The Camera as a Transducer: From Muybridge to Motion Capture and Videometrics

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1. The Camera as a Transducer

Images have been used to make measurements since Eadweard Muybridge examined the motions of horses in June and July of 1878[1]. The concept is not new, but the tools—the hardware, the analytical methods and the software—we now have at our disposal are now far superior to those used by Muybridge. Muybridge conducted a study of horses using twelve "single-shot" still cameras with rudimentary triggers. He employed elementary analytical procedures … and "software" didn't exist.

1.1 Hardware developments

By the middle of the 20^{th} century, high-speed cameras that could record several thousand pictures per second on film were being assembled from carefully machined mechanical components and creative ways had been found to record images at more than one million frames per second—albeit for a very limited number of frames. (For a detailed review of the hardware that was available in 1962, refer to Hyzer[2].)

The 1980's saw the introduction of consumer video equipment and personal computers: and the shift to electronic imaging began. This new (electronic) hardware and the ability to extract and treat data on the desktop made it much easier to exploit the potential of high-speed photography. By the mid-1980's, investigators could extract coordinate data from a video signal, store the data in a workstation, and reconstruct three-dimensional trajectories soon after a test had been conducted[3]. At about this time (1985/86) the animation industry and Hollywood began to adopt the technology and they renamed it *motion capture*. By 1990 various vendors were offering video-based motion measurement equipment[4].

As we moved into the 1990's, the technology used to acquire image sequences changed rapidly. New and innovative electronic hardware was introduced, high speed "photography" became high speed "imaging", and the scientific analysis of video sequences became well-known as *videometrics*[5]. By the end of the century, high-speed imaging was an established measurement technique and the transition to entirely electronic systems that could bypass the inherent physical limitations of mechanical hardware was well underway. (For a detailed review of the state-of-the-art of high-speed imaging in 1997, refer to Ray[6].) Today (2007) mechanical devices are rapidly being replaced by digital video cameras, sophisticated image processing boards, and fast (personal) computers with the ability to store millions of images. Moreover, it is now possible to capture and view image sequences without the depth of knowledge of a "journeyman". In brief, we have seen the birth of "Point and Click High Speed Imaging".

The core technology employed by high speed "photographers" continues to change. Fresh opportunities are emerging and engineers developing the technology have begun to redirect their efforts. New products are being created, new vendors have appeared, and the industry has found new end-users with innovative applications; but the focus of the high-speed imaging community has steadfastly remained on hardware.

1.2 Software developments

There can be little dispute that in the last thirty years the most significant advances in high-speed imaging have been hardware related. Driven by consumer markets, the capabilities of (high speed) video cameras have made remarkable advances, but development of software to support the use of cameras as measurement devices—as transducers—has been slow at best.

Typically, in the mid-1970's the high-speed imaging community relied upon 16-mm framing cameras to capture film sequences at up to 500 frames per second, or rotating prism cameras to capture (full frame) film sequences at up to 11,000 frames per second. The subsequent analysis of these images was accomplished using projection devices with hand-cranked reticules and custom software written in FORTRAN or machine code.

In 1976, this author described how the motions of athletes could be measured in three-dimensions using several high speed cameras[7]. A subsequent, more detailed report of this work was presented in 1981[8]. This report contains a detailed historical review of the measurement procedures that had been used in high speed photography during the first seventy-five years of the 20^{th} century—that is, before the introduction of the personal computer; moreover, it included the first comprehensive “motion capture” software—a package that was coded in FORTRAN for use on IBM mainframes. At that time it was necessary to extract coordinate data from the images, point by point, frame by frame, view by view, and the time required to acquire sufficient data was significant. (A formal validation study that used four cameras operating at approximately 100 frames per second was described in the report. Three simple gymnastics skills were examined and data for 12 body landmarks were recorded from approximately 1160 frames. The recovery of these data took approximately four weeks.)

