A CINE-PHOTOGRAMMETRIC SYSTEM FOR THE MONITORING OF A DYNAMIC EVENT UNDERWATER

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ABSTRACT

A close-range cine-photogrammetric system (CRCPS) was developed to quantify the dynamic parameters of displacement, velocity and acceleration of two interacting rigid bodies in an underwater environment. The system provided relative displacements of an event that occurred in a second or less, to an accuracy of 3mm. This paper describes the overall photogrammetric system design and highlights some of the unique problem areas that needed to be addressed. Among these were remote operation of specially modified 16mm high-speed, semi-metric cameras in an ocean environment; automatic mensuration and reduction of up to 500 epochs of photogrammetric network data from eight cameras in 36 hours; network design considerations given specific time, accuracy, and operational constraints; and determination of rigid-body displacements through coordinate transformation parameters. Results of the system implementation and operation, including the accuracy level attained are briefly summarized.

INTRODUCTION

The technique of close-range photogrammetry has been successfully coupled with a high speed data acquisition subsystem to form a Close-Range Cine-Photogrammetric System (CRCPS). The CRCPS was developed to quantify the dynamic properties of displacement, velocity, and acceleration of a test vehicle (TV) and a hemispherical enclosure cap, termed simply a closure, as they travelled over a vertical distance of 1.5m in an undersea environment. Figure 1 provides a sketch of the relative positions of the TV and closure along with the test fixture assembly prior to launch, and a photograph of the assembly showing the above-deck layout is shown in Figure 2.

The test vehicle was approximately 2m in diameter and 7m in length, and was tapered over the top 1.5m to form the nose cap. In its pre-launch position on top of the launch tube, the closure provided a watertight seal over the TV. The closure was formed as a partial hemisphere of 1.2m radius and was contoured on the inside to absorb impact energy from the TV. At each test event, which lasted for only one second, the TV was ejected at high velocity by air pressure. Within milliseconds of the first motion, a pyrotechnic cut severed the seal between the closure and launch tube, and following a few tenths of a second the closure was cut, again by explosive charges, into eight 'orange-peel' segments. The TV would then pass through these segments, as is illustrated by the sequence of sketches in Figure 3.

