3D Measurement Accuracy of a Consumer-Grade Digital Camera and Retro-Reflective Survey Targets

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Abstract

During the construction of a large ship, a set of reference points was measured using an Industrial Total Station. The reference points were retro-reflective survey targets, which provide excellent targeting for photogrammetric imaging. The targets were photographed using a consumer-grade digital camera and their positions were calculated using the PhotoModeler Pro software. The consumer-grade camera produced coordinate accuracy in the order of 1 part in 10,000. This paper recounts the measurement process and provides insight into the practical benefits of Photogrammetry and the challenges faced in industrial measurement.

Introduction

As the consumer market embraces digital imaging, digital cameras are becoming less expensive and providing higher resolution images. This explosion in camera technology, coupled with PhotoModeler Pro software by Eos Systems Inc, has made the use of digital cameras for accurate measurement and modeling, affordable.

This study investigates the accuracy of a measurement system based on:
- PhotoModeler Pro 4.0,
- a Fujifilm MX-2900 (a $1000 Cdn., consumer-grade digital camera), and
- readily accessible survey retro-reflective targets**.**

We compare the coordinate values determined by this equipment to those coordinates determined by a Leica TC2002 Industrial Total Station.

Project Layout

The project involved a real-world industrial measurement task in the shipbuilding industry. This was not a "laboratory" study but instead conducted in a real production environment. The targets used to measure coordinate points were not chosen to satisfy the photogrammetry technique but were in fact part of the established production process.

Figure 1: Bow of the Ferry prior to the installation of the Bow Ramp, (arrows at hinge locations).

This particular study was performed on the structure of a double-hulled passenger/ car ferry during its construction. The measurement project focussed on the bow of the ship, shown in Figure 1. The top of the bow is 8 meters above the ground and the bow width is 19 meters.

The ferry was built in an enclosed shed that has large doors to facilitate the construction and launch processes. The shed also has overhead lighting and cranes.

When the ship is complete the bow structure supports a ramp which can be lowered or raised to facilitate the passage of cars on and off of the vessel. When the ramp is installed, it articulates about 4 hinges that are bolted to pads on the bow structure.

To ensure the 4 hinges articulate efficiently the 4 hinge pads had to be machined co-planer and square to the ships' longitudinal axis. The hinge pads were machined using a portable milling machine large enough to machine one pad per setup. The milling

machine was oriented square to the ship's longitudinal axis by using a dial indicator to sense the position of 9 reference points on each hinge pad.

Retro-reflective targets, 9 per hinge pad, provided the reference points for the milling machine setup. The coordinates assigned to the targets were determined by measuring their location using a Leica TC2002 Total Station. The TC2002 was aligned to the ship's longitudinal axis, which was physically defined by a series of punch-marked steel plates embedded in the concrete floor.

The retro-reflective target's coordinates, being measured for the machinists, provided a good opportunity to evaluate the accuracy of using a consumer-grade camera with the PhotoModeler software.

The coordinate determination, using the TC2002, was done with extra care, as this survey was the most demanding on the ferry project. The measuring personnel had to be extremely vigilant about controlling the environment during the survey. The large access doors were kept closed to avoid drafts from thermally distorting the instrument's tripod. Heavy machinery and curious co-workers were kept at bay during the survey to avoid vibration, which could cause the instruments position to shift. Physical obstructions, such as raw materials, which were in the positions required to setup the instrument, had to be moved prior to the survey. The TC2002 survey took approximately 3 hours.

The photogrammetry fieldwork, by contrast, required none of these concerns to be addressed. This greatly reduced the field time needed to 20 minutes, and reduced the operational demands placed on the Accuracy Control personnel.

Equipment

The Total Station Used in Production

As described above, a TC2002 Total Station was used to control alignment of the milling machine during the construction of the ship. The Leica TC2002 Total Station was designed for work requiring a high angular accuracy (+/- 0.5 arc seconds) and a high distance measuring accuracy (+/- 1.0 mm). The built-in laser system measures distance by emitting laser pulses that reflect off of adhesive backed retro-reflective targets. These targets are stuck directly on the object being measured and thus provide the physical definition of the work-points.

