The Ray Projection Method: A Numerical Approach for Determining Ideal Camera Placement

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ABSTRACT

Data piloting is important to ensure accurate marker coordinate data and to minimize camera drop-out. Camera drop-out results when a camera fails to image a marker; often caused by markers merging or becoming occluded. In this paper, we present the conceptual framework for a numerical method of determining where video cameras, if placed, would have an occluded or a merged view of the tracking markers. Experimental data are presented to demonstrate the efficacy of the method as a tool to complement existing data piloting procedures.

***Keywords**: 3-dimensional, motion, capture, analysis, data piloting*

INTRODUCTION

Three-dimensional video-based motion capture combines information from two or more cameras to resolve the *XYZ* spatial location of a marker in space. The role of the camera is not to determine the *XYZ* coordinates of a marker; it is used to define the direction of the marker. The marker lies along a line (i.e., a ray) extending from its spatial *XYZ* location thru the perspective center of the lens onto a 2-dimensional imaging surface (e.g., CCD array) at a location, *u,v*, in the camera's internal reference. Thus, the correspondence between a marker in space and its projection as imaged by a camera is not unique because a marker anywhere along this line will have the same *u,v* coordinates.

The *XYZ* coordinates of a marker are computed from the intersection of multiple camera rays (Gill et al., 1997; Manal & Buchanan, 2003). In general, the rays do not actually intersect and the marker is assigned *XYZ* coordinates that minimize the least squares distance between the rays. From this description it is easy to visualize how a marker's position is sensitive to the number of rays contributing to its reconstruction, and how rapid changes or jumps in a marker's trajectory are possible. For example, from a camera's perspective, a marker may become occluded as it passes behind another. The camera will fail to detect the marker in the background and therefore it will not contribute to the marker's spatial reconstruction (i.e., camera drop-out). That is, the *XYZ* coordinates for the marker will be resolved using one fewer camera ray. In subsequent images when the marker becomes visible the camera will once again contribute to reconstructed *XYZ* coordinates (i.e., camera drop-in). Thus, as cameras drop-in and –out a marker trajectory may appear to jump from one video frame to the next because a different number of rays will have contributed to the reconstruction of the *XYZ* coordinates.

Minimizing camera drop-out (and –in) is one of the objectives of data piloting. Historically, this has been done by trial and error; modifying the arrangement or placement of markers on the subject and the position of the cameras in the laboratory. While this approach may be functional, it is neither practical nor efficient. In this paper we present a conceptually straight forward technique, the ray projection method, for determining ideal camera placement to minimize cameras dropping-in and –out.

METHODS

The conceptual framework of the ray projection method is outlined in this section rather than detailing specific algorithms or lines of code. Our goal is to describe the method in a general sense so that it may be implemented by others to complement their data piloting efforts.

Conceptual Framework

The motion capture volume within which a movement is recorded is a subspace of a larger laboratory volume. Both volumes are defined by 4 walls, a floor and a ceiling (Figure 1).

Each surface (e.g., wall) is divided into smaller rectangular regions (1 cm x 1 cm) and will be used to identify an element of a two-dimensional array. The reason for sub-dividing a wall in this manner will soon become apparent. The ray projection method is best described by initially considering two markers at a single point in time. The apex of a cone is set at the midpoint between the two markers, opening in the direction of one (e.g., marker 2) and encircling its perimeter exactly (Figure 1). The cone continues outward, intersecting the walls, floor or ceiling of both volumes. A camera placed within this cone will have an occluded or merged view of marker 1 and the camera will not contribute to the marker's reconstruction. For the sake of presentation we only consider cases in which a cone intersects a wall. The intersection of a cone and the wall forms a conical section and array elements corresponding to the rectangles within this section are assigned a value of 1. A cone opening in the opposite direction (i.e., towards marker 1) is also projected and its intersection recorded. This process is repeated for every possible 2-marker pairing and at every point in time forming n * (m! / (m – 2)!) cones, where *n* is the total number of video frames and *m* is the number of markers. A value of 1 is added to an array element each instance the corresponding rectangle is within the intersection of a cone.

The rectangle corresponding to the array element with the largest value is shaded black. The other rectangles are shaded gray proportional to the number of intersections. Regions along the wall associated with array values of zero (i.e., no intersections) are not shaded and therefore they appear white. The end-result is a grayscale mapping of the motion capture and laboratory volumes. The mapping depicts regions in which a camera if placed would have an obstructed or merged view of 1 or more markers. The darker the region, the more often a camera in that region would drop-out due to marker occlusions and merging.