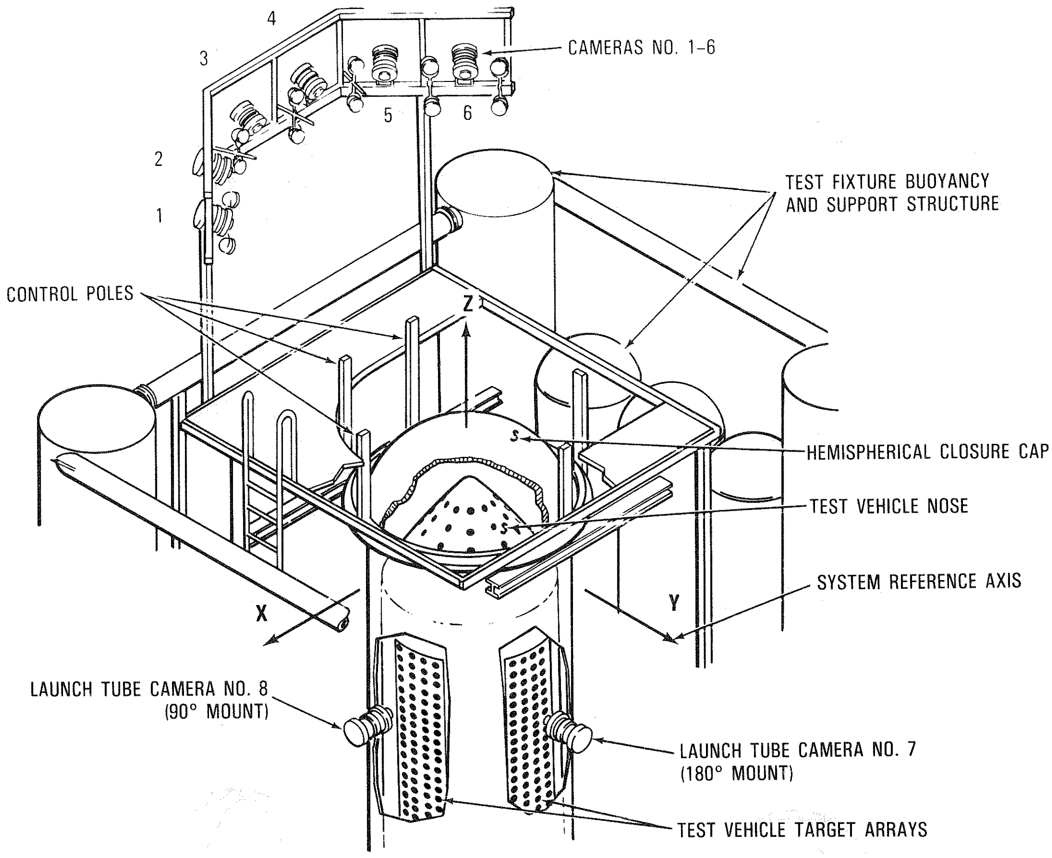

Figure 1: Test fixture assembly

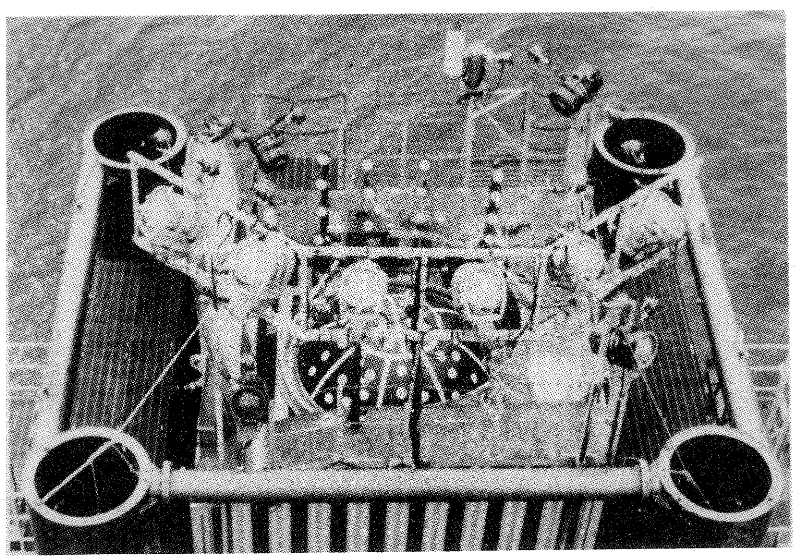

Figure 2: Cine-cameras and object point layout for closure network

The role of the CRCPS was to gather a time history of the relative positions and orientations of the closure segments with respect to both the TV and the launch tube at each event. From this basic position and attitude data, relative displacements, rotations, velocities and accelerations could be derived. To yield acceleration data of sufficient resolution, a sampling rate of two milliseconds was necessary. Thus, some five hundred separate 'epochs' of synchronized high-speed photography were required to cover the one second period of each test event.

