Improved Pose Measurement and Tracking System for Motion Correction of Awake, Unrestrained Small Animal SPECT Imaging

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***Abstract*–An improved optical landmark-based pose measurement and tracking system has been developed to provide 3D animal pose data for a single photon emission computed tomography (SPECT) imaging system for awake, unanesthetized, unrestrained laboratory animals. The six degree of freedom animal position and orientation measurement data are time synchronized with the SPECT list mode data to provide for motion correction after the scan and before reconstruction. The tracking system employs infrared (IR) markers placed on the animal's head along with synchronized, strobed IR LEDs to illuminate the reflectors and freeze motion while minimizing reflections. A new design trinocular stereo image acquisition system using IEEE 1394 CMOS cameras acquires images of the animal with markers contained within a transparent enclosure. The trinocular configuration provides improved accuracy, range of motion, and robustness over the binocular stereo previously used. Enhanced software detects obstructions, automatically segments the markers, rejects reflections, performs marker correspondence, and calculates the 3D pose of the animal's head using image data from three cameras. The new hardware design provides more compact camera positioning with enhanced animal viewing through the 360 degree SPECT scan. This system has been implemented on a commercial gantry and tested using live mice and has been shown to be more reliable with higher accuracy than the previous system. Experimental results showing the improved motion tracking results are given.**

I. Introduction

Oak Ridge National Laboratory (ORNL) and Thomas Jefferson National Accelerator Facility (JLab) have continued development of a new high-resolution SPECT instrument to image awake, unanesthetized, and unrestrained laboratory animals. Previous work has been described here [1]-[4], [6]. This technology allows functional imaging studies to be performed on animals without the use of anesthetic agents and has further clinical applications for human patients who 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 scanner and is designed to measure the spatial position and orientation of the animal at a rate up to 60 frames per second with submillimeter accuracy. Animal brain studies are prime examples where the effects of anesthetic agents or physical restraints on results are of greatest concern.

Primary motivation for imaging awake, unrestrained animals is that anesthesia and physical restraints can induce physiological changes due to stress or chemical influences. These physiological influences in turn can affect the measurement being studied (e.g., brain function). The system described here is designed to minimize stress while allowing the animal to move naturally during imaging.

II. Tracking System Description

The tracking system is mounted integral to the SPECT scanner and employs retro reflective infrared (IR) markers placed on the animal's head along with synchronized, IR ring lights to illuminate the reflectors and freeze motion while minimizing effects of reflections. A new design trinocular stereo image acquisition system using IEEE 1394 CMOS cameras acquires images of the animal with markers. The small animal is contained within a transparent enclosure but is otherwise unrestrained. The trinocular camera configuration provides improved accuracy, range of motion, and robustness over the binocular stereo previously used. Loss of tracking is significantly reduced through the camera redundancy where a measurement can be calculated when the markers are visible to only two of the three cameras. The new hardware design also provides more compact camera positioning with enhanced animal viewing through the 360 degree SPECT scan and has been integrated into a commercial SPECT/CT gantry. Fig. 1 shows the overall system architecture including the mouse tracking PC along with other components of the system previously described [1].

The photographs in Fig. 2 below show the SPECT detector and animal burrow along with the tracking cameras and optics. Three cameras capable of up to 60 frames per second are mounted in a triangular pattern inside the scanner facing the front of the transparent tubular burrow where the animal will

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be imaged. The positions of the cameras are raised above horizontal and angled to look slightly down on top of the head of the animal.

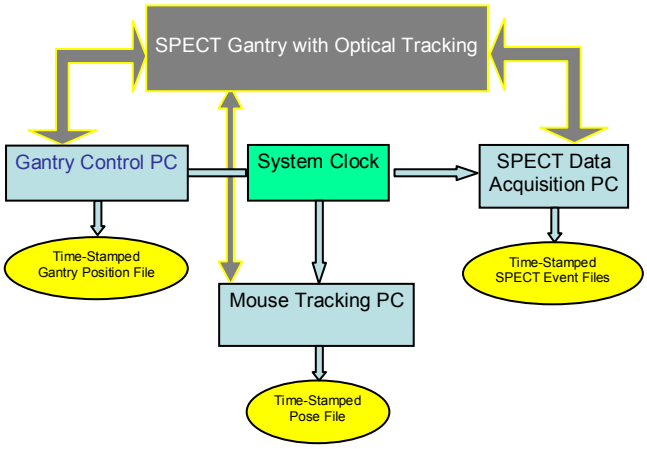

Fig. 1 Overall system architecture of SPECT scanner showing motion tracking PC and time synchronization

