Real-time Landmark-Based Unrestrained Animal Tracking System for Motion-Corrected PET/SPECT Imaging

J. S. Goddard, S. S. Gleason, M. J. Paulus, S. Majewski, V. Popov, M. Smith, A. Weisenberger, B. Welch, R. Wojcik

***Abstract*--Oak Ridge National Laboratory (ORNL) and Jefferson Lab and are collaborating to develop a new high-resolution single photon emission tomography (SPECT) instrument to image unrestrained laboratory animals. This technology development will allow functional imaging studies to be performed on the animals without the use of anesthetic agents. This technology development could have eventual clinical applications for performing functional imaging studies on patients that cannot remain still (Parkinson's patients, Alzheimer's patients, small children, etc.) during a PET or SPECT scan. A key component of this new device is the position tracking apparatus. The tracking apparatus is an integral part of the gantry and designed to measure the spatial position of the animal at a rate of 10-15 frames per second with sub-millimeter accuracy. Initial work focuses on brain studies where anesthetic agents or physical restraint can significantly impact physiologic processes.**

I. Introduction

Research into human disease states and pharmaceutical development depend heavily on biomedical investigations involving animal models. Advances in nuclear medicine based small animal imaging technology have enabled researchers to acquire in vivo images of the biodistribution of radio labeled molecules in small animal models. These studies are limited, however, by the use of anesthetic or physical restraint during image acquisition. Both methods of restraint have the potential to alter the neurological and physiological processes that are under study. For this reason, the Department of Energy Oak Ridge National Laboratory (ORNL) and Thomas Jefferson National Accelerator Facility (Jefferson Lab), in collaboration with Royal Prince Alfred Hospital in Sydney, Australia are developing a high-resolution single photon emission computer tomography (SPECT) based system to image unrestrained, un-anesthetized small laboratory animals. The optical-based animal position tracking apparatus is presently under development at ORNL. This tracking system measures the position of externally placed registration marks on the animal to determine the overall pose of the animal's structure under examination to correlate it with the SPECT data. Initially, we are attempting to track the position and pose of the animal's head so that a rigid body registration can be assumed. A gantry system allows for the positioning of a tube in which the mouse will be allowed to rest and/or roam. The system concept is shown below in Figure 1.

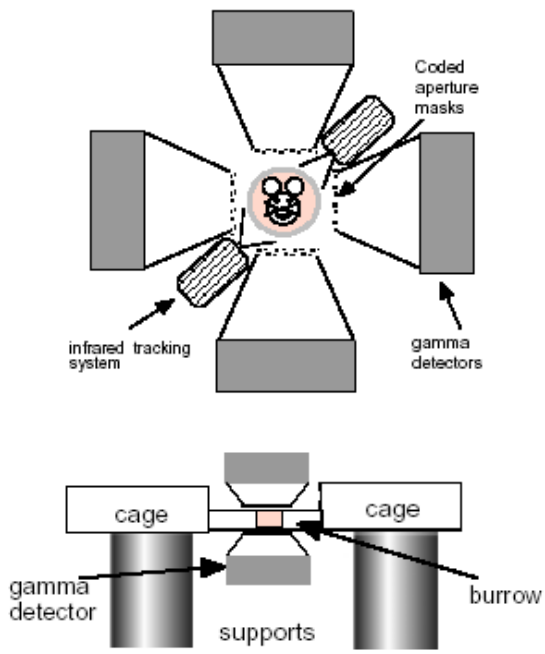

Figure 1 Diagrams illustrating system concept. The top figure is a view looking down the tube which is the "burrow" while the bottom is a side view.

II. Approach

The tracking system measures the animal's head motion through external markers and infrared imaging. Two optical cameras in a stereo configuration are used to measure the 3D point coordinates of the markers located on the animal's head. Infrared (IR) illumination at a wavelength invisible to the

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JSG, SSG, and MJP are with Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA (telephone: 865-574-9034, e-mail: goddardjsjr @ornl.gov).

SM, VP, MS, AW, BW, RW are with Thomas Jefferson National Accelerator Facility, Newport News, VA.