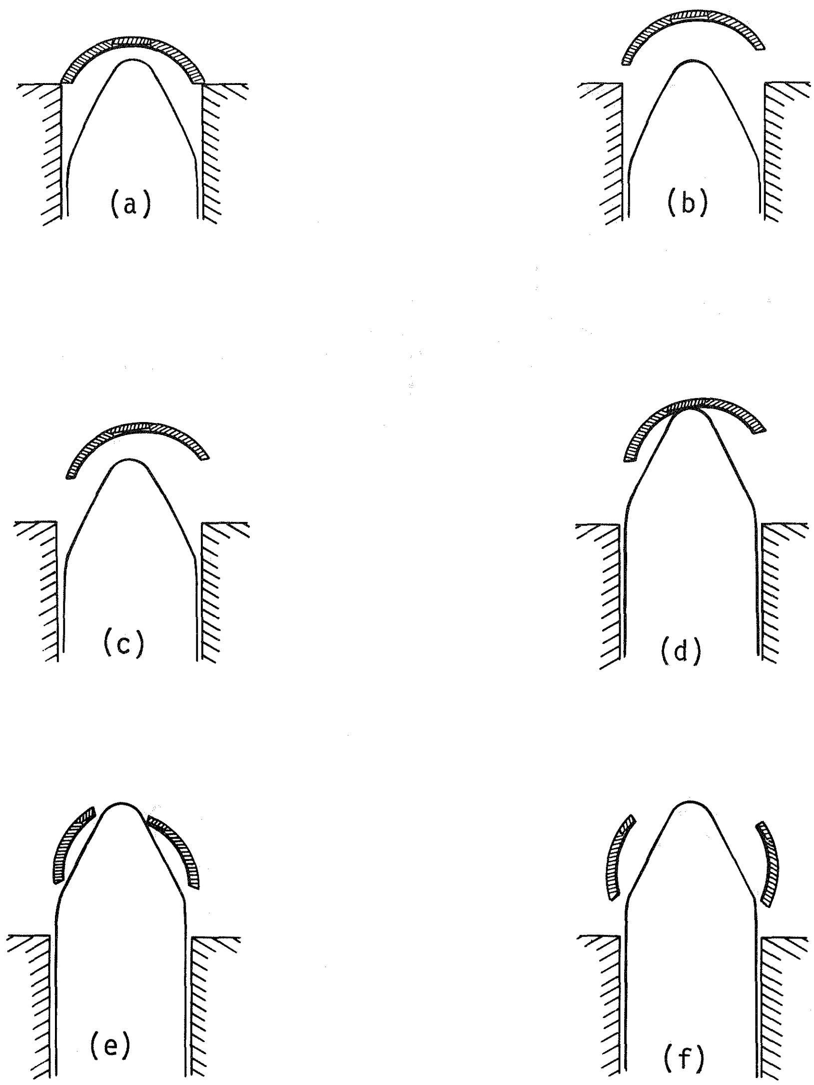

Figure 3: Interaction of TV and closure during a test event

Two distinct photogrammetric measurement operations were involved for each test event sequence. As well as the dynamic tracking phase, the CRCPS was required to undertake static measurements of the pre-launch shape of the closure and TV, along with their respective positions in the reference coordinate system of the launch tube. For these two functions of the CRCPS, separate system components of hardware and software were necessary.

In the case of the pre-launch measurements of stationary objects, all necessary equipment and software was obtainable 'off the shelf' from commercial sources. For the dynamic measurements, on the other hand, a completely new system level design was called for. In short, what was necessary was a system that could capture 500 epochs of photographic data in a second, measure 3000 photographs and reduce all the resulting photogrammetric networks in under 36 hours, and yield positional accuracies of around 3mm on two interacting rigid bodies located some 10-30m below the sea surface. In many respects the CRCPS represented a unique solution to a formidable problem of dynamic measurement, and it is the purpose of this paper to provide a broad overview of the system, from its design to operational stages.

The development of the CRCPS was performed under contract for Westinghouse Electric Corporation, Marine Division by DBA Systems and Geodetic Services Inc. (GSI), both of Melbourne, Florida. DBA was responsible for overall system development, while GSI coordinated and developed the photogrammetric network design as well as all data reduction software, including that for camera system calibration. The subject of this paper is largely confined to the purely photogrammetric aspects of the CRCPS and system engineering concerns are only briefly touched upon.

PHOTOGRAMMETRIC NETWORK REQUIREMENTS

In their most basic terms, the CRCPS system requirements dictated that the relative motions of the closure and TV were to be determined to a given accuracy which applied to displacement, rotation, velocity and acceleration. From this straightforward primary specification followed a number of secondary requirements which emerged as the conceptual design for the CRCPS developed. To take an example, consider for the moment Figure 1. What first strikes the photogrammetrist is that dynamic tracking of two bodies is required and yet until the TV emerges through the segmented closure, it cannot be seen from outside the launch tube. Moreover, the TV interacts with the underside of the closure and thus closure shape must be 'mapped' to relate the inside surface, which cannot be seen, to the outside, which can be readily photographed.

At the outset of the photogrammetric planning process, formulation of a network design in general terms was first necessary. It was surmised that the relative motions of the closure and TV could only be established by having a separate photogrammetric network for each, and this design strategy was pursued. The final scheme arrived at is indicated in Figure 1. For the closure, the network would comprise six cine cameras arranged so that targets on the closure surface could be measured over a vertical range of travel of 1.5m. Photogrammetric triangulation was to be performed using a standard bundle adjustment approach. The TV warranted a very different strategy. Here it was decided to position two cameras such that two small areas of the vehicle would be imaged through viewing ports in the launch tube wall. Target arrays would be established on the TV so that at any time during the test event the exterior orientation of these two cameras could be established by space resection. The apparent changes in position and orientation of the two cameras would represent the actual motion of the TV. These so-called launch tube cameras were to be positioned on the X and Y coordinate axes to both enhance and simplify the recovery of axial rotation data for the TV.

