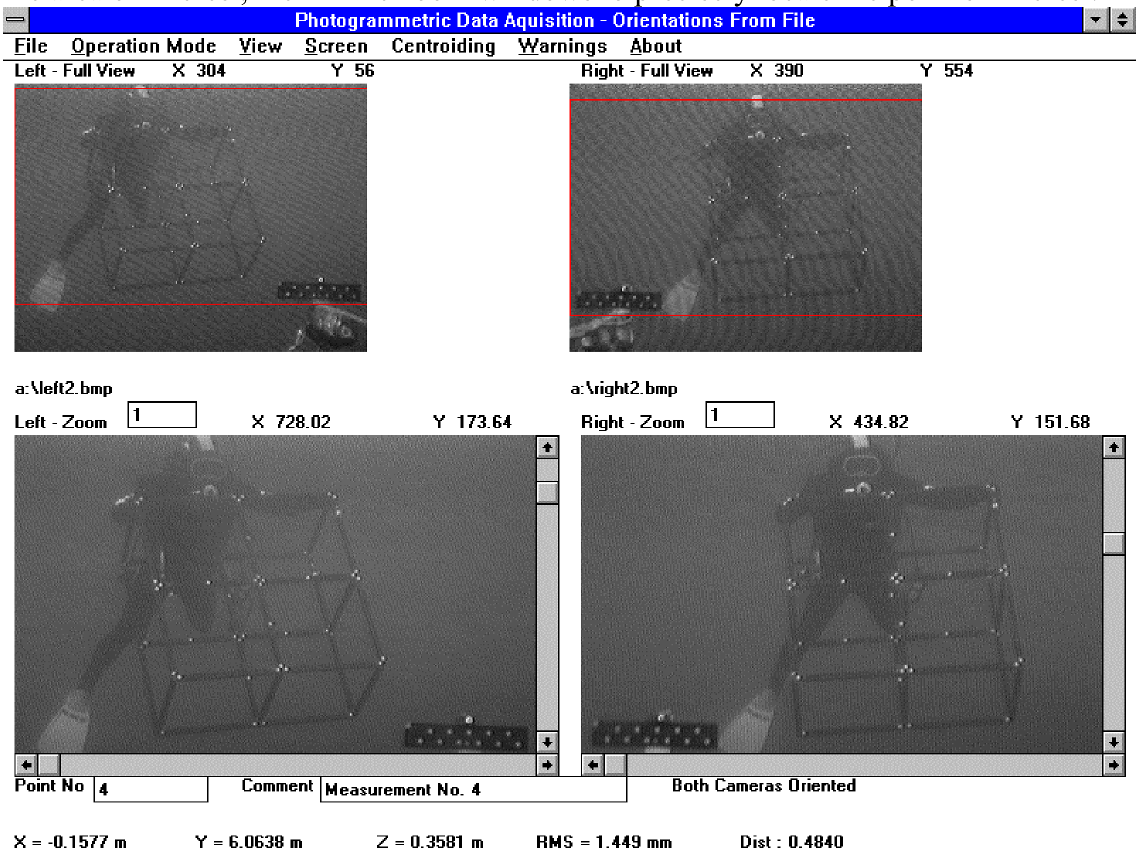
Whilst the camera calibration data are used directly in the subsequent calculations, the location and orientation data must first be transformed. The data for the 8 or 16 pairs of synchronised exposures are initially in the frame of reference of the calibration frame. Each pair is transformed into a local frame of reference for the camera base (see figure 2). The local frame of reference is adopted as the centre of the base between the camera perspective centres, with the axes aligned with the base direction and the mean optical axis pointing direction. The final parameters for the relative orientation are computed as the average of the values for the 8 or 16 pairs. From a typical set of calibration images, the repeatabilities for the targets on the calibration frame ranges from 0.5 to 1.0mm.

It must be assumed that the camera calibrations and relative orientation of the cameras are stable during a dive, or indeed the period between calibrations. Any gross departure can be detected using the calibration plate which appears in the field of view of each camera, but this is not intended to be a correction mechanism. Investigations into the frequency and reliability of the system calibration are beyond the scope of this paper and will be reported in a separate paper.

Measurement System

Once the relative orientation is established, measurements within the common field of view of the cameras can be made by locating objects of interest in the left and right stereo images. Again, the images must be synchronised to avoid systematic errors caused by the false shift of objects in one frame relative to the other.

The computer interface for the stereo measurement is shown in figure 3. The left and right overviews are at the top of the screen, whilst variable zoom windows into the overviews are at the bottom of the screen. Locations in the camera fields of view are located by simple cursor positioning and mouse clicks, first in the overviews to locate the area of interest, then in the zoom windows to precisely locate the point of interest.



