TECHNICAL NOTES

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Optoelectric (Selspot) Gait Measurement in Two- and Three-Dimensional Space—A Preliminary Report[a]

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Abstract

Traditional studies of human movement by photographic methods require tedious, error-prone, and expensive data reduction. Various optoelectronic methods have been designed. A commercially available system, SELSPOT®, purchased for the Cleveland VAMC Motion Study Laboratory, is described. Sequentially pulsed light-emitting-diode targets on the subject are observed, with data fed into a computer for combination with force plate data (Cohen, Orin, and Marsolais, Technical Note, BPR 10-33). Calibration methods, errors, and practical difficulties are described. Though problems remain after revisions (see progress reports in BPR), it is believed that SELSPOT offers potential for clinically useful real-time acquisition and analysis of three-dimensional data.

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Introduction

Traditional studies of the kinematics of human movement have made extensive use of photographic and cinematographic data registration, followed by tedious and error-prone manual data-reduction procedures. Even though such data reduction is now becoming amenable to automation by the use of film scanners and pattern recognition algorithms, the delay between data acquisition and presentation exceeds clinically acceptable turnaround times and hinders real-time data processing for feedback purposes (Simon et al., 1978, Bresler and Frankel, 1948—and many others in the years between).

In recent years, a number of optoelectronic methods avoiding these drawbacks have become available (Woltring, 1974). The work at the Delft Institute of Technology (Furnee, 1967) appears to be one of the first utilizing T.V. in automated body-marker tracking; similar work has since been conducted at the Children's Rehabilitation Centre in Winnipeg (Winter et al., 1972; Winter, 1979), at Ohio State University (Cheng, 1974), and at the University of Strathclyde (Jarret, 1976). Other approaches include the use of linear photodiode arrays obviating the need for lenses (Fuchs, Duran, and Johnson, 1977), or of optical data digitizers such as by Lehmann at the University of Washington, Seattle (NIH 1977). However, all these approaches were used in individually designed installations and are not readily available to other users.

Monitoring of Infrared Light-Emitting Diodes

A commercially available system for multipoint movement monitoring exploits a position-sensitive photodetector based on the "lateral photoeffect" (Woltring, 1975). In its standard version, it is capable of tracking up to 30 infrared (IR) LEDs at a repetition frequency of 312.5 Hz, using one or two specially designed cameras. This "SELSPOT-system" (an acronym for "Selective Light SPOT recognition") was originally developed at the Bioengineering Department, Chalmers Institute of Technology, Gothenburgh, Sweden (Lindholm, 1974). It was based on a commercially available position-sensitive photodiode exhibiting limited position linearity and noise performance (Woltring, 1974, 1975). A superior photocell (Woltring, 1975) was subsequently developed at the same institute (Petersson and Lindholm, 1978) and an improved SELSPOT system has since been available from SELCOM AB of Partille, Sweden. More