Pre-Launch Measurements

Successful implementation of the proposed network design was contingent upon relating the two component networks into a common coordinate datum. The task of bringing the closure and TV into the launch tube reference system was performed as part of a pre-launch measurement phase. To achieve this, four separate operations were required:

i) The positions of the 350 or so targets forming each of the two arrays on the TV were to be measured relative to a network of 50 points positioned on the nose of the vehicle. This operation could take place at a convenient time prior to loading the TV into the launch tube, and would likely have to occur at sea.

ii) Following the positioning of the TV in the tube, and prior to installation of the closure, the network of points comprising both targets on the nose of the TV and a number of points on control poles was to be photographed. The resultant photogrammetric triangulation would establish the coordinates of the points on the nose in the launch tube reference system. Through 3-D similarity transformation it would then be a simple matter to bring the resection targets (and consequently the launch tube cameras) into this same datum.

iii) A third photogrammetric procedure was involved for the closure. Separate networks were established to both 'map' the contour of the energy absorbing underside surface and measure the positions of tracking targets on the closure surface relative to known tooling points.

iv) The coordinates of the tooling points around the rim of the closure were known in the launch tube reference system and so once the closure was installed, all object point coordinates were established in the same XYZ datum, that of the launch tube. To cover the possibility of the closure deforming when the test assembly was submerged, the pre-launch measurement design had to accommodate static underwater measurement, though this capability did not prove necessary during the actual test measurements.

The photogrammetric measurement tasks forming the pre-launch phase were reasonably specific in nature. It was envisioned, however, that further measurement needs could likely be met by photogrammetry and so the system assembled for the pre-launch work exhibited a general measurement capability. The individual components, which are more fully described in a later section, comprised a 70mm semi-metric camera (with undersea housing), an inexpensive toolmakers microscope to serve as a monocomparator, and associated photogrammetric triangulation software. Accuracies surpassing the 0.3-0.5mm requirements were readily attainable with this system in the pre-launch measurement operations.

Dynamic Measurement of Closure and TV

In attempting to come up with an optimum camera station configuration for the closure monitoring network a number of designs were investigated. The selection of a suitable imaging geometry was, however, severely constrained by the operational nature of the test process. To obtain the most desirable coverage of the closure and closure segments for the duration of a test event, an optimum height for the cameras would have been about 5m, with six cine cameras being positioned at 60° intervals around the closure. Unfortunately, this scenario was unacceptable since the necessary provisions for an all-around camera support structure and control reference frame could potentially interfere with the dynamic interaction of the closure segments and TV. Moreover, the required structure would certainly affect the hydrodynamic parameters that the test program was designed to model and characterize. A last concern centered on the question of whether bubbles, excessive turbidity or even fish would give rise to unacceptable imaging conditions over a distance of 6-7m.

The network geometry finally adopted is indicated in Figures 1 and 2. The six cine cameras forming the network were positioned at 20° intervals on an arc above the deck, beside the hatch cover which opened to expose the closure. Each camera station was at a height of about 3.5m above the base of the closure and 2.8m radially out from its center. With this geometry only a portion of the closure surface could be seen, namely the cap and four of the eight orange-peel segments (see Figure 4).

During each test event both vibration and pressure waves in the water were expected to induce movement in the camera platforms. Thus, it could not be assumed that camera exterior orientation would remain stable from epoch to epoch. As a consequence of the dynamic properties of both the object and the camera stations it was necessary to provide a field of object space control points. These control points, which were positioned on rigid poles in front of and behind the closure, provided a stable tie to the launch tube reference coordinate system. They also served a secondary purpose, that being to provide extra strength to the photogrammetric network in the event that one or more of the high-speed cine cameras either failed or lost time synchronization with the remaining units. In all, some 25 control points were established, though depending on the position of the closure at any epoch during the test event only a subset (typically a dozen) of these were imaged, as indicated in Figure 4.

By traditional design standards the network for the closure was not optimal from a geometric standpoint, but it was the best conditions would allow. Simulation studies indicated that positional accuracies (1-sigma) of 3mm would be attained so long as control pole vibration and camera synchronization were kept within design tolerances. Moreover, this accuracy level would be maintained for the bulk of the closure targets in degraded network conditions in which one or two cameras failed to operate properly. The reader need only examine the series of photographs shown in Figure 4 to appreciate that imaging conditions for the closure network were far from ideal. In photo (a) the closure is shown at Epoch 90 (about time t = 0.18 sec.) shortly after being 'cut' from the tube. It then proceeds upwards as shown in photo (b) before being segmented at about Epoch 200 (t = 0.4 sec.) as indicated in photo (c). By photo (d), at around Epoch 300 (t = 0.6 sec.), the closure approaches the extremity of the desired tracking range. Note the fuzziness of the 10 cm diameter targets, as well as the problems caused by bubbles.