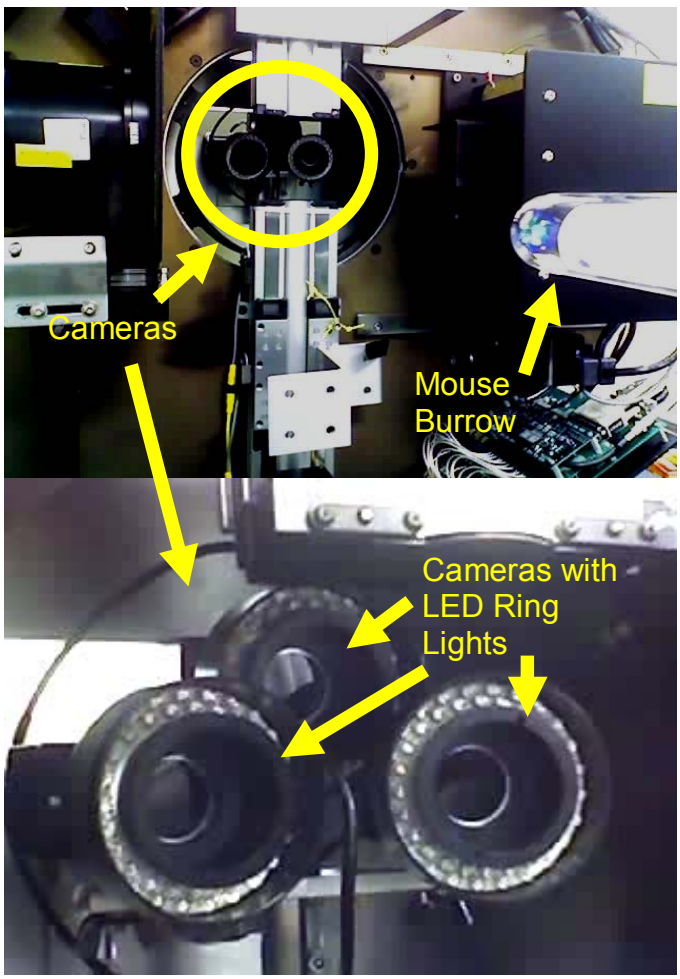

Fig. 2 Optical hardware including cameras and illumination mounted on scanner

An IR LED ring light is mounted on each camera's lens and provides near coaxial illumination of retro reflective markers placed on the animal's head. The markers are spherical with one side flattened for attaching to the body. The LED lights are pulsed to freeze motion and synchronized with the image frame acquisition from the cameras. Pulsing is staggered, however, to remove adjacent ring light reflections. Software running on the tracking PC performs image acquisition, automatic marker segmentation, reflection rejection, marker correspondence, and 3D pose calculation. The motion tracking system is also time synchronized with the detector system so the list mode SPECT detector data can be merged with the tracking data for motion compensation during reconstruction after the scan is complete.

III. Measurement Approach

Significant progress and development have been made since earlier results were described in [2], [4]. The principal improvements have been the use of trinocular stereo cameras and image processing enhancements as compared to binocular stereo used earlier. An offline calibration is performed to determine both intrinsic (focal length, distortion) and extrinsic calibrations for each camera as well as the relative coordinate transformations among the three cameras. During 3D position calculation, an accurate determination of marker image location and marker correspondence is provided for accurate 3D measurement. When available, data from all three cameras are used in the 3D measurement. Accuracy in this case is improved due to least-squares error fitting of the 3D triangulation. Measurement continues, however, as long as markers are visible from any two of the three cameras improving reliability for more extreme mouse head motion. Fig. 3 below is a block diagram of the tracking system showing the individual components in the 3D pose calculation.