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animal (850 nm) is used to minimize the impact of the measurement on the animal. To facilitate image segmentation, the markers are retro reflective and require that the illumination be directed coaxially along the camera's optical axis. Figure 2 shows the concept where partially reflecting mirrors are used to direct IR illumination towards the tube. The tube itself is under development and a prototype made of a special glass is presently being fabricated. This material has high transmission to IR at this wavelength but is opaque in the visible range to 700 nm. To use this approach for accurate measurement requires that both intrinsic and extrinsic calibration initially be performed for each camera. This is an offline operation not required for 3D measurement during SPECT imaging. Then, the six degree of freedom coordinate transformation between cameras is calculated. During normal operation, a minimum of three marker 3D locations are used to calculate full position and orientation (pose) of the head and to track the pose from frame to frame.

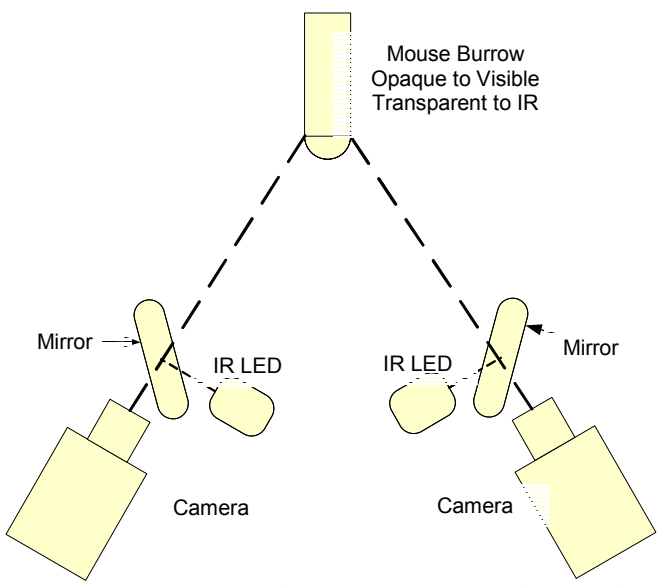

Figure 2 Diagram of tracking system cameras and optics showing arrangement of infrared illumination coaxial with camera optical axis.

A. Calibration

Intrinsic and extrinsic camera calibration is performed offline and is automated through the use of a special planar target shown in Figure 3. Intrinsic camera calibration calculates the internal camera parameters that include effective lens focal length, optical center, and lens distortion. Based on the work of Zhang [1], the intrinsic calibration method used here assumes a pinhole camera model in which the relationship between a 3D point and a 2D image point is given by,

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \mathbf{A}\begin{bmatrix} \mathbf{R} & \mathbf{t} \end{bmatrix}\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}, \tag{1}$$

where s is an arbitrary scale factor, and $\mathbf{R}$, $\mathbf{t}$ are the rotation and translation transformations between the object coordinate system and the camera coordinate system. These are referred to as the extrinsic calibration parameters. Matrix $\mathbf{A}$ is the intrinsic camera matrix and has the form

$$\mathbf{A} = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

where α, β are the effective focal lengths for the image axes, u, v. u_0, v_0 are the optical center coordinates, and γ is a factor representing the skewness between the image axes. By estimating the homography between a 3D point and its corresponding image location, the matrix $\mathbf{A}$ can be calculated given a sufficient number of images. A closed form solution is first calculated using a minimum of three images as an input to a nonlinear minimization that minimizes projected image error over the parameter space including $\mathbf{A}$, $\mathbf{R}$, $\mathbf{t}$, and a distortion model that incorporates radial and tangential distortion coefficients.

The calibration procedure requires the acquisition of multiple images of the planar target in Figure 3 placed in the field of view of both cameras. The corner locations of the pattern are extracted from each image as shown in this figure. Between images, the target is moved both by translation and rotation, although knowledge of the exact motion is not required. By performing the simultaneous calibration of both cameras on the same object, the extrinsic transformation from one camera to another can be calculated at the same time as well. This entire calibration procedure is performed offline and is only required once as long as the cameras are fixed relative to each other and focus or aperture settings remain unchanged.