Unlike the above-deck camera network for the closure the two cameras for the TV imaged through air. Each was mounted in a special housing which was bolted to the launch tube. The targets on the TV were then viewed through a 5cm thick glass port which provided a circular field of view of around 30° for the cameras. This corresponded to an area of approximately 40cm diameter on the TV as indicated in Figure 5 which shows a typical photograph. Also shown in the photo are the fiducial marks and BCD-encoded timing block which allowed precise exposure time to be recorded on the film. Illumination was provided by lights mounted inside the housing.

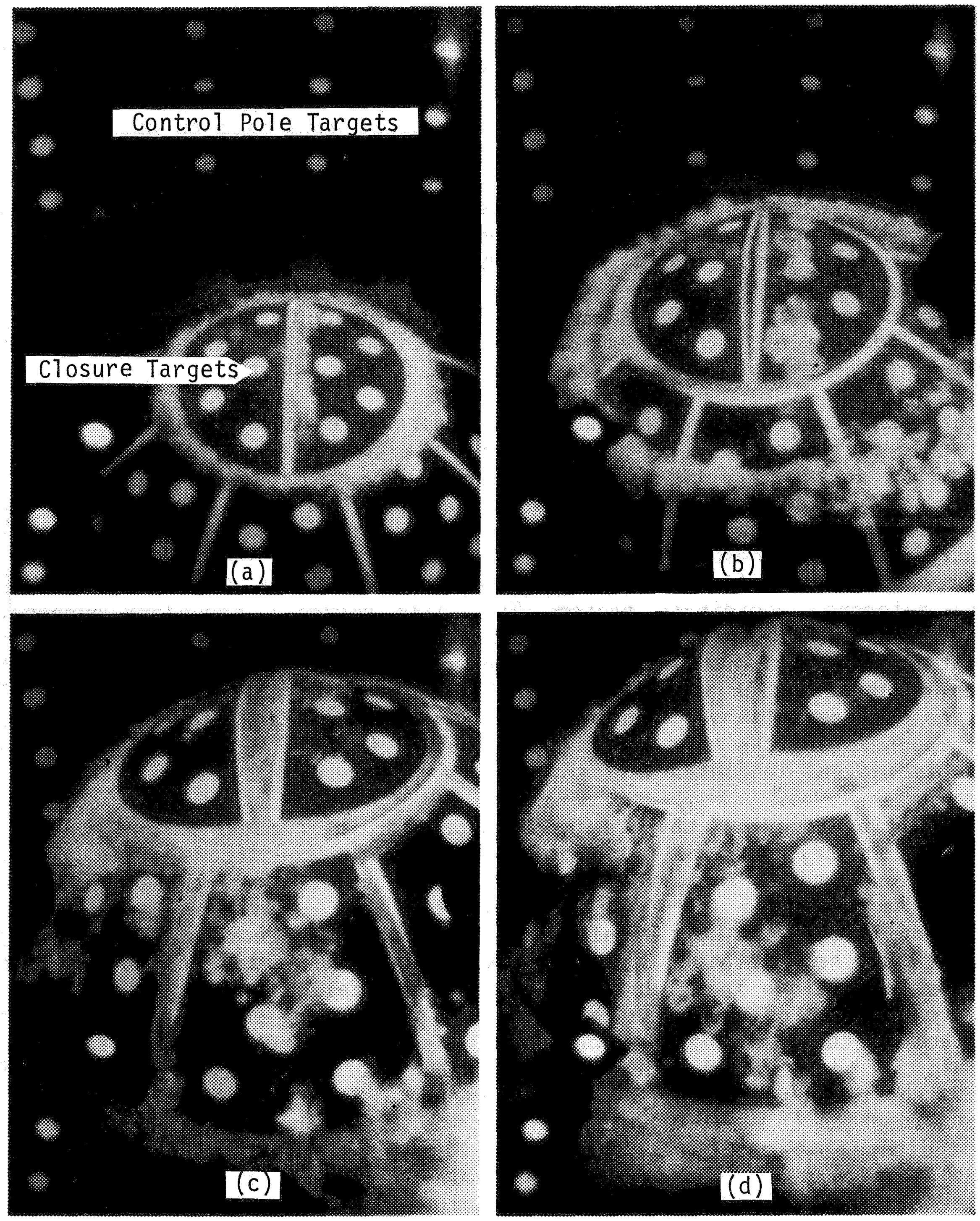

Figure 4: The closure at four epochs during a test event, as viewed from camera #4

With such a narrow camera view angle, coupled with a near planar target array, there was some concern that the resection solutions would display excessive correlation between parameters of position (XYZ) and rotation. Simulation studies indeed indicated that these concerns were well founded. Two actions were taken to enhance the decoupling of TV displacement from its rotation. The first was the mounting of the two launch tube cameras at right angles to one another, and the second was to impose damping constraints via a form of Ridge regression on the least-squares computation of the camera station coordinates.