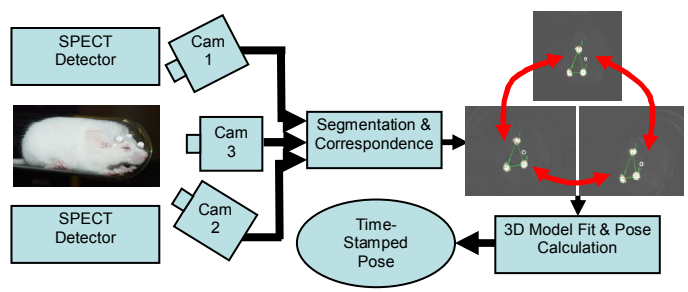

Fig. 3 System block diagram for motion tracking

A. Calibration

An offline calibration procedure is performed on each camera by acquiring multiple simultaneous images of a pattern similar to that given in [4]. The intrinsic camera parameters including lens focal length, optical center, and lens distortion are determined along with the extrinsic 3D transformation of each camera with respect to the reference camera. This optimization is subject to the constraint,

$$\mathbf{T}_{23} = \mathbf{T}_{12}^{-1}\mathbf{T}_{13}\,, \tag{1}$$

where $\mathbf{T}_{xy}$ is the homogeneous transformation matrix from camera x to camera y. This constraint provides consistency since the three cameras are rigidly mounted together.

As described in [2], calibration of the SPECT detector geometries and transformation of the tracking camera to gamma camera reference frame are also performed.

B. Segmentation and Correspondence

Marker segmentation from each camera image is accomplished through an automatic thresholding and seeded region growing method. Geometric criteria including size and shape are further used to filter the thresholded objects. Centroids are calculated on the remaining objects. An example of thresholded images is shown in Fig. 4 where simultaneous images from all three cameras are shown with the markers segmented and highlighted. The illumination reflection from the mouse burrow is also present in each image but is not segmented.

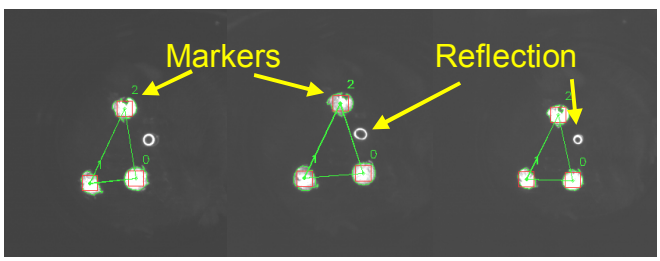

Fig. 4 Images of live mouse from three simultaneous views with thresholded markers

The trifocal tensor is calculated from the camera calibration matrices and is used to determine correspondence among the centroid points from three cameras. The correspondence relationship for the trifocal tensor with three corresponding points $\mathbf{x}^i$ is given by,

$$[\mathbf{x}']_\times \left(\sum_i \mathbf{x}^i \mathbf{T}_i \right) [\mathbf{x}'']_\times = \mathbf{0}_{3\times 3}, \qquad (2)$$

where i refers to the coordinate from the i-th camera view and $\mathbf{T}_i$ is the i-th camera matrix from the trifocal tensor [5], [8]. This relation is used to find corresponding points by applying a threshold to the norm of the resulting matrix and selecting the points that are less than the threshold. Points meeting this criterion are uniquely determined. In many cases, however, matches will not be found for all three points due to obstructions or mouse movement out of the camera view. Measurements can still be made if marker points are present in any two of the three camera views. To aid in correspondence with two cameras, fundamental matrices are calculated from the calibration matrices for each pair of cameras. The correspondence condition used to detect correspondence is given by,

$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0, \qquad (3)$$

where $\mathbf{x}'$ and $\mathbf{x}$ are corresponding points from a pair of camera images and $\mathbf{F}$ is the fundamental matrix of the camera pair [5]. This condition does not uniquely determine the points in contrast to the trifocal tensor condition, since it applies to any point on the epipolar line for each camera. In practice, however, the corresponding point is identified correctly in a high percentage of images.