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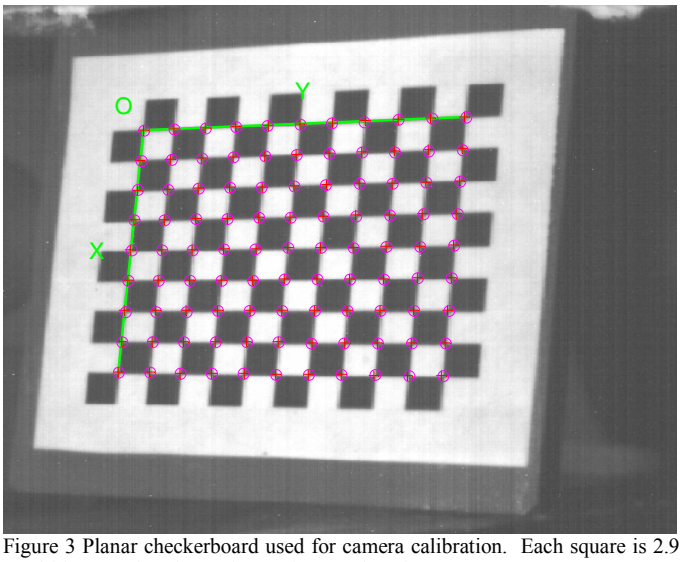

Figure 3 Planar checkerboard used for camera calibration. Each square is 2.9 mm/side. Overlay shows detected corner locations.

The fundamental matrix is also calculated as part of this calibration. The fundamental matrix, a 3 by 3 matrix with seven degrees of freedom, encompasses the epipolar geometry between two cameras as described by Hartley [2] and Faugeras [3]. In particular, the correspondence condition,

$$x'^T F x = 0, \tag{3}$$

where, x' and x are corresponding points from two images and F is the fundamental matrix, provides a means for assigning correspondence between points from two images. The large number of matching points between images that are determined during this calibration procedure is used to calculate the fundamental matrix to high accuracy. In addition, the fundamental matrix calculation is calculated independently from the intrinsic and extrinsic parameters.

B. *Pose Measurement*

From each acquired image of the retro-reflective markers, the marker regions are segmented and the centroid of each is calculated. A minimum of three points is required although more are desirable for redundancy and accuracy. The fundamental matrix and the correspondence condition are used to assign matches between the points in each image by finding the minima in each row and column of an n point match matrix where n is the number of points in each image. For each valid point found, the 3D coordinates relative to the second camera are transformed to the frame of the reference camera so that all coordinates are referenced to the same frame. As given in [2], the image plane coordinates and camera origin define a 3D line for each camera and marker point. These lines when extended to the 3D point location approach each other but are likely to be skew and do not intersect due to noise and measurement error. The midpoint of the line connecting the closest points of approach for these two 3D lines defines the location of the marker point. The result from this measurement is a set of 3D coordinates relative to the reference camera. While one or more points can define a translation between the reference camera and the head reference frame, three or more are needed to define an orientation plane so that the three rotation parameters can be calculated. A 3D model is defined for this head-centered frame and a best fit of 3D points to the model is used to determine the correct point assignment. Horn's method is used to calculate the transformation and resulting error [4]. The complete pose of the mouse frame with respect to the camera is then calculated.

III. Experimental Results

A photograph of the SPECT instrument under development is shown in Figure 4. The tracking cameras, mirrors, and LED arrays are shown in relation to the gamma cameras. Note the tube with markers visible near the center. The accuracy of the tracking system was tested using three IR reflectors on a plastic phantom. At this point we have tested tracking accuracy in three directions: axially (along the axis of system rotation) and transaxially in x and y (horizontal and vertical relative to axis of system rotation). Six target images were used to perform the intrinsic and extrinsic camera calibration. For the axial measurements, the phantom was mounted to x-, y-, and z-translation stages that were moved via micrometers. Measurements of noise have also been made for all six degrees of freedom by repeatedly measuring a stationary target. The results obtained to date are shown in Tables 1 and 2 below. With a desired accuracy of 0.1 mm over 10 mm of motion, both x and y translation measurements are seen to fall within this error range. The z-axis translation error, at 0.17 mm is seen to be just above this range. However, it is expected that better calibration using more than six calibration images will reduce this error. More experiments and more degrees of freedom (e.g. rotations) in the motion measurement are desirable and planned. Initial results have also shown that a processing rate of approximately 10 frames per second have been obtained with a 2 GHz. PC implementation.

Figure 5 shows the gamma point source experimental results for a point source moved in a single plane. For the individual steps in motion shown in Figure 5(a)-(d) and the continuous motion in Figure 5(e)-(f), the motion correction is seen to provide a significant improvement in the resulting image.