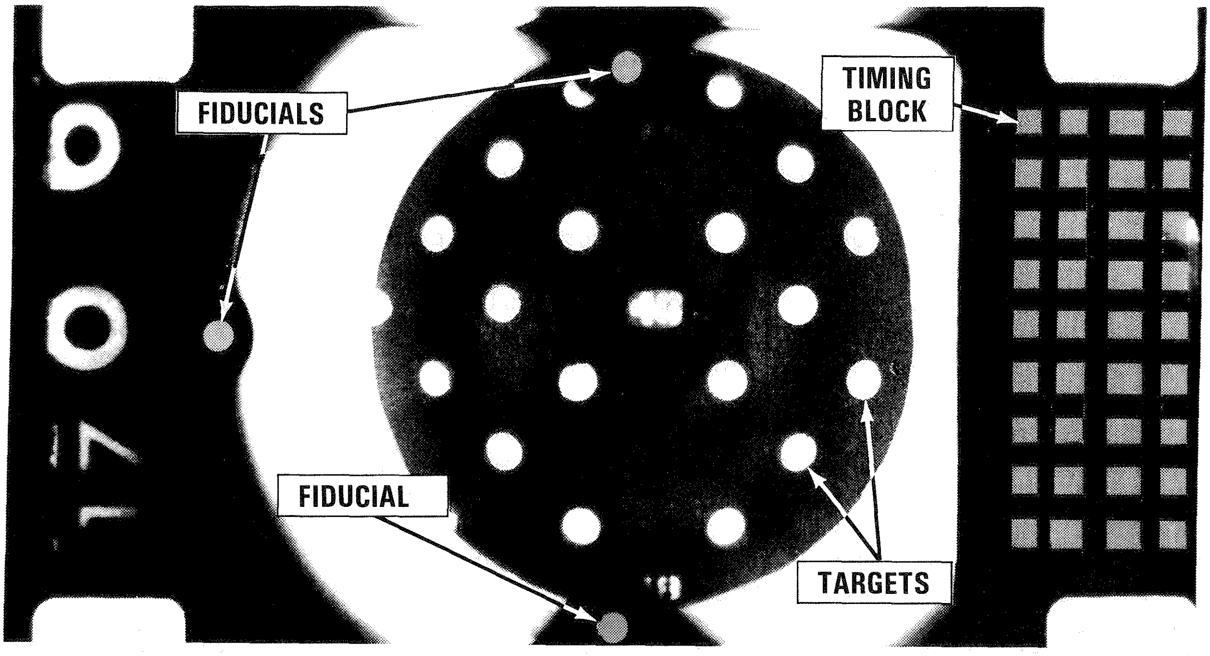

Figure 5: Photograph of TV resection targets as seen by camera #7

SYSTEM COMPONENTS

Pre-Launch Measurement

The pre-launch measurement phase called for a photogrammetric system capable of moderate accuracies (up to say 1:30,000 of object size) and also capable of both in-air and underwater operation. These requirements were met by a system comprising a Rolleimetric SLX Reseau camera, a Mitutoyo TM-201 Toolmakers microscope which served as an inexpensive monocomparator for the 70mm film, and the STARS software system from GSI (e.g. Fraser & Brown, 1986). The data reduction and analysis software was installed on a VAX 11/730 which served as the host computer for the entire CRCPS system.

For the anticipated underwater operation of the Rollei camera an Aquamarin WKD-SLX Subsea housing was used. A Nikonos V 35mm underwater camera was also procured to serve as a backup to the Rollei. An extensive test procedure was undertaken to examine accuracy aspects of the use of these two cameras for underwater measurement and the results of this work were earlier reported by Fryer & Fraser (1986).

Cine-Photogrammetric System

Unlike the pre-launch measurement system, the cine-photogrammetric system was special purpose in nature, required a new system level design and comprised components which were in most cases not readily available on the commercial market. Three distinctive subsystems required development: the camera subsystem, and one each for automatic film measurement and data reduction.