Today, an end-user can choose from a wide variety of digital video cameras that can capture (color) sequences in user-selectable formats at frame-rates that exceed 1 million frames per second. Images can be streamed directly from the camera to a personal computer or, when higher frame-rates are required, they can be buffered in on-board memory to be downloaded after each test has taken place. Furthermore, a variety of vendors now offer “low-end” (machine vision) products that can record up to 500 frames per second. Competition among vendors is beginning to bring prices down to levels that heretofore have not been seen. But these advances aside, the ability to extract generic kinematic data (time-series) from the images produced by these new cameras lags far behind. As a consequence, many end-users are still writing custom software to analyze the data they recover from their high-speed imaging equipment, albeit in newer, more sophisticated languages such as C or C++.

Historically, vendors of high-speed cameras have shown a reluctance to become involved with data analysis software. Some commercial products are now available and alliances have been formed, but there is still ample room for improvements to be made. Fortunately (for the industry) many of the traditional applications for which high speed cameras have been used require only a qualitative analysis of the images. Thus rudimentary software that allows end-users to simply capture high-quality images in close to real-time has been sufficient for many high-speed imaging applications. However, the ability to capture synchronized image sequences from several high speed cameras has made it possible to do far more with the images. With appropriate software, an end-user can now perform analytical tasks that heretofore would have been considered far too time consuming to be used in an industrial environment. The goal of this paper is to point out that the development of good software that can be used to support new and innovative applications is in the best interest of the discipline as a whole—not just the end-users, but also the manufacturers and vendors of high-speed cameras.

1.3 A transducer? A software package for making measurements?

A transducer is simply a device that converts a signal from one form to another. In industrial environments, transducers are frequently used to acquire test data. The incoming electronic “signal” is scaled and treated in software and meaningful data (forces, accelerations, temperatures, etc.) are produced. Since 4DVideo™ was formed we have encouraged people to think of the camera as a ***transducer***, not just a device for capturing image sequences[9]. Typically, our applications work involves the capture and processing of image sequences with the intent to extract kinematic ***data*** from the images.

Imagine, for example, a personal computer without Word, Photoshop, Acrobat, Web development software, and other well known software packages. The development of compact computer hardware was a very necessary part of the transition to desktop computing, but without software our ability to create and edit documents and images would be severely limited, and our ability to communicate with each other over the Internet would be impossible. In brief, without applications software the personal computer would have a limited number of uses. Likewise, without software applications to process image streams, high-speed cameras are failing to reach their full potential. More thought needs to be given to this issue. Vendors and end-users alike need to be re-educated and a new mindset needs to be created. What is “the full potential” of a high speed camera and how can we expand their use as measurement devices?

Ten years ago, we talked about a (monochrome) camera with 512 x 512 spatial resolution that could acquire 1000 frames per second. Today, we can stream these images to disk … but what are we doing with them? Could we increase the use of high-speed photography by providing the right software tools? If so, how should the package be structured? What are the essential elements of a suitable software package? Certainly, we can learn from our knowledge of existing high-speed imaging applications, from image processing and machine vision techniques—and from software packages that have been produced to support the “digital imaging revolution”. The fact that we acquire “high speed” images is, in most instances, irrelevant, but we do need to consider the fact that we deal with image sequences, not isolated images. 4DVideo has been attempting to address these issues with a new software package, 4DCapture™.

2. 4DCapture™: Motion capture in a software package.

4DCapture™ is a software package for the PC platform that will allow end-users to extract kinematic *data* from video sequences. In brief, **the package has been designed to encourage the use of video cameras as transducers**. The software continues to evolve, but the core objectives of the package remain unchanged. First, and foremost, it is essential that the package provide an ability to acquire and display accurate and repeatable *data*. Secondly, the package must be easy to use and insulate the end-user from the technology required to obtain the data. (Few end-users want to learn the details of the disciplines required to extract meaningful data from images. They want to "drive the car", not understand how it works.) Finally, the package must have a modular structure that allows components to be added or removed as new technology is introduced or as the existing technology becomes out-dated; otherwise, the entire package will rapidly become obsolete.