Experimental Validation

The ray projection method was tested using a 3 camera Qualisys motion capture system (Qualisys Medical AB, Gothenburg, Sweden). The data were sampled at 100 Hz and saved in C3D format. Camera contributions for each marker were determined from the camera mask stored in the C3D file.[1] Ground reaction forces were collected with an AMTI force platform (Advanced Mechanical Technology, Inc., Watertown, MA, U.S.) and used to determine stance phase. Reflective markers were placed on the right leg and shoe of a subject as per the modified Helen Hayes marker set.

Two separate experiments were conducted. For experiment 1, the video cameras were placed symmetrically as shown by the dark circles in Figure 2. The subject walked along the X-axis of the laboratory at a self-selected speed. The ray projection method was applied to the data collected in Experiment 1 and a grayscale mapping was generated. Bar graphs were used to display individual camera contributions to the reconstructed *XYZ* coordinates of the heel marker.

[1] The C3D file format. http://c3d.org/HTML/default.htm.

The heel marker was chosen from the available data because it best exemplified the utility of the method.

For experiment 2, camera 3 was moved to a location (i.e., open circle Figure 2) the ray projection method predicted would have minimal camera drop-out. The cameras were recalibrated with camera 3 in the new location and the subject repeated several walking trials at a self-selected speed. The marker trajectories for both experiments were filtered using a bi-directional low pass Butterworth filter with a cut-off frequency of 6 Hz.

RESULTS

The ray projection grayscale mapping for a representative trial from Experiment 1 is shown in Figure 2. Note that camera 3 was located in a darkly shaded region indicating it would experience a significant amount of drop-out. This was confirmed using a bar graph depiction of the camera mask shown at the bottom of Figure 3. Black bands indicate when during stance a camera did not image a marker. Camera 3 failed to image the heel marker for the majority of the stance phase. In contrast, cameras 1 and 2 imaged the heel marker for every video frame during stance. The thick gray line in Figure 3 is the displacement of the heel marker along the Y-axis of the laboratory. There was a 5 millimeter jump in the trajectory at approximately 70% of stance when the number of camera rays contributing to the marker's reconstruction increased from 2 to 3. Another jump occurs when camera 3 drops-out in subsequent frames. Note how simply filtering the data failed to retain the natural curvature of the trajectory.

The likely or true trajectory of the heel marker is best represented by cutting out the portion of the curve between the dashed vertical lines and interpolating over the interval using a cubic spline. Note how the overall shape of the interpolated trajectory is similar to the displacement of the heel marker in Experiment 2 (Figure 4). Camera 3 imaged the heel marker for all but 1 video frame during stance when moved to a location the ray projection method predicted it would have minimal drop-out.

DISCUSSION

The purpose of this paper was to present a numerical approach, the ray projection method for determining where to place video cameras to reduce the frequency of camera drop-out. The ray projection method is best suited for laboratories using 2 or 3 cameras to collect uni-lateral data, or laboratories that track bilateral data using 2 or 3 cameras per side. Our experience suggests that a single camera dropping-out (or –in) will have a minimal effect when a marker's trajectory is reconstructed from 4 or more cameras.

An interesting feature of the ray projection method is that grayscale mappings for different experimental movements can be combined to produce a composite mapping of the laboratory volume. For example, a grayscale mapping for a walking and a stair climbing trial can be combined to identify camera locations that would work well for both tasks. It is important to note that the method only requires the coordinate data for the markers and not explicit information about the camera mask. The camera masks were presented to verify the predicted location in Figure 2 (i.e., open circle) would reduce camera drop-out. Indeed, the mask obtained from the C3D file revealed that camera 3 contributed to the heel marker's trajectory for all but 1 video frame in Experiment 2.

A limitation of the ray projection method is that the grayscale mapping provides a relative indication of maker occlusions and merging. That is, it is not possible to determine from the grayscale mapping exactly how many times a cone intersected a particular region of the wall. Thus, the rectangle corresponding to the largest array value will always be shaded black regardless of the number of times it was within a conical section. Another limitation of the method is that the grayscale mapping represents all intersections of 2 marker pairings and therefore does not convey information about which marker(s) might not be imaged by a camera in a specific location. Consequently, the grayscale mapping alone can not be used to determine how better to arrange the markers on a subject so that they are easier to detect. Future additions to the method could include incorporating environmental obstacles such as stairs or a chair. The physical dimensions of the obstacle can be included in the algorithm so that lines extending from a marker through the vertices of the obstacle would project against a wall forming a shadow in which a camera, if placed, would have an obstructed view of the marker.