Camera Subsystem

Photosonics 1PL pin-registered high speed 16mm cameras capable of synchronous operation at a rate of 500 frames per second were specified for the camera subsystem. These cameras were to be controlled from a surface support vessel by an automatic remote control and monitoring system. Amongst its other functions the control system maintained and monitored shutter synchronization to 40 microseconds and controlled timing such that the computer readable time code on the film was accurate to 0.1 milliseconds. A specially designed and insulated sea cable bundle of 160m length connected the remote controller to the cameras. Power for additional lighting was also provided by cable.

Special underwater housings capable of providing protection for the cameras for a duration of four days at a depth of 100m were required. The presence of a 2.5cm thick glass viewing port in each camera was tantamount to the addition of an extra lens element, and this fact coupled with the air-to-water interface at the port necessitated that due attention be paid to calibration. All six cameras forming the closure network were self-calibrated both in a swimming pool and on site prior to installation. A standard 'physical' model comprising principal distance and principal point offset, along with coefficients of radial and decentering distortion formed the additional parameter set in the self-calibration. The approach proved to be more than satisfactory. All perturbations to the multimedia imaging were projectively accounted for to a sufficient degree by these additional parameters. Each self-calibration adjustment comprised eight photographs of a target field of 50 or so points, and an RMS value of image coordinate misclosures of close to 3 μm was routinely obtained. The 16mm cameras were fitted with lenses having a nominal focal length of 10mm, which translated to an effective principal distance of near 13mm when the camera was used underwater.

Film Measurement Subsystem

A maximum data turnaround time of 36 hours was desired for each test event. Thus, only a few days were available for the measurement of up to 3000 frames (each with 20-30 targets) of closure photography and another 1000 frames of TV photography, along with the accompanying data processing. Of this period around 24 hours was to be dedicated solely to film measurement. A quick survey of automatic film readers available at the time indicated that there was no instrument on the commercial market capable of meeting these stringent time requirements, which translated to the need for an image centroid measuring rate of better than 10 points per second, or about one frame every three seconds, and an accuracy of 3-5 μm.

The answer to this vexing film measurement problem was found in the Semi-Automatic Video Reading System (SAVRS) developed by DBA Systems. This instrument had been designed for the measurement of photography of aerial trajectories. It essentially comprised a video camera and film transport system, coupled with a solid state target tracker and associated computer hardware and software. For the CRCPS, a substantially modified version of SAVRS was required. Most notably, the standard vidicon camera was replaced by a CCD camera of 800 x 800 pixel resolution (12.5mm square format), and the video tracker was enhanced to allow the automatic frame-to-frame tracking of multiple targets per frame. SAVRS operated as a stand-alone unit, driven by its own dedicated computer (a PDP 11/23 plus). Measurement data was to be transferred to the data reduction subsystem via magnetic tape.

Although SAVRS provided automated measurement of both the timing block and image coordinates, its operation still required constant supervision by an operator. Manual intervention was often necessary in order to pick up new targets as they entered the field of view, drop targets as they left, sort out problems in cases of partial target obscuration, handle disappearance and reappearance of targets and so on. The task of measuring a full set of photography for a test event was a daunting one. In excess of 100,000 image coordinate measurements were routinely required and the fast reading rate denied an opportunity to the operator to impose a level of quality control normally associated with photogrammetric film measurement. This fact had a significant impact on the design of the data reduction subsystem which had to provide extensive error checking and automatic data editing.

Data Reduction Subsystem

Four major tasks were identified for the Data Reduction Subsystem: determination via bundle adjustment of XYZ coordinates of target points on the closure at each epoch; computation by 'moving resection' of position and rotation data for the TV at each epoch; subsequent determination of displacements and rotations for the closure and closure segments via 3-D similarity transformation, along with computation of relative displacements of the closure and closure segments with respect to the TV; and computation and display of final displacement, velocity and acceleration parameters with their respective standard errors.

In most respects, the algorithms for the bundle adjustment and resection followed the traditional formulations well known to photogrammetrists. What was unique about the photogrammetric aspects of the data reduction system was the degree of automation incorporated. Prior to bundle adjustment, preliminary resections and triangulations were computed for each epoch of the closure measurement. This served both the normal purpose of providing refined approximations for the camera station parameters and object point coordinates, and, more importantly, afforded two extra levels of blunder detection.