Left - Full View X 304 Y 56

Right - Full View X 390 Y 554

a:\left2.bmp

Left - Zoom 1 X 728.02 Y 173.64

a:\right2.bmp

Right - Zoom 1 X 434.82 Y 151.68

Point No 4 Comment Measurement No. 4

Both Cameras Oriented

X = -0.1577 m Y = 6.0638 m Z = 0.3581 m RMS = 1.449 mm Dist : 0.4840

Figure 3. The computer interface

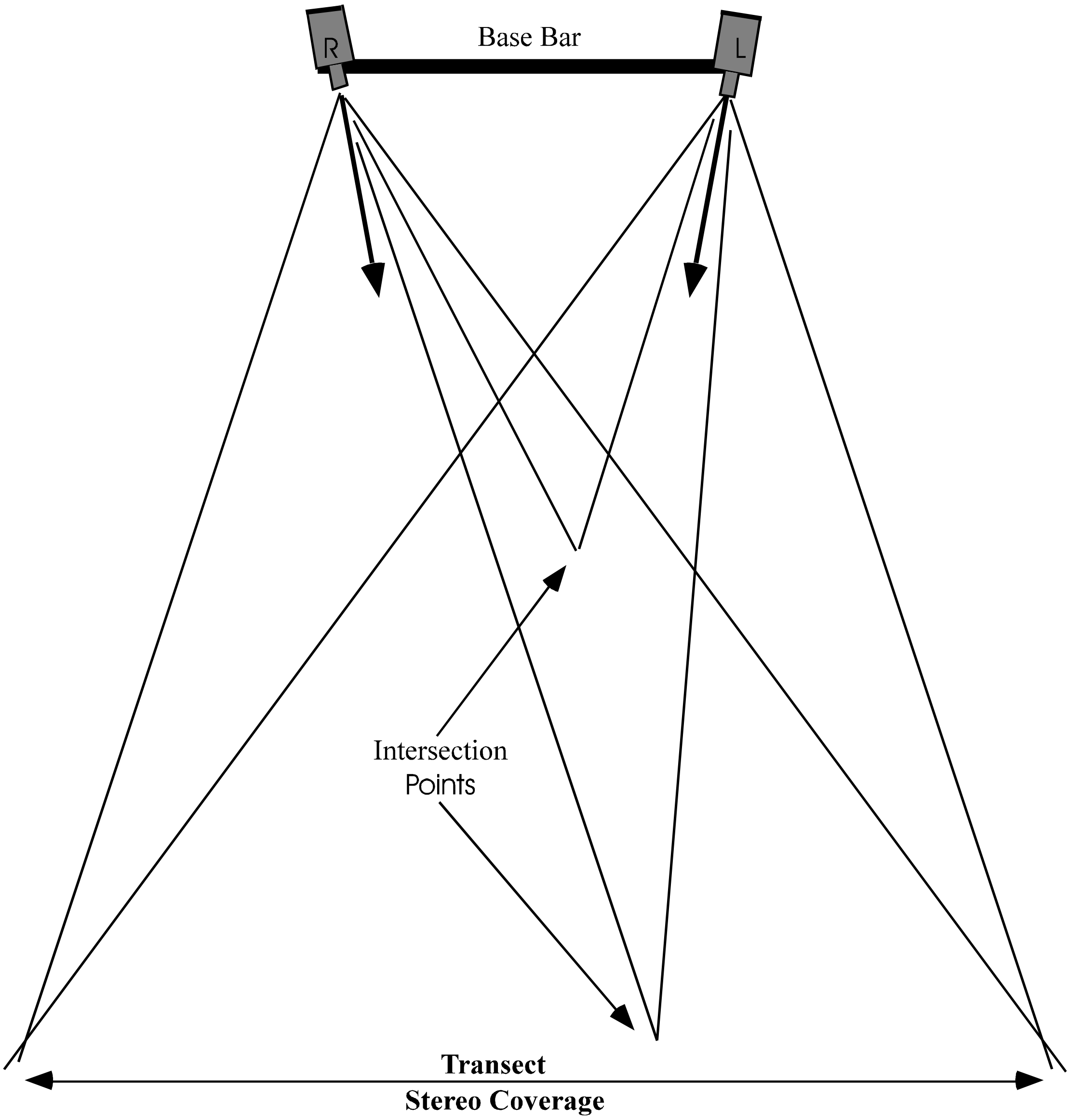


Figure 4. Geometry of the stereo photography and intersections

Shown in figure 4 is the geometry of the intersection and the field of view. It is apparent that the angle of intersection becomes shallower, and therefore less precise, with distance from the cameras. It can be shown from the geometry of the intersection that the precision of the intersection decreases with distance and the square of the distance for the lateral and longitudinal directions respectively. Whereas the depth away from the cameras is the more critical tolerance for acceptable measurements in general, the majority of measurements made with the system have the principal component in the less critical, lateral direction.