The evolution of 4DCapture™ from 2002 to 2006 has been described elsewhere[10, 11]. It will not be repeated here. However, setting aside the (essential) analytical components of the software, a considerable amount of time has been spent deciding how to structure the package and how to manage and store the data. Several versions of the application were created before an interface with natural flow was produced. The key functions to be embedded in the application have been assigned to four groups. Many of the functions assigned to these groups are now available; but others remain to be developed. It is anticipated that additional capabilities will be incorporated, but the core structure of the application is unlikely to be changed for some time.

2.1 Setup

The *Setup* functions are the functions that must take place before testing begins. They are non-iterative, that is, they are (typically) performed only once for a particular project. These functions can be sub-divided into administrative procedures and the calibration procedures.

The administrative procedures are used to create and manage a test matrix and (implicitly) define the file structure. The administrative procedures are used to define basic quantitative parameters: dimensions, units and the bounds of the test region. They are also used to define the cameras and lighting used in the project and (implicitly) the corresponding hardware interfaces. The administrative procedures are used to set the sample rate, and the spatial and temporal resolution of the images.

The calibration procedures are used to calibrate the cameras and scale the images in two or three dimensions. The fact that these procedures require the capture of stand-alone calibration sequences made it necessary to duplicate the capture function; however, by making this provision the natural "top-to-bottom" flow of the project was maintained. It is here that the core photogrammetry is embedded.

2.2. Capture

Capture is the first of the testing procedures; that is, the procedures that are (typically) used in an iterative fashion. Each time a test is conducted, it is here that the end-user acquires (synchronous) image streams. It is here that the sequences can be played side-by-side and appropriate time-matched sections can be extracted (or "edited") from the streams. The Capture section also includes provision to performing image pre-processing, that is, use image processing procedures to isolate features that are to be tracked.

2.3 Analysis

The *Analysis* procedures generate meaningful (scaled) kinematic data or "results" from the unscaled information acquired by the *Capture* process. It is here that the trajectories of points and boundaries are reconstructed. This section is structured to allow the multi-dimensional time-histories of the points and boundaries to be processed with filters and other analytical procedures. It is also where the kinematics of rigid bodies can be reconstructed.

2.4. Output

Here, the end-user can plot, animate, and export the data generated by the application. Of particular value is the ability to animate events while simultaneously displaying the original video streams and plots of kinematic data. This allows the end-user to view the subject matter from viewpoints other than those of the cameras and relate them to events seen in the numeric data.

Within the application, the overall flow of events is managed by a floating menu we describe as the FlowStack™. This menu provides continuous feedback to the end-user to ensure that the necessary data have been provided and the appropriate sequence of events has been performed. The FlowStack™ provides feedback to the end-user in the form of colored "Traffic Lights" associated with the sub-functions within each of the four sections previously described. The purpose of these lights is to assess the logic of the processing sequence created by the end-user. In effect, each traffic light responds to the question: "Given the data and sub-functions that are located higher in the FlowStack, can this sub-function produce meaningful results?" If the answer is "No", a red light is displayed. If the answer is "Yes", a yellow or green light is displayed. Yellow and green lights are used to differentiate the basis upon which a "Yes" decision is predicated. If the "Yes" is based on explicit information provided by the end-user, a green light is displayed; however, if a default or pre-existing value is used, a yellow light is displayed.

From the perspective of the end-user, the traffic lights provide feedback—a means to determine where there are "issues" that need to be addressed before tests can be conducted. A "right-click" on a red light provides more detailed information; specifically, it describes why a red light is being displayed. The "Traffic Light" concept is still under development. From a coding perspective, it certainly presents some interesting challenges, but it should take 4DCapture™ beyond the familiar (and frustrating) dialog (message) boxes that simply report: "You have an error".

We've come a long way since Muybridge, but there is ample room for improvement. The brief synopsis provided here describes our current thinking on the software issue. Certainly, we expect to find alternate (and perhaps better) ways to address the issue … but at least we are now talking about it.

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