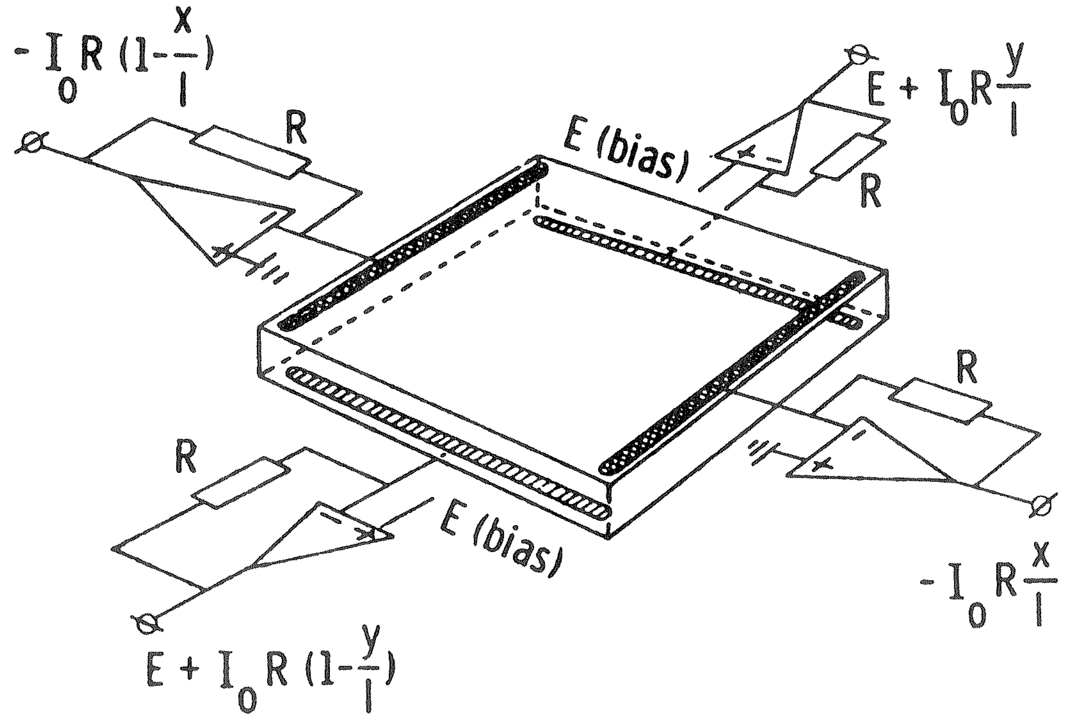

FIGURE 1.
Dual-axis, duo-lateral, position-sensitive photodiode (from Woltring, 1975)

recently, Hamamatsu Television of Japan has marketed a similar device.

The advantage of real-time, on-line direction monitoring of multiple light sources is counteracted by the need for wired light sources; it will depend on the individual application whether this advantage outweighs the drawback of wired body-markers.

Principle of Operation—Basically, the position-sensing photodiode may be regarded as a 2-dimensional potentiometer, in which the physical wiper is replaced by the projected image of an external light source, through the use of a suitable optical system. The four end-contacts of this potentiometer (2 for x, 2 for y) are each connected to an operational amplifier (Fig. 1); it can be shown that the sum of the output currents per axis equals the generated photocurrent, and that the difference equals this photocurrent times the mean position x (or y) of the incident light distribution on the photosensitive surface, where x and y may vary between -1 and $+1$. By ratioing these two quantities, the influence of light intensity is eliminated; this is typically done by an analog-to-digital (A/D) converter, in which the sum serves as the reference signal, and the difference as the analog signal to be digitized. In the SELSPOT system, this A/D converter has 10 bits resolution, which corresponds to 3-mm-per-axis resolution for a field width of 3 m—as is the case at an observation distance of 6 m from the camera when using standard 50-mm optics.

If the impingent light distribution is simply the image of a single point, the digitized signals are linear measures of the position of the image on the detector's surface. Multiple points cannot be simultaneously measured, since the detector would yield their composite mean value, weighed in their respective intensities on the detector's surface. However, by time-multiplexing a number of light sources, multipoint monitoring becomes feasible. Ordinary incandescent lamps are too slow for this purpose, but infrared light-emitting diodes (IR LEDs) are sufficiently fast, and they yield the most power of all currently available LEDs.

The influences of background light and diode leakage current are eliminated by measuring the change in output signals when an LED is turned on; thus, steady background illumination will not affect measurement precision.

The digitized x–y coordinates for each LED and camera may be transmitted to a recorder or computer; alternatively, they may be D/A-converted for display on an X–Y oscilloscope, or demultiplexed and low-pass filtered for multipen strip-chart recording (Fig. 2.).