The two pairs of image space coordinates are converted into three object space coordinates and an estimator of the quality of the measurement. As length measurements are of particular interest, the three dimensional distances between consecutive point measurements are computed automatically.

The quality estimator effectively indicates the closeness of the image measurements to a perfect intersection in the object space. Experience with the system has shown that, on average over many observations, the quality does deteriorate with distances as expected. The readily visible source of the deterioration with distance is the effectively poorer resolution of the discrete samples of the CCD sensor.

However the principal use of the quality estimator is to detect mistakes in the image measurements. The measurements made with the stereo observation system are dependent on the clear definition of the objects to be measured. The discrete sampling of the CCD sensors combined with noise artefacts from the video tape recording and frame grabber tends to smear edges and blur detail, which can lead to mis-identification of left and right images of objects to be measured. The quality estimator is tested against a preset criterion and non-identical points produce very poor quality estimators. Image measurements which fail the test can be immediately re-observed to correct the error.

Testing Methodology

The accuracy and precision of the system were tested using a simple procedure used for calibrating diver estimates of the lengths of reef fish. PVC sticks or plywood silhouettes of fish are placed in the water and the length estimated (GBRMPA, 1979; Bell et al., 1985; English et al, 1994). The accuracy of the diver estimates can then be assessed by the difference between the real size and the estimate. To determine the accuracy and precision of the stereo-video system, 16 plastic silhouettes of fish, ranging in size from 100 to 470 mm in length were placed at distances between 2.5 and 6.6 metres from a rope in a saltwater pool at the Portobello Marine Laboratory. The stereo-video system was moved along the rope recording each of the sixteen silhouettes. This process was repeated four times.

Ten measurements of the recorded silhouette were made from each set of paired images of the 16 silhouettes. In all 64 paired images of silhouettes were recorded and a total of 640 measurements made.

Analysis of Data

Accuracy is described as the nearness of a measurement to the actual value being measured, while precision refers to the closeness of repeated measurements of the same subject to one another (Zar, 1974).

St John et al. (1990) calculated accuracy as the ratio of the estimated value to the true value. Values less than 1 represent underestimates of the length of silhouettes while values greater than 1 are over estimates. Therefore the use of this calculation also expresses any biases associated with the measurements made by the stereo-video system. We have also presented the maximum error for each silhouette. We have defined the maximum error as the largest absolute value resulting from the difference between estimated length of the silhouette and the known length.

The coefficient of variation (CV) has been described as a useful measure of precision (Thresher and Gunn, 1986) and is widely used in field research. CV is calculated by dividing the standard deviation of the estimate by the value of the estimate, expressed as a percentage. Most field work aims for a coefficient of variation of the order of 10% (Thresher and Gunn, 1986). Andrew and Mapstone (1987) note that coefficient of variation is actually not a measure of precision, but of the relative variability of the sample data standardised for the magnitude of the mean. However, as the CV is widely used it has been adopted in this paper as the measure of precision.

In this paper, the accuracy of the stereo-video system will be presented in the forms of the St. John ratio and the maximum error. The precision of the system will be presented in the forms of standard deviation and CV.

Initial Results

Accuracy

The mean accuracy of all 640 measurements made with the system was 0.954, or 95.4%. The mean accuracies for the 16 silhouettes ranged from 0.901 - 0.998. The mean error of all the 640 measurements made of all the silhouettes was 13.19mm while the mean error for each of the 16 silhouettes ranged from 3.7mm through to 24.3mm. The mean maximum error of all the 640 measurements was 23.75mm and ranged from 9mm through to 49mm while the standard deviation of the measurements was 6.31mm. The mean CV for the 16 silhouettes was 2.55% which lies well below the 10% level stated by Thresher and Gunn (1986) as being acceptable for field work. The CV ranged from 0.6 to 7.5% for each of the 16 silhouettes.

Chart 1 shows that the mean length estimate of the silhouettes made by the stereo-video was consistently below the real length. Only 44 measurements out of the 640 made (6.8%) had a positive bias. The negative bias is most likely caused by the edges of the subject being unclear and poorly defined within the paired images. Therefore there is a tendency to select points on the paired images which do not represent the real ends of the object to be measured, but points which are actually inside the ends, therefore underestimating the real size or length of the subject.

Effects of Changing Angle of Orientation of the Subject

While processing the paired video images it was observed that as the angle of orientation of the silhouette changed from perpendicular to the cameras through to 90 degrees away from the cameras, the precision and accuracy of the measurements also changed.