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Table 1 Tracking system measurement results for axial components

Direction	Actual Distance	Result from Tracking System
axial (z)	10 mm (micrometer)	9.83 mm
transaxial (x)	10 mm (micrometer)	10.02 mm
transaxial (y)	10 mm (micrometer)	9.94 mm

Table 2 Tracking noise in all directions with stationary object

Direction	Stationary Noise (standard deviation)
axial (z)	0.0013 mm
transaxial (x)	0.0016 mm
transaxial (y)	0.0026 mm
Roll (angle about z)	0.0339 degrees
Pitch (angle about x)	0.0220 degrees
Yaw (angle about y)	0.0281 degrees

IV. Summary and Future Plans

A tracking system for a SPECT instrument presently under development to provide motion correction for unrestrained small animal imaging has been described and initial results presented. High accuracy results that are close to the desired error limits have been obtained thus far and immediate plans are to evaluate all degrees of freedom and improve calibration to reduce errors. Speed of tracking needs to be improved to meet the target frame rate of 15 frames/sec. Future plans include the segmentation of natural features from the animal in real time in order to dispense with artificial markers.

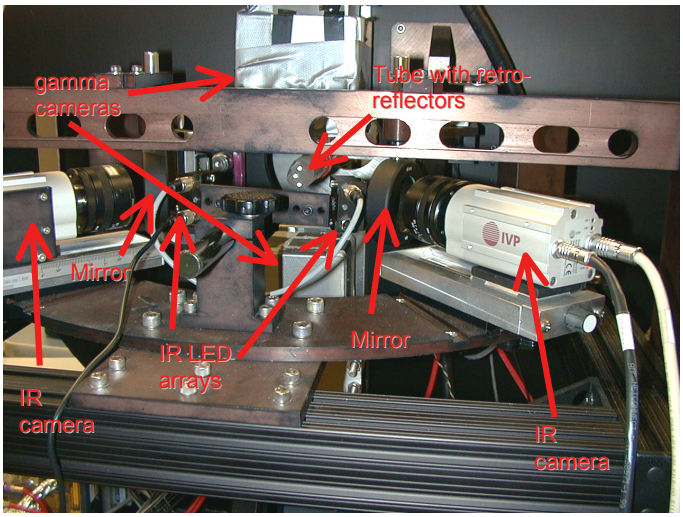

Figure 4 Photograph of gantry with gamma cameras and tracking system components.

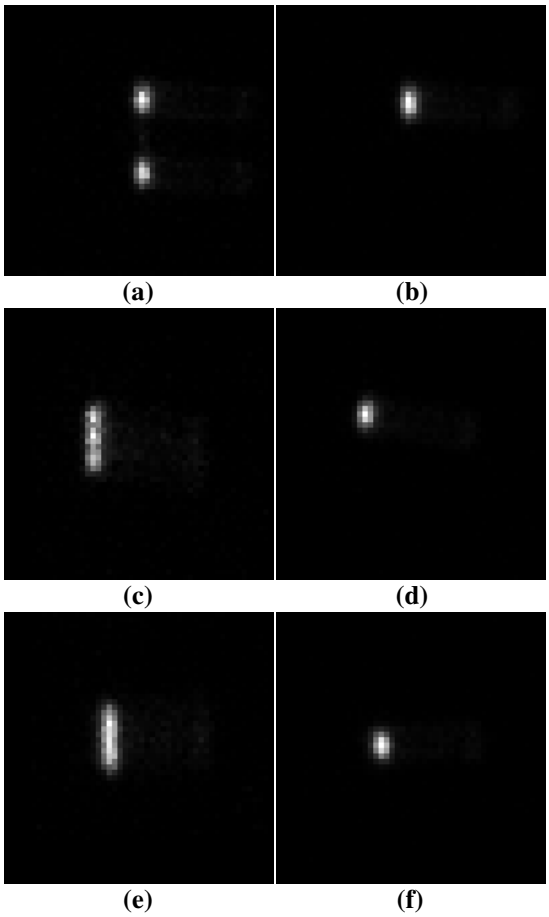

Figure 5 Gamma imaging experiment results with motion, (a) and (b) show a 10 cm. planar movement before and after correction, (c) and (d) show before and after correction of two 5 cm steps, (d) and (e) show continuous back and forth 12 cm motion.

V. References

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