The multiplexing character of the system necessitates synchronization between the SELSPOT main receiving unit and the LED Control Unit (LCU) typically worn by the subject. This synchronization is achieved either optically or by wire. In the former case, synchronization is possible by pulsing the designated first LED for 55 μsec, whereas the other LEDs are pulsed for 50 μsec only. If the first LED is temporarily lost because of shadowing or out-of-range effects, synchrony in optical mode may be lost. However, that usually occurs only after a few seconds, since both sides of the system are crystal-controlled.

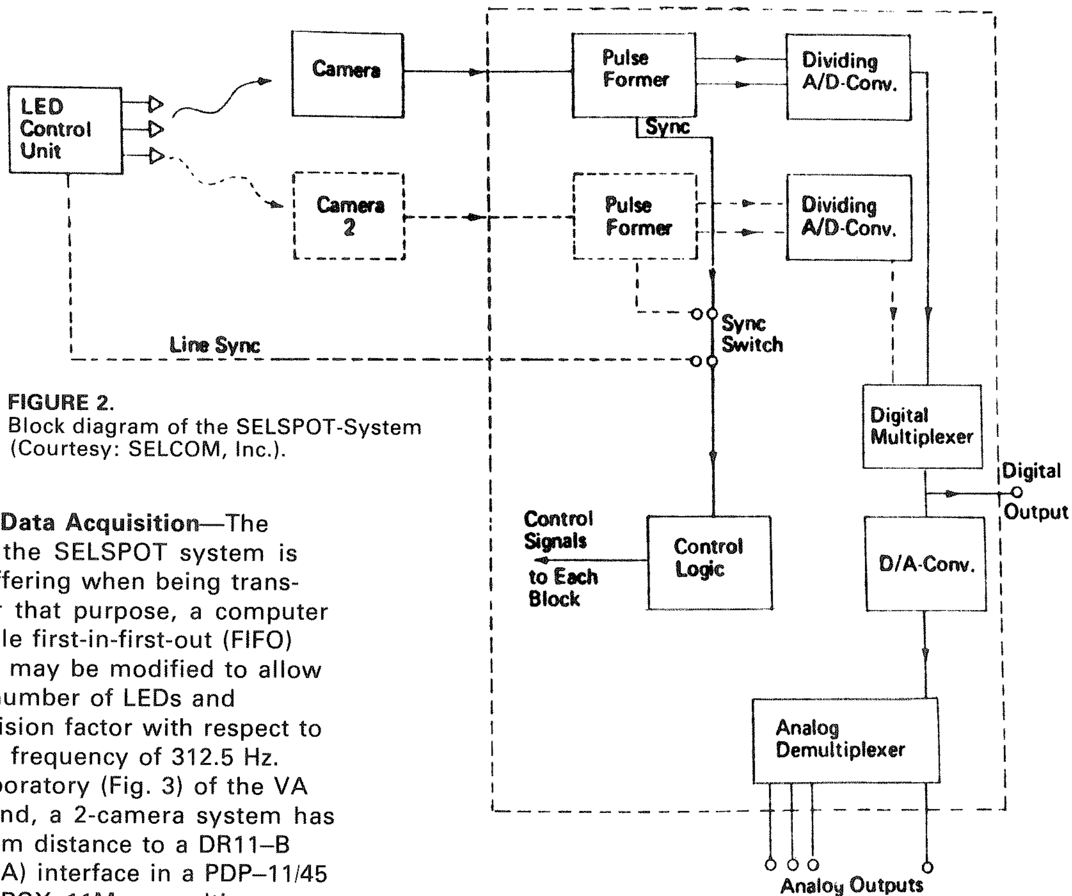

FIGURE 2.
Block diagram of the SELSPOT-System (Courtesy: SELCOM, Inc.).

Computer Interfacing and Data Acquisition—The 40-kHz data stream from the SELSPOT system is continuous, and needs buffering when being transmitted to a computer. For that purpose, a computer interface and programmable first-in-first-out (FIFO) buffer are available; these may be modified to allow software-selection of the number of LEDs and cameras, and of a rate-division factor with respect to the fundamental repetition frequency of 312.5 Hz.