To test this phenomenon plastic silhouettes of fish sized 100, 360, and 395 mm in length were placed perpendicular to a rope at a distance of 3 metres from a transect line. The stereo-video rig was then moved along the transect rope videoing each of the three silhouettes. This was repeated a further two times. After the three recordings had been made of each silhouette the angle of orientation of the three silhouettes was increased to 25 degrees in relation to the transect and again the three silhouettes were each recorded a further three times. The process was repeated for 50 degrees, 75 degrees and finally 90 degrees. In addition one silhouette of 395 mm in length was placed at a distance 5 metres from the transect and the process repeated to investigate whether the combined effect of increasing distance and angle had any effect on the accuracy and precision of measurements.

Processing of the paired images revealed that increases in the angle of the orientation increased from 0 to 90 degrees resulted in increasing values for the CV (Chart 2), the standard deviation (Chart 3) and the maximum error (Chart 4). Large increases in the CV, standard deviation and maximum error occurred when the orientation of the silhouette was at 75 and 90 degrees to the transect. However, surprisingly the angle of orientation of the silhouettes had little effect on accuracy (Chart 5) except at angles of 75 and 90 degrees. This was especially notable at 5 metres.

The changing values of the CV, standard deviation, maximum error and accuracy are probably caused by the base separation of the cameras, and the consequent change in perspective (see figure 5), combined with the finite sampling and system noise as previously discussed. Between 0 and 50 degrees both the head and the tail of the silhouette can be seen. When the angle of orientation increases to 75 and 90 degrees one camera, for example the left camera, can distinguish both ends of the subject clearly. However the second camera, the right, will record images in which only the tail or head of the fish and can be distinguished, making it virtually impossible to make accurate measurements of length.

Based on the information attained on the effects of increasing angle of orientation on accuracy and precision we reviewed all the images and removed data where the orientation of the silhouettes was greater than 50 degrees or where the images did not show the head or the tail. A total of eight paired images was removed from the total of sixty four leaving a remaining 56 images.

Table 1.

	Mean Accuracy	Range of Accuracy	Mean CV %	Range of CV %	Mean error mm	Range of mean error mm	Mean maximum error mm	Maximum error mm	Standard deviation mm	Range of standard deviation mn
Unadjusted	0.954	0.901-0.998	2.55	0.6-7.5	13.22	3.7-24.3	23.75	49	6.31	2-14.6
Adjusted	0.953	0.901-0.987	2.27	0.6-7.5	12.7	3.7-24.3	12.55	29	4.01	2-12.7

Table 1 shows the changes in the unadjusted values of the measurements resulting from the removal of paired images which were either unclear or where both the head and tail could not be clearly seen in the paired images. The removal of the data from these paired images resulted in a decrease in the CV of the measurements and very significant decreases in the maximum error and standard deviation. A very slight decrease in the mean accuracy was also recorded.

Conclusions

Biologists making visual estimates of size or length should aim for the maximum achievable accuracy and precision realistically available to them. As the accuracy and precision of size or length estimates decreases, so does the ability to detect real or relative changes in variables involving biological length or size. Stereo-video offers an alternative to standard visual census techniques where data collection emphasis is on accurate and precise estimates of size or length. The system described in this paper is a prototype. However, the initial testing has clearly demonstrated the potential for efficient and appropriate under-water measurement. The system can be scaled down or up for various applications with corresponding changes in accuracy and precision. The technique is robust and insensitive to user experience, therefore removing biases resulting from inter-observer variability. Underwater stereo-video measurement has many advantages over visual census techniques, and it is clear that stereo-video systems will gain widespread acceptance in the future.

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Chart 1. Graphs the known length of the silhouettes and the mean length estimates made with stereo-video system and the 95% confidence intervals for the measurements.