The Retro Reflective Targets Used in Production

The targets used were created by cutting out a circular shape, diameter = 25mm, from 3M Scotchlite Diamond Grade Reflective Sheeting.

Testing the Total Station System

A small sub-study was done to quantify the Leica TC2002's repeatability in measuring the 3D geometry of the bow targets.

Four targets were arranged at distances that enveloped the geometry of the ship's bow. The Leica TC2002 was then setup sequentially at four station locations. While setup at each station, the TC2002 was used to measure the 3D coordinates of each of the 4 targets. The distance from target to instrument and overall target separation was of the same range as that used to obtain the coordinates of the targets on the ship's bow.

Given the 4 stations and the 4 targets there are 24 pairs of independently measured target locations available for comparison. The RMS (one sigma) difference between the 24 independently measured target locations was 0.74 mm.

As a result of this repeatability test and for the purposes of this study, a 1 mm RMS (one sigma) value will be used to quantify the accuracy of the target locations measured using the Leica TC2002, in the ship's bow study. The extra tolerance allows for any slight de-centering of the crosshairs, used to define the Leica point, relative to the center of the reflective tape circle, used to define the photogrammetry point.

The Digital Camera

A FujiFilm MX-2900 digital camera was used to acquire the images in the study. The features of this camera include:

- 2.3 Megapixels (1800x1200) resolution
- 3.3mm - 7.6mm focal length range
- Manual Exposure Control
- Hot Shoe for mounting an external flash

The camera cost in April 2001 was approximately $1000 Cdn.

Camera Calibration

The accuracy of a photogrammetric measurement system will be largely determined by the accuracy of the images produced by the digital camera. The physical and optical characteristics of the camera have to be accurately quantified to allow PhotoModeler to use the image data for measurement. The quantification of the camera parameters is a process called camera calibration.

PhotoModeler comes with a camera calibration program that automatically calibrates the camera by analyzing images of a standard grid. Projecting a slide, supplied by Eos, onto a flat wall creates the standard grid. Eight images are taken of the projected grid and then the images are loaded into the camera calibration program. The program automatically processes the images and reports the characteristics of the camera.

Figure 2a: Eos' Standard Calibration Grid
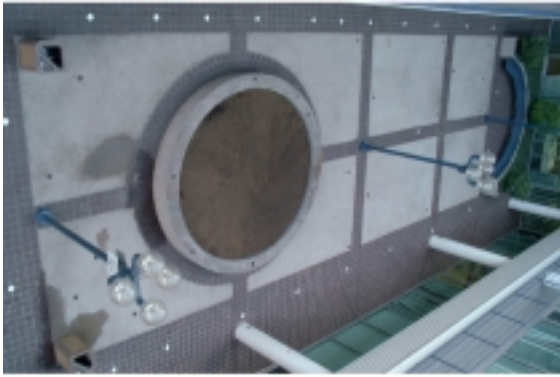
The camera used in this study was initially calibrated in this way which would produce good results for small objects. The camera was then further calibrated by setting up a collection of targets, 4" circles, over an area approximately the same size as the bow structure. Eight images were taken of the targets and a full field calibration was performed. This produced camera characteristics better suited for when the camera is focussed at a distance typical of the bow structure images.