At the Motion Study Laboratory (Fig. 3) of the VA Medical Center in Cleveland, a 2-camera system has been connected over a 15-m distance to a DR11–B direct-memory-access (DMA) interface in a PDP–11/45 computer operated under RSX–11M—a multiuser, multitask, real-time operating system from Digital Equipment Co., Maynard, Mass. A standard driver (SPDRV.MAC) has been designed for controlling this combination.

A comprehensive data acquisition package for synchronized SELSPOT and analog data acquisition is being written; the analog data originate from a force plate in the Laboratory and from EMG signals, and are required in kinetic gait studies following kinematic analysis. For the time being, analog data will be obtained through the VA Medical Center's LPS–11 (Laboratory Peripheral System) with 16 A/D channels. However, this device is not capable of DMA when in multichannel operation, and the standard driver is rather slow; it is anticipated that a faster multichannel A/D system will be necessary, in order to allow sufficiently high A/D-sampling frequencies.

Two- and Three-Dimensional Camera Calibration and LED Position Reconstruction—The raw data collected from SELSPOT are basically LED direction signals. In planar analysis, assuming no significant image distortion, the "bilinear transformation",

$$X = (a_1x + a_2y + a_3)/(a_7x + a_8\,y + 1)$$
$$Y = (a_4x + a_5y + a_6)/(a_7x + a_8\,y + 1)$$

allows transformation of image-plane coordinates (x,y) into object-plane coordinates (X,Y); if the two planes are parallel, the denominator reduces to 1 ($a_7 = a_8 = 0$).

The unknown calibration parameters $[a_j]$ may be estimated by observing a suitable distribution of calibration LEDs with known coordinates $[(X_i,Y_i)]$, and by conducting a least-squares, iterative adjustment procedure on the unknown $[a_j]$, based on the known $[(X_i,Y_i)]$ and the observed image coordinates $[(x_i,y_i)]$: see Woltring (1978). At least four calibration LEDs forming a true quadrangle are required, but a distribution covering the full observation area should be preferred.

This approach may be generalized to 3-D camera calibration and target position reconstruction. Interchanging the (X,Y) and (x,y) points for each camera, one obtains the "Direct Linear Transformation" of Karara and his associates (Abdel-Aziz and Karara 1971; Marzan and Karara 1975),

$$(b_1X + b_2Y + b_3Z + b_4) - x(b_9X + b_{10}Y + b_{11}Z + 1) = 0$$
$$(b_5X + b_6Y + b_7Z + b_8) - y(b_9X + b_{10}Y + b_{11}Z + 1) = 0$$

the parameters of which may be estimated by recourse to a 3-D "control distribution" of LEDs with known coordinates $[(X_i,Y_i,Z_i)]$. Note that the perspective center of a camera may not be located at the origin of object-space in this model, and that the line connecting the perspective center with the origin should not be parallel to the image plane.

3-D reconstruction of an observed target is feasible by adjoining the above equations for at least two

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cameras through some form of least-squares adjustment, once the $[b_j]$ for each camera have been estimated. These models may be expanded to accommodate systematic image distortion and stochastic measurement errors: see the references cited.

Such a calibration procedure allows maximum flexibility in camera positioning, in order to balance between depth precision (which requires a large camera base) and data loss due to shadowing or other out-of-range effects (which is minimal for a short camera base). However, a crucial problem is the construction and maintenance of a sufficiently precise and stable 3-D calibration object; in the case of an observation area of a few cubic meters, that may become quite cumbersome. For this reason, a different model and calibration procedure were chosen in which only a planar distribution is required.