It should also be noted that our definition of ideal camera placement is based on the frequency of camera drop-out and does not consider the angle of separation between adjacent cameras. Theoretically, the ideal separation angle between adjacent cameras is 90 degrees, which in practice may be difficult to obtain when using 3 or more cameras to acquire uni-lateral data in a confined laboratory space. A large angle of separation between cameras helps promote a sense of depth within the field of view. For example, the rapid change in the trajectory (Figure 4) occurred along the Y-axis of the laboratory; the direction most closely aligned with depth based on our camera placement. Our experience suggests that precise and accurate coordinate data are possible when the angle of separation between adjacent cameras is 45 degrees or greater. Similar observations have been reported elsewhere (Pedotti & Ferrigno, 1995). This has important implications for how to interpret the grayscale mapping. White or lightly shaded regions that also maximize the distance between adjacent cameras should be given preference as potential camera locations.

Cameras dropping-in and -out can cause notable discontinuities in a marker's trajectory. These jumps or rapid changes can be significant (cf., Figure 3) and may influence the interpretation of the data. For example, Holden and colleagues showed how a 4 millimeter shift in the vertical direction of a marker attached to a 76 millimeter Helen Hayes like wand caused a 3 degree misalignment of the medial-lateral axis of the tibia (Holden et al., 1994). We computed the frontal plane ankle angle (data not shown) and found that the jump in the heel marker caused the foot to move from an inverting angular displacement relative to the tibia back into a brief period of eversion. Although the eversion excursion was only 1 degree, the change in direction might be interpreted as an increase in tibial torsion which is believed to be associated with over-use injury (McClay and Manal, 1997). Pellegrini et al. (2004) recorded tremor during a pointing task using a 3 camera system to track markers on the arms and hand. In such studies, low pass filtering the marker data to remove errors due to camera drop-out is not possible because the tremor itself is of a low frequency. Thus, unless the data are inspected specifically for camera drop-out, reconstruction errors will contaminate the data and will likely go unnoticed.

In conclusion, the ray projection method can be used to identify locations in a laboratory that will minimize the frequency of camera drop-out. The method is not intended to replace data piloting, but rather it was developed to complement existing data piloting practices. Extensive time and effort associated with data piloting can be reduced using the method described in this paper and by minimizing camera drop-out the precision and accuracy of marker coordinate data can be enhanced.

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Figure Captions

Figure 1. Schematic representation of the ray projection method. A cone projects from the mid-point between markers 1 & 2 encircling the perimeter of marker 2 exactly. The circular outlines depict intersections of the cone with the walls of the motion capture and laboratory volumes. A camera located within this cone will have an occluded view of marker 1. Regions of intersection are shaded gray to indicate potentially problematic camera locations.

Figure 2. Grayscale map depicting locations in which a camera if placed would have an occluded or merged view of one or more markers. The darker the shade of gray the more frequently a camera in that location will drop-in and –out. The solid circles denote the camera locations for Experiment 1. Note that camera 3 was in a location where significant camera drop-out was expected. Camera 3 was moved to a new location for Experiment 2 (open circle) where the ray projection method predicted it would have minimal drop-out. The subject walked along the positive X-axis

Figure 3. The bold gray line is the unfiltered heel trajectory for a representative trial from Experiment 1. Note the rapid changes or jumps in the trajectory when camera 3 drops-in and –out. The bar graph at the bottom of the figure indicates camera contributions to the heel marker's trajectory. Gray = camera contributed, Black = camera did not contribute. Camera 3 failed to image the marker for the majority of the stance phase. The thin black line is the filtered marker trajectory. The bold-dashed line is the interpolated trajectory over the interval between the vertical dashed-lines. Note how the shape of the interpolated trajectory is most similar to the trajectory of the heel marker in Figure 4.

Figure 4: The bold gray line is the unfiltered heel trajectory for a representative trial from Experiment 2. The bar graphs at the bottom of the figure indicate camera contributions to the heel marker's trajectory. Gray = camera contributed, Black = camera did not contribute. Camera 3 imaged the heel marker for all but 1 video frame.

Figure 1