Figure 2b: Full Field Calibration in Building Atrium

Image Acquisition Details

In this study five images were taken from ground level. The angular distribution of the 5 camera locations is shown in Figure 3. The images were taken while the camera was zoomed to a focal length of 7.6mm. The images were framed so that all the targets mounted on the ship's bow and the three targets on the floor, representing the ship centerline, were included. An external flash was used, mounted in the Hot Shoe. Manual exposure was set low to ensure high contrast between the target surface and the background. High contrast is required to make accurate use of the sub-pixel target marking facility within PhotoModeler.
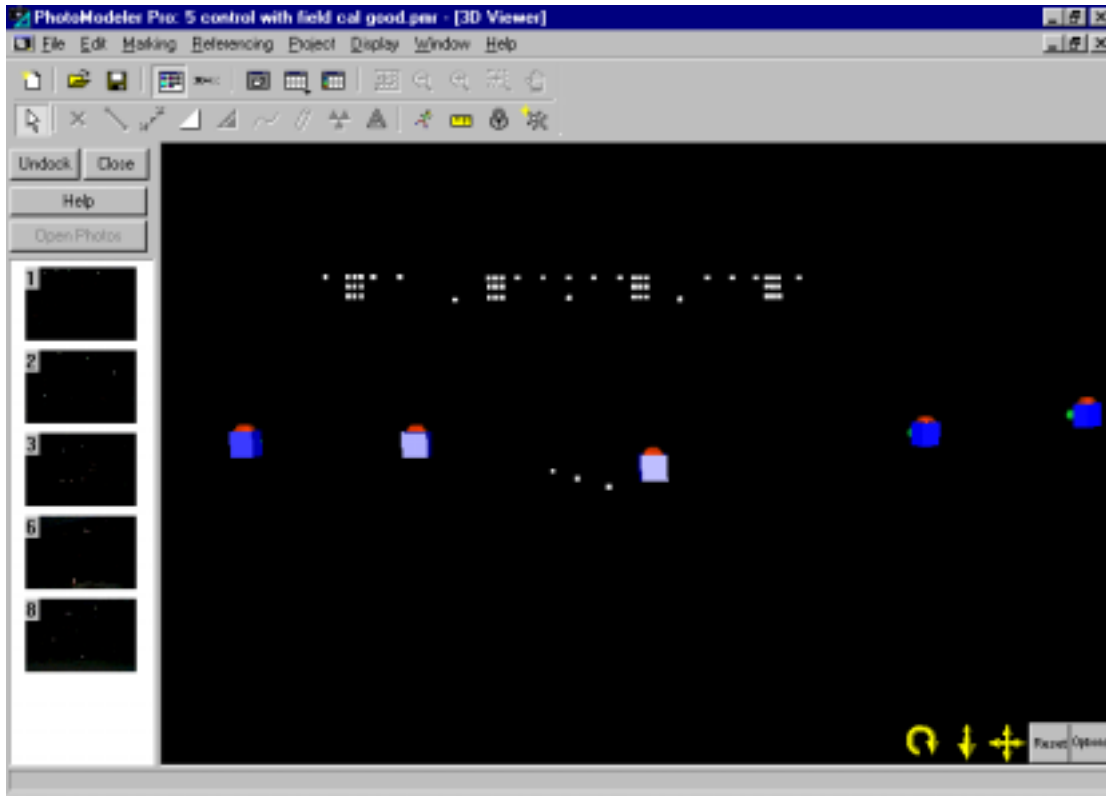

Figure 3: PhotoModeler screen showing: 51 Bow Targets, 3 Floor Targets and 5 Camera Positions Used

Processing of Photographs

The five images taken of the ship's bow were loaded into PhotoModeler Pro 4.0. The identification of the target centers was accomplished using the sub-pixel marking tool in PhotoModeler. The referencing tool was used to ensure that the 54 points in every image were labeled consistently.

Once all the points were marked and referenced it was necessary to supply some geometrical information to allow PhotoModeler to scale and orient the model. The scaling of the model was accomplished using two methods available in PhotoModeler.

Method 1: Processing With Control Points

In heavy construction projects a grid of reference points is often established prior to the start of the construction process. Usually a survey instrument, such as a TC2002, is used to layout the reference points before the area gets too crowded with materials or workers. These reference points are then used throughout the construction process to tie local measurements into the project's global coordinate system.

The PhotoModeler "Control Points" facility allows the use of existing reference grid points to tie local measurements into the project's global coordinate system. Five reference points were assigned as control points in this study. These points function to scale and align the model created by PhotoModeler, so that coordinate values can be directly compared to the coordinates determined by the TC2002.

Method 2: Processing Using Distance Constraints

At times there are no reference points available and the only available scaling information is linear distances. These linear distances are typically measured using a tape measure.