For a given camera configuration in which the optical axes should preferably converge, proper calibration becomes possible by observing a known planar distribution at various positions and oblique attitudes; one of these positions and attitudes, together with the known marker positions on the plane, defines an object-space frame of reference, and the remaining plane positions and attitudes become unknown parameters to be solved for simultaneously with those of the cameras (Fig. 4). The unknown plane parameters are simply intervening variables incurred during calibration; after calibration they are no longer needed, although their a posteriori covariance matrix will give an estimate of attainable reconstruction precision for individual targets. In this approach, the bilinear models discussed above are replaced by models in terms of camera positions, attitudes, and internal camera parameters, including those describing systematic image distortion caused by lens aberrations and processing electronics. See Woltring (1978, 1980) for a discussion of this method of "Simultaneous Multiframe Analytical Calibration".

Based on that model, an observed image point (x_i,y_i) may be transformed into an observed object-space direction $\mathbf{S}_i$. For given coordinates $\mathbf{X}_a$ and $\mathbf{X}_b$ of the cameras' perspective centers, a simple estimate for the observed target's object-space position $\mathbf{X}$ is the midpoint of the interconnecting perpendicular between the two direction lines $\mathbf{S}_a$ and $\mathbf{S}_b$ when originating from the cameras. The symbol ′ denotes the transpose of a vector; * denotes a vector product:

$$\mathbf{X} = (\mathbf{X}_a + \mathbf{X}_b)/2 + \mathbf{L}'\mathbf{S}_a \cdot \mathbf{S}_b + \mathbf{L}'\mathbf{S}_b \cdot \mathbf{S}_a$$

with:

$$\mathbf{L} = (\mathbf{X}_a - \mathbf{X}_b) * (\mathbf{S}_a * \mathbf{S}_b) / |\mathbf{S}_a * \mathbf{S}_b|^2$$

It should be noted that this estimate is biased if observation noise is additive to the observed coordinates; usually, however, this bias will be negligibly small with respect to stochastic errors.