C. Pose Measurement

A minimum of three marker points is required for full pose measurement. The segmentation and correspondence operation discussed above provides image centroid measurements from either three cameras or from one or more pairs of cameras for each marker point. Using an optimal triangulation method from Hartley [5], the marker centroids from camera pairs are corrected to minimize the geometric error subject to the epipolar constraint as discussed in [2]. For each set of matched point measurements, a least square inhomogeneous method is used to calculate the 3D coordinates with respect to the base reference coordinate frame of the reference camera. These points are matched to an automatically defined model so that both 3D position and orientation may be calculated [7]. The difference in orientation and translation between the current position and initial position defines the head motion.

IV. Results

Initial experimental results have been obtained with the three camera system for baseline noise levels, accuracy, and measurement robustness. The SPECT detectors and optical tracking system have been implemented on a Siemens MicroCT commercial gantry at Johns Hopkins University. Phantom testing and live mouse testing have been performed with SPECT scans ranging from 20 to 30 minutes.

A. Noise

A baseline noise level has been measured on a phantom target with three markers whose spacing and distance from the cameras are similar to those encountered with live mice. The stationary standard deviation noise levels for each of the six pose components are given in Table I below.

Table I
Noise Level For Stationary Target Pose Measurement

Noise Standard Deviation					
X (mm)	**Y** (mm)	**Z** (mm)	**Yaw** (deg)	**Pitch** (deg)	**Roll** (deg)
0.0136	0.0098	0.0085	0.1108	0.0429	0.0411

The noise levels are much lower than the SPECT resolution of 1 mm and the desired accuracy level of 0.1 mm and 0.5 degrees.

B. Accuracy

A phantom with markers was moved vertically through several steps of 10 mm each using the stage on the Siemens scanner. The mean of the measured distance using the optical tracking versus the step distance across 60 mm of total motion is given in Table II.

TABLE II
TRANSLATION MEASUREMENT FOR STEP TRANSLATION MOVEMENT

True Distance	10 mm	10	10	10	10	10
Measured	9.93	9.98	10.05	9.98	9.99	10.04

The maximum error in this simple translation move is 0.07 mm, which is below the desired level of 0.1 mm. While this measurement is indicative of the accuracy values to be expected, additional testing is needed to completely characterize the overall accuracy within the volume envelope where mice will be tracked.

C. Robustness

Loss of tracking measurements over a scan occurs due to obstructions and to the mouse turning its head away from the camera. These missing measurements are typically proportional to the activity level of the mouse. The improvement of three cameras over two can be quantified by comparing the missing measurements for three cameras with all combinations of camera pairs. The graph shown in Fig. 5 for five live mouse tests shows improvement in all cases for three cameras with lower rates of tracking loss. The improvement is highly significant in tests 4 and 5, which correspond to active mice. Successful tracking percentages average greater than 85%.

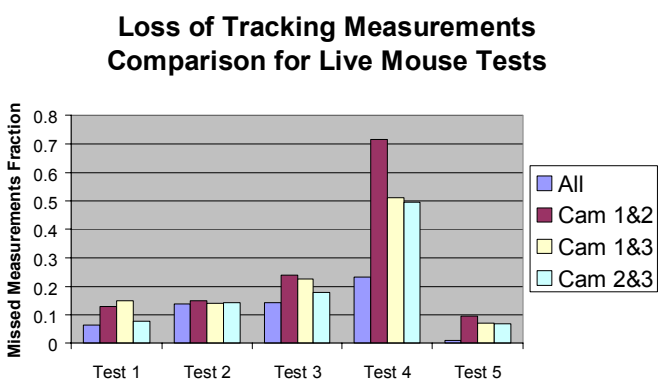

Fig. 5 Comparison of three cameras versus camera pairs for loss of tracking measurements

V. SUMMARY

An improved pose measurement and tracking system has been described for use in unanesthetized awake animal imaging during SPECT scanning. A three camera system along with robust measurement software has been developed and implemented on a commercial scanner for use during live animal testing. The overall functionality of this system over the previous two camera system has been presented. Initial experimental results show that lower noise and higher accuracy can be obtained with the system. The major improvement with the three camera setup has been the reduction in the number of missed measurements during a scan. Results have been presented showing significantly reduced numbers of missed measurements on live mouse tests for the three camera setup in comparison with two cameras. Future work will further categorize the pose tracking accuracy and performance in live mouse testing.

REFERENCES

[1] A. G. Weisenberger, B. Kross, S. Majewski, V. Popov