To simulate this situation two scale distances were derived from the survey data and were assigned in PhotoModeler as distance constraints. One scale constraint was along the top of the object (in a right to left direction) and the other scale constraint was along the floor (in a front to back direction).

Using the two distance constraints, PhotoModeler solved for the coordinates of the 54 points. Once determined, these 54 coordinate points were rotated and translated into a coordinate system consistent with the TC2002 coordinates so direct x,y,z comparisons could be made.

Accuracy Study

Results: Method 1: Processing With Control Points

The differences between the PhotoModeler coordinates and the TC2002 coordinates are summarized in Figure 4a.

Direction	Minimum Difference (mm)	Maximum Difference (mm)	Mean Difference (mm)	Root-Mean Square Difference (mm)
X (across ship - port / starboard)	0.0	2.5	0.0	1.0
Y (along ship - forward / aft)	0.0	5.2	0.1	2.4
Z (vertical)	0.0	2.5	0.0	1.1

Figure 4a: Deviations Using Control Points

Results: Method 2: Processing With Distance Constraints

The differences between the PhotoModeler coordinates and the TC2002 coordinates are summarized in Table 4b.

Direction	Minimum Difference (mm)	Maximum Difference (mm)	Mean Difference (mm)	Root-Mean Square Difference (mm)
X (across ship - port / starboard)	0.0	3.5	0.0	1.4
Y (along ship - forward / aft)	0.0	6.8	0.0	2.9
Z (vertical)	0.0	2.8	0.0	1.3

Figure 4b: Deviations Using Distance Constraints

Discussion

What is most evident in the results is that the differences between the TC2002 coordinates and the PhotoModeler coordinates were highly directionally dependent. The "X" and "Z" coordinates, whose axes are similar to the plane of the images, were much stronger than the "Y" coordinates whose axis was generally perpendicular to the plane of the images.

The use of 5 camera stations, all at ground level, and with limited rotation most likely limited the accuracy obtainable by PhotoModeler. If additional images were taken, at

positions 7 – 10 meters off the ground, the PhotoModeler coordinates would likely be closer to the TC2002 coordinates.

Previously in this article, we estimated the accuracy of the TC2002 Total Station, based on a test of repeatability, as 1 mm RMS (one sigma). If we express the 1 mm in a three axis system, and for simplicity sake assume it is equally divided, we would assume each axis has accuracy of

$$\text{Accuracy} = 1\text{mm} = \sqrt{RMS_X{}^2 + RMS_Y{}^2 + RMS_Z{}^2}$$

therefore, $RMS_X = RMS_Y = RMS_Z = 0.58\text{mm}$

Thus the error contributed by PhotoModeler could be estimated as being

$$= \sqrt{RMS_{XPhoto}{}^2 - RMS_{Xtc2002}{}^2}$$

The RMS (one sigma) differences of this photogrammetry system are shown in the Table below. The size of the differences, relative to the size of the structure (bow width = 18633 mm), are also shown in Figure 5.

Processing Method	Direction	PhotoModeler Root-Mean-Square Difference (mm)	Estimated Accuracy
5 Control Points	X (across ship - port / starboard)	0.8	23000:1
5 Control Points	Y (along ship - forward / aft)	2.3	8100:1
5 Control Points	Z (vertical)	0.9	21000:1
2 Distance Constraints	X (across ship - port / starboard)	1.2	16000:1
2 Distance Constraints	Y (along ship - forward / aft)	2.8	6700:1
2 Distance Constraints	Z (vertical)	1.1	17000:1

Figure 5: Accuracy of the Photogrammetric System

Conclusions

A relatively low-cost digital camera and retro-reflective survey targets can be used to create images that PhotoModeler can use to determine accurate 3D coordinates. Coordinate accuracy in the order of 1:10,000 was obtained which is suitable for many applications in architecture and model building and in some industrial measurement applications.

Further studies with: additional camera positions, improved camera angles and the use of different flash configurations, would be useful to test the effect they may have on improving accuracy.

The speed and convenience of the imaging process compared to measuring coordinates with a Total Station is very attractive. As consumer grade camera resolutions increase, the accuracy of low-cost photogrammetry will increase and be more widely utilized.