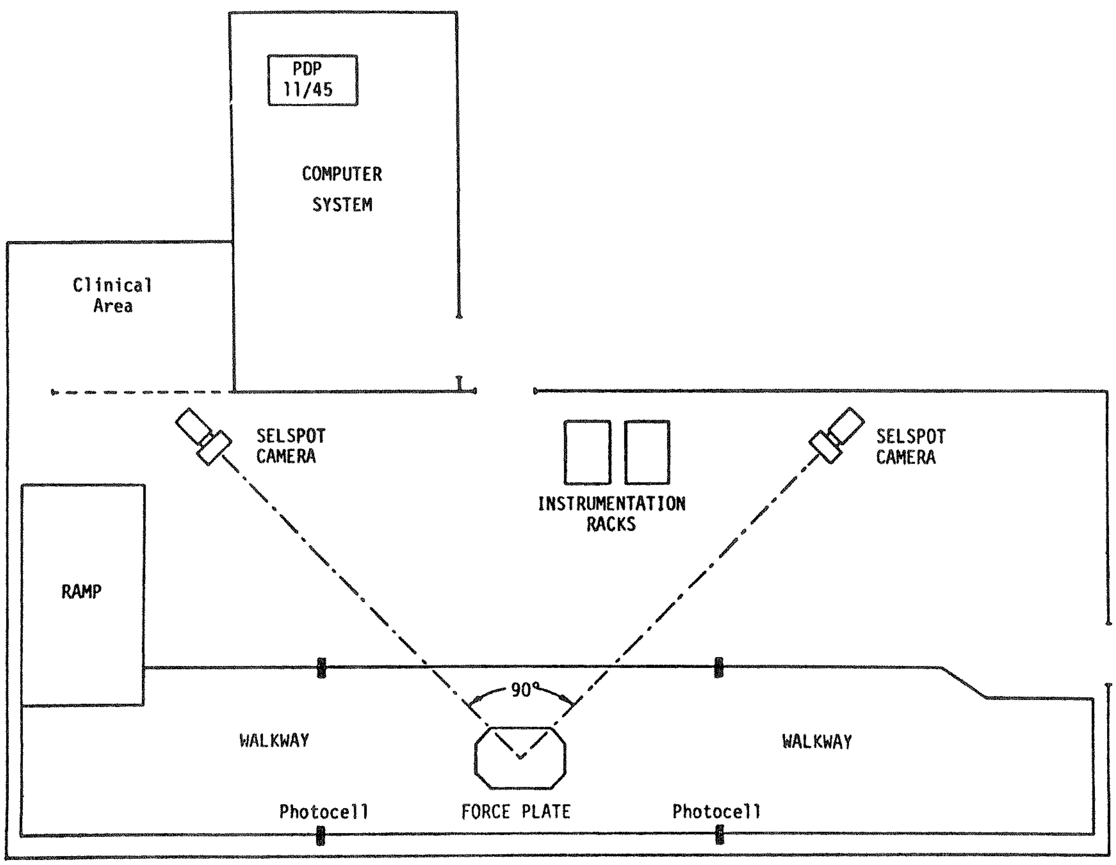

FIGURE 3.—VAMC Cleveland Motion Study Laboratory.

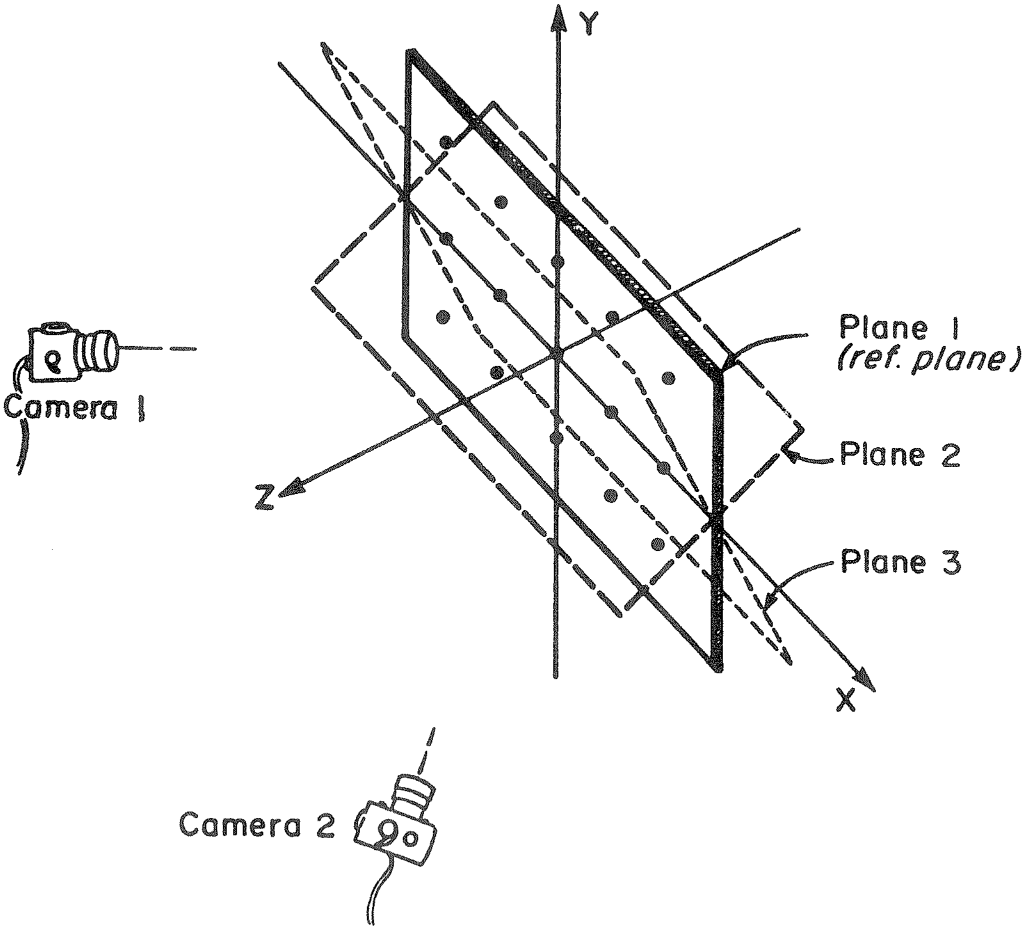

FIGURE 4. Example of camera and calibration-plane lay-out in "Simultaneous Multiframe Analytical Calibration" (from Woltring, 1980).