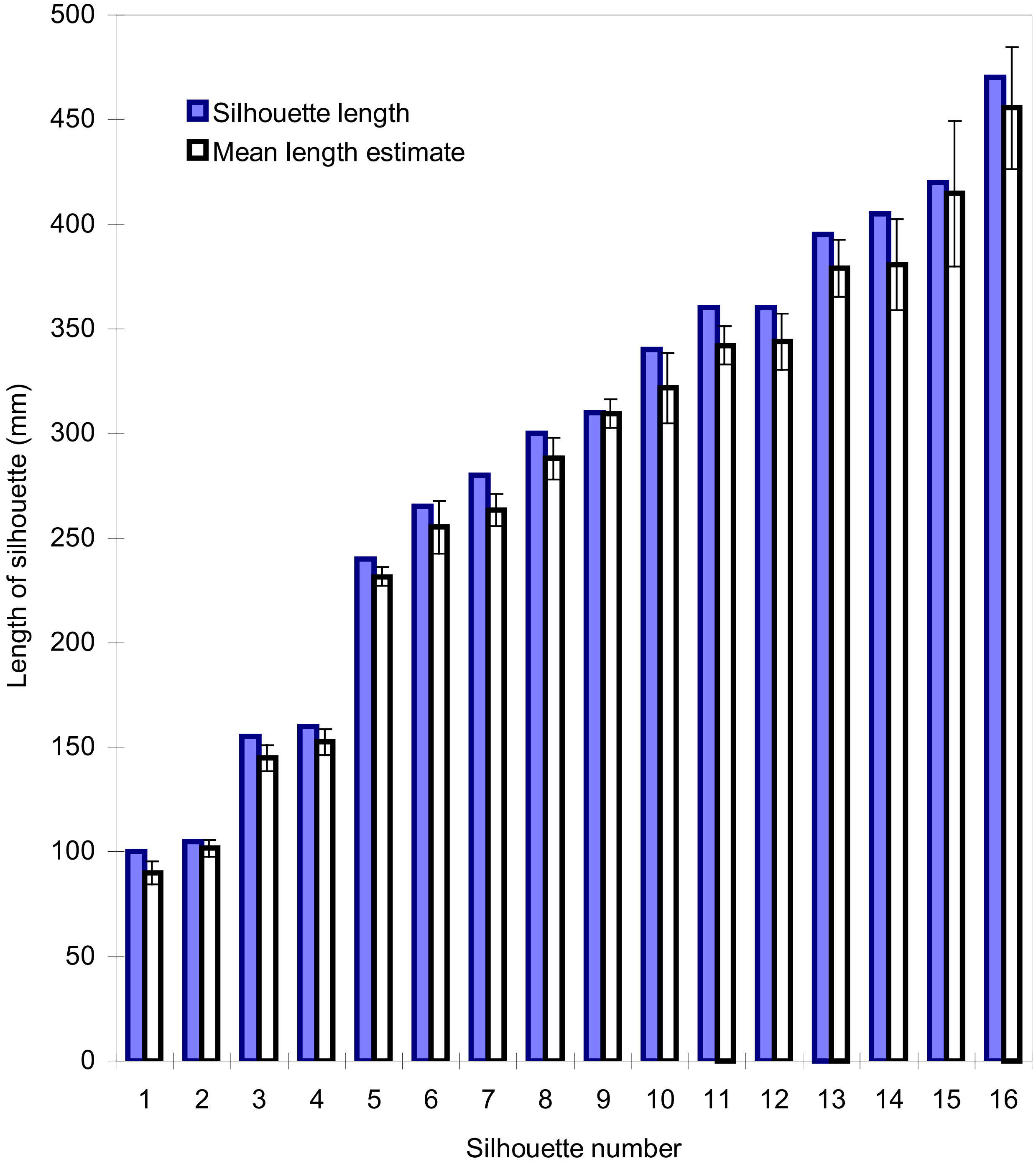

Chart 2. Graphs the effect of increasing angle on CV for three silhouettes at 3m from the camera and one silhouette 5m from the camera.