A time budget of about a minute was allotted for the bundle triangulation of the closure network at each epoch. The results of each adjustment were summarized in a single record on the computer screen for the operator to monitor. Listed quantities included the number of camera stations used, the number of points successfully triangulated, the RMS value of image coordinate misclosures, the number of observations rejected, plus a few key status indicators. The software accommodated both the periodic dropping and picking up of camera stations as well as object points. It was also possible to step through the data reduction process commencing and stopping at any epoch and the choice could be made to skip epochs (some were automatically skipped and flagged as rejects). The operator could employ interactive data editing to rerun bundle adjustments for epochs at which unsatisfactory results were obtained.

Similar operator interfaces were created for the TV resection and 3-D transformation phases. Since the data reduction subsystem was designed to be operated by a non-photogrammetrist, most decisions regarding quality control and data integrity were left to the computer. As it turned this approach worked well, though it was not without minor problems. In many instances the experience and intuition of the supervising photogrammetrist was called upon to rectify data errors which the software had trouble accommodating (e.g. the excessive mis-identification and mislabelling of targets over a series of epochs).

Within the data reduction phase, the bundle adjustments for the closure network and the TV resections could be run concurrently, the former taking substantially longer than the latter. Of course both these stages had to be completed before relative displacement data could be computed. For the test launches conducted image coordinate residuals of close to 7-10 µm were invariably encountered for both the least-squares bundle and resection adjustments. This level of image coordinate misclosure was somewhat higher than designed for, but not altogether unexpected given the difficulties of the overall environment. Once displacement and rotation data were obtained for each epoch, profiles of acceleration and velocity could be compiled for both the closure and TV, thus giving a comprehensive picture of the dynamics of the launch.

SYSTEM OPERATION AND RESULTS

At the completion of the development stage, the CRCPS was put through a series of acceptance tests using a simulated TV/closure assembly. This testing phase presented an opportunity to verify that the system would meet general performance requirements, especially in regard to photogrammetric accuracy and the operation of camera and film measurement subsystems. Two of the factors central to the success of the CRCPS were accurate synchronization of the eight cine cameras and the ability of SAVRS to maintain a film measurement precision of better than 5 µm. The acceptance tests indicated that both these specifications were consistently met as the accuracy of derived displacement, velocity and acceleration data was within allowable tolerances.

Full implementation of the CRCPS took place in 1986 when a series of 16 test launches was conducted off the California coast. Although it performed well in the environment for which it was designed, the amount of system redundancy built into the CRCPS soon proved beneficial. Numerous minor problems ranging from broken film to insufficiently precise camera pointing, to intermittent camera failure and even to the presence of fish meant that the majority of the tests exhibited a degraded imaging configuration for at least a part of the one second event. This fact was aggravated somewhat by the appearance of more blunders than anticipated in the film measurement operation. Film reading errors were mainly a consequence of the speed of measurement, coupled with the varying presence of bubbles and fish. It was not possible for the SAVRS operator to adequately monitor target tracking in situations, for example, where targets were in close proximity and the tracker would pick the wrong target and continue measuring it in subsequent frames. The data reduction subsystem could handle these blunders but much potentially good image coordinate data was lost and this weakened the overall strength of the photogrammetric solutions, especially in the case of the closure network. Nevertheless, the CRCPS operated successfully and still managed to produce sufficiently accurate data on displacement, velocity and acceleration (both relative and absolute) of the closure and TV in all but one of the test events.

CONCLUDING REMARKS

The CRCPS represented a unique photogrammetric system development in a number of respects: the use of high-speed, semi-metric cine cameras for accurate dynamic measurements underwater; the adoption of two networks linked through synchronized cameras to afford simultaneous measurements of rigid body motion of the closure and TV; the use of a video film reading system to provide automated film measurement at a rate of close to 10 points per second; and the provision of a highly automated data reduction system to handle in a very short time period the mass of data generated.

As a development costing close to two million dollars, the CRCPS embodied some very sophisticated and complex system engineering. In this paper it has not been possible to give but a cursory overview of the CRCPS and many interesting features have not been mentioned at all in an attempt to confine the discussion to primarily photogrammetric aspects. From the photogrammetric standpoint alone, though, the system certainly constituted an interesting example of the application of highly automated photogrammetry for the monitoring of a dynamic event in a difficult undersea environment. In addition to its primary purpose for underwater measurement, the CRCPS is also potentially applicable to other dynamic monitoring tasks; for example, wind tunnel testing.

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