Limb Segment Trajectory Reconstruction—3-D reconstruction of individual body markers is of limited interest on its own, and hampered by temporary data losses caused by shadowing, limb rotations and other out-of-view effects. At the expense of a rather heavy computational burden, contemporary state-space estimation procedures (see, e.g., Gelb 1974) promise a unified approach for simultaneous estimation of limb segment positions, attitudes, and their numerical derivatives as required in kinetic analysis, based on complete or partial observations on markers defining these limb segments: see Woltring (1979). Also, the time-shifts between LED observations caused by the system's time-multiplexed functioning may be accommodated: for example, the interval between the first and last LEDs in a frame is approximately 3 msec. Unlike more traditional frequency-domain methods, temporary data losses are naturally accounted for in such time-domain models. Moreover, error propagation and parameter sensitivity studies may be an inherent part of this approach.

Discussion

Optoelectronic and cinematographic methods in gait measurement each have their own advantages and drawbacks. As mentioned before, film processing is tedious, error-prone, and non-real time, but SELSPOT requires wired body markers emitting IR light. Film-cameras are of the non-metric type (i.e., not designed for mensuration) and exhibit large interframe instabilities, whereas electronic signal-to-noise (S/N) ratio is a crucial limitation in the SELSPOT system.

Distance Influence on Image Resolution—Typically, when an LED is moved away by a factor 2 from a SELSPOT camera, the intercepted amount of light per light pulse is reduced by a factor 4; this tends to decrease S/N ratio in the digitized A/D output by the same factor—although quantization noise, in the A/D converter proper, limits this effect to some extent. Also, IR LEDs often have a limited aperture angle of up to 100 deg. In cinematography, when observing passive body markers, such effects do not occur.

Background Light Interference—a.c. background-light interference is another source of difficulty. Even though the position-sensitive photodetectors are covered by IR lowpass filters restricting the detectible spectrum to a range extending from 800 nm to the detector's cut-off wavelength at 1100 nm, standard fluorescent or incandescent light when powered from the 50- or 60-Hz a.c. system may cause significant optical hum at

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twice the a.c. frequency, due to the fact that the IR background light level varies significantly between the measurement instants prior to and during an LED light pulse. For example, using a standard camera system with a 50 mm/0.95 CANON lens, at 6 meters distance from a series of Texas Instruments TIES–27 IR LEDs pulsed at 10 A, the standard deviations of observed image coordinated were found to increase by up to a factor of 4 when turning on the fluorescent lamps in the VAMC's Motion Study Laboratory. Note, however, that these lamps were not selected for their IR properties; they are one of the most common types used in federal agencies (General Electric, F40CW).

Background light effects may be compensated by using optical interference filters selected for the narrow-band IR light emitted by the LEDs, instead of IR lowpass filters; however, such filters attenuate the LED signal light by approximately 50 percent, which has been found to be marginally acceptable for the typical measurement configuration referred to above. More powerful LEDs are available at moderate cost (e.g., Texas Instruments SLH44, SLH8), but those require even higher pulsing currents—possibly causing too much heat dissipation on the subject. Alternatively, one might connect a number of adjacent LEDs in series (e.g., SELCOM's LED 7), but it may become difficult to guarantee a point-light-source character as required in 2-D and 3-D. In fact, a much better solution would be to change the SELSPOT system's pulse-processing circuitry to allow measuring background light prior to and after a light pulse—the mean value should be subtracted from the signal measured during a light pulse. In this context it is of some interest to note that position-sensitive detectors are currently being made with standard integrated circuit technology; this would promise integrated, rather than the discrete, signal-processing components currently employed in the SELSPOT system (Noorlag and Middelhoek, 1979).