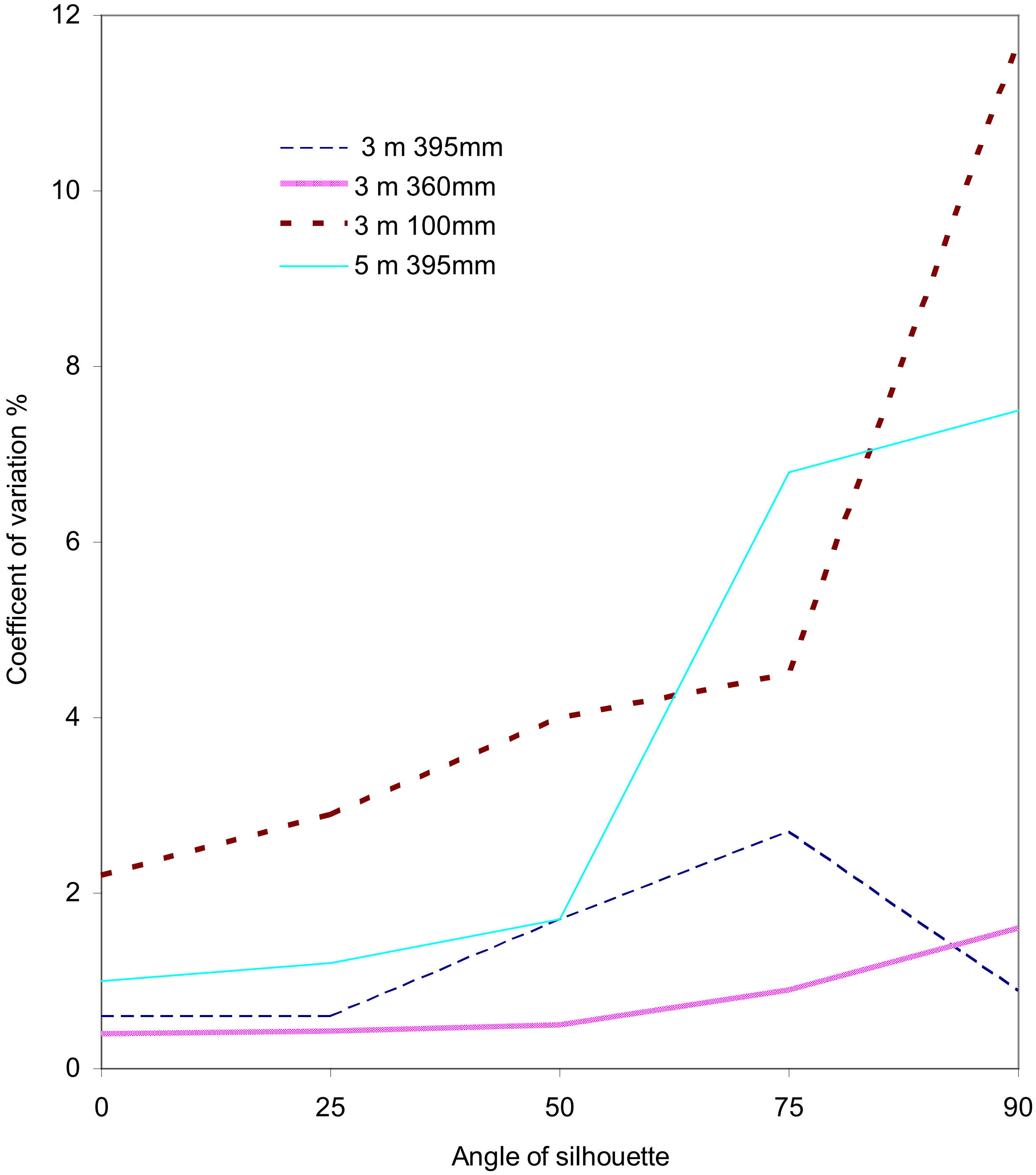

Chart 3. Graphs the effect of increasing angle on standard deviation for three silhouettes at 3m from the camera and one silhouette 5m from the camera.

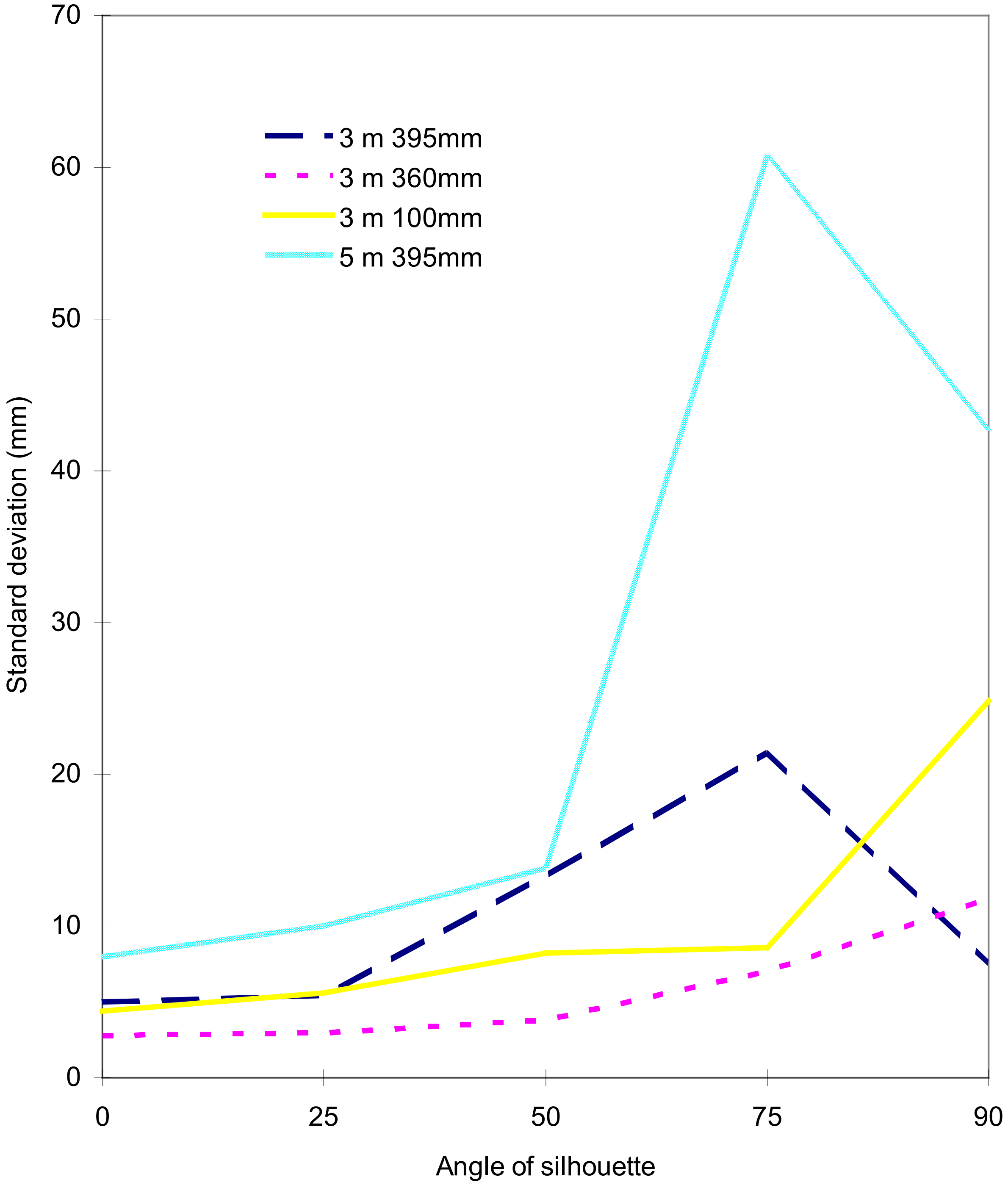

Chart 4. Graphs the effect of increasing angle on maximum error for three silhouettes at 3m from the camera and one silhouette 5m from the camera.

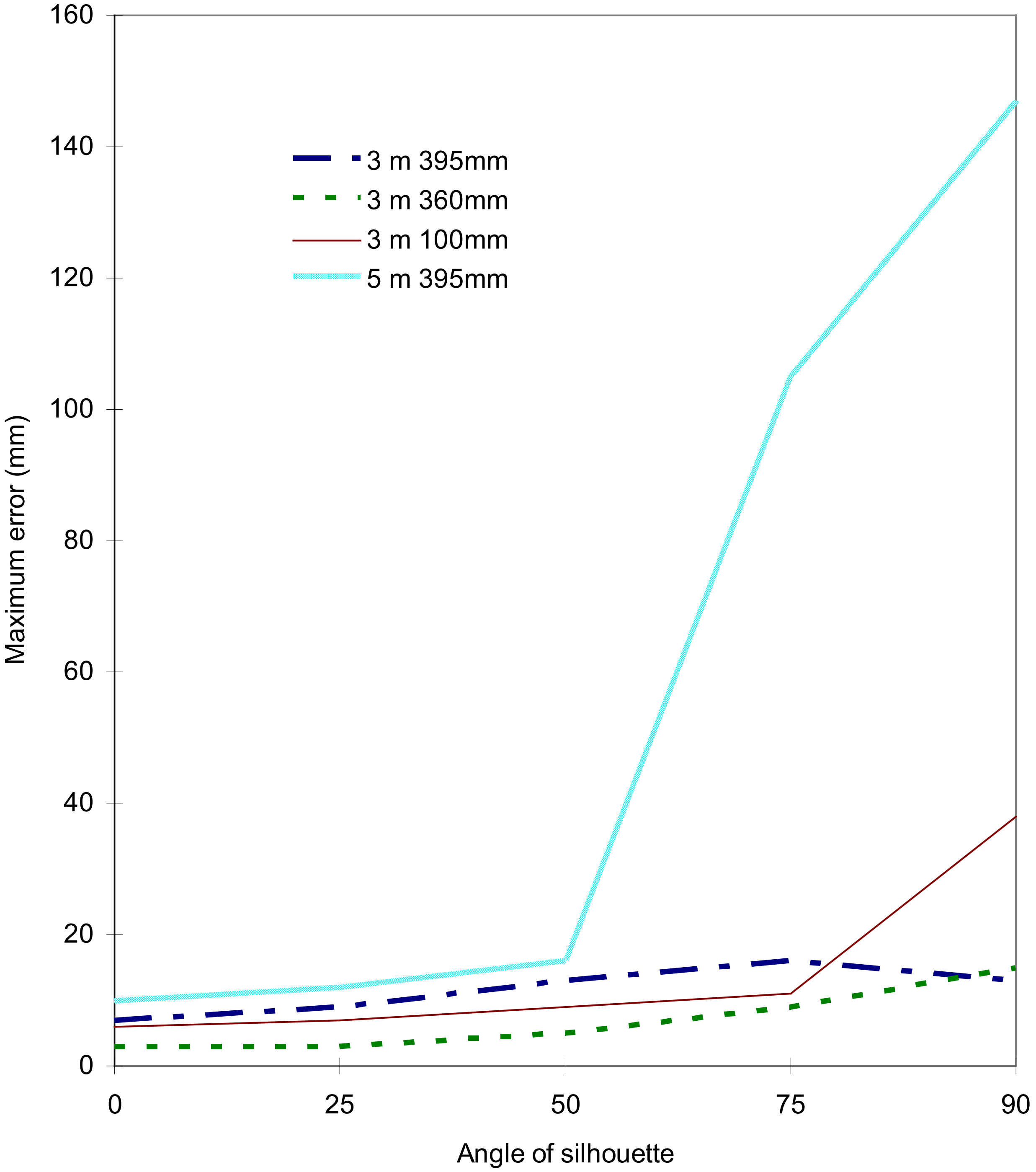

Chart 5. The effect of increasing angle on accuracy for three silhouettes at 3m from the camera and one silhouette 5m from the camera

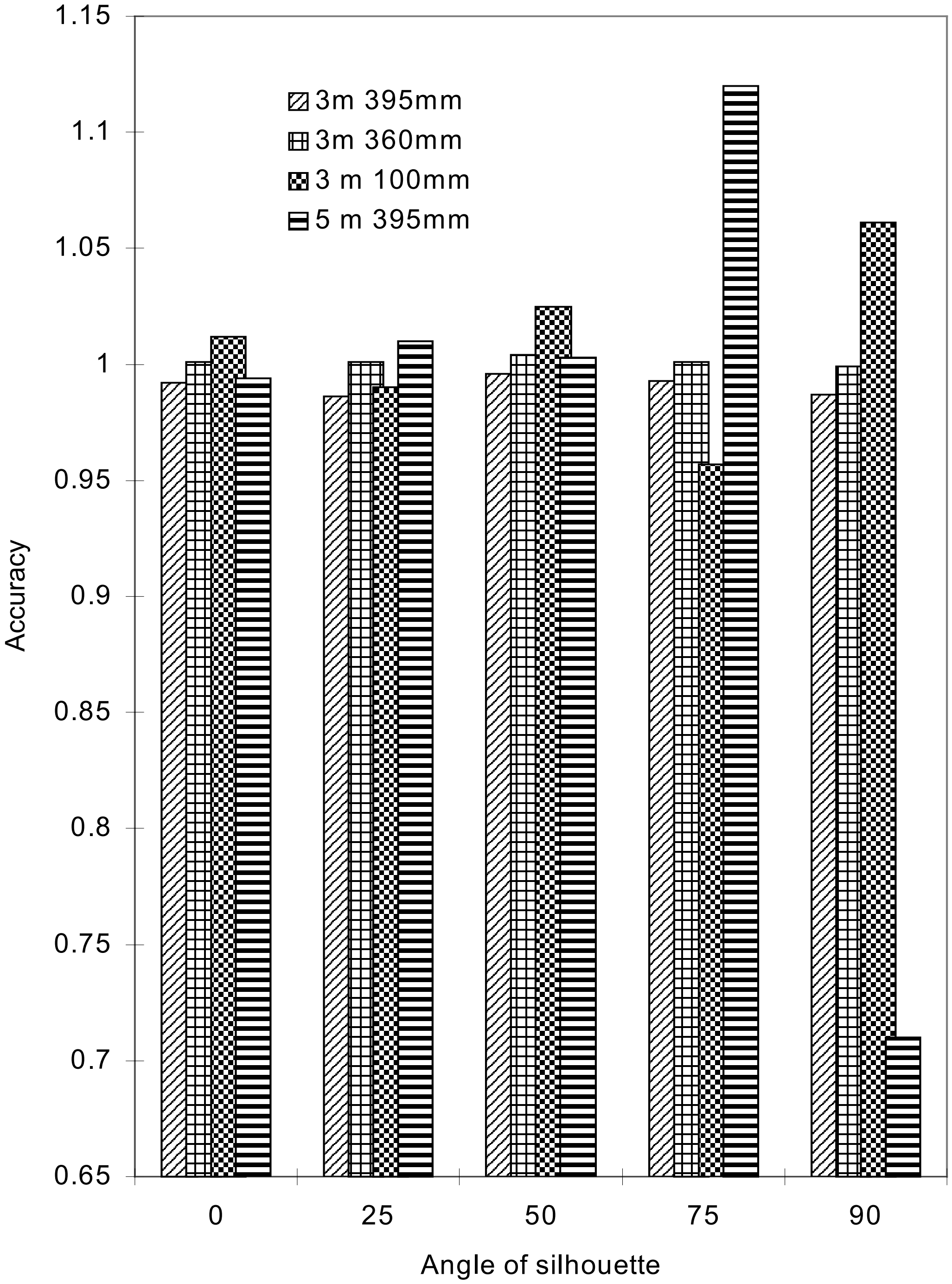

Figure 5. Effects of changing subject orientation on image perspective.