Image Distortion, Reflections, and Body-Marker Instability—Image distortion in the SELSPOT system is significantly worse than in cinematography. This is caused in part by the large-aperture lenses required to intercept sufficient IR light from the LEDs; linearity of the electronic system proper is on the order of 1%. The CANON lenses usually delivered with the SELSPOT system have been designed for maximum acuity in non-metric imagery; distortion is of minor concern in such applications.

Lens-distortion compensation in software is reasonably feasible, although computationally expensive if distortion is to be reduced down to the quantization noise level when relying on global mathematical models: see Woltring (1977). A better approach might be to employ two-dimensional spline functions covering adjacent image sections.

Another potential source of significant image distortion is intrinsic to the lateral photo-effect upon which the SELSPOT system is based. Any secondary images due to reflections from neighboring surfaces will affect the apparent image coordinates of the LEDs under observation. Since the LEDs may rotate away from the cameras in an unpredictable fashion, it is virtually impossible to model, and thus compensate for, this type of distortion; instead, one must attempt to prevent its occurrence. Narrow-angle LEDs do not necessarily constitute a solution because of these very rotations, and also because (in the stereo case) they would impose a relatively small camera base with consequent loss in depth resolution. A more promising approach is to use non-specular surfaces with minimal reflectance in the near infrared (900–950 nm), perhaps in combination with shields in front of the cameras with apertures limiting the field of view.

To some extent, distortion is of minor importance in gait studies; when not compensated it has the effect of low frequency noise during movement, and has less influence than high frequency noise caused by distance variation and quantization when estimating velocities and accelerations from displacement observations. Similar effects are caused by body-marker shifts during movement, due to the soft structure of the skin and underlying tissues.

Head-on Preprocessors—Such signal processing might also be conducted in dedicated hardware processors, which are becoming available at moderate cost. A typical example would seem to be the AP–400 array processor from Analogic (Mass.), which would also allow synchronized data acquisition from other sources while at the same time reducing the central processing unit load of its controlling host-computer. Also, the simple algorithm for individual LED position reconstruction, presented above, might thus be implemented; however, the use and computability of those coordinates is limited, as indicated.

Software Aspects—Software development in gait studies has too often started from scratch, without proper attention to parent disciplines. Marsolais (1966) initiated major communication with the photogrammetric community in 1966 (see also Marsolais 1969) followed by Lippert's 1973 paper on the feasibility of photogrammetry as a clinical research tool. A good introduction is available in Ghosh (1979). A similar remark may be made on the general reconstruction problems of dynamic movement processes. Formally, some of the kinematic and kinetic models in locomotion studies are equivalent to those occurring in aero- and astronautical navigation, whether concerned with orbiting satellites or rockets, reentry vehicles and ballistic missiles, or military and civilian aircraft. Somewhat philosophically, one might realize that these mathematical tools have been predominantly designed for the annihilation of man, while only later becoming available for his rehabilitation—a phenomenon not uncommon in science and engineering.

Conclusion

At the present state of this project it is believed that SELSPOT constitutes a viable alternative to cinematographic gait studies, once its inherent limitations are acknowledged. In a clinical environment with adult subjects, it would appear that its on-line and real-time features outweigh the disadvantage of its wired body markers, and that its relatively low spatial resolution is offset by its high sampling frequency; the latter may allow sufficient lowpass filtering when estimating velocities and accelerations from displacement observations (Gustafsson and Lanshammar, 1977). However, it remains to be seen whether fast-movement processes such as those investigated in sports will exhibit a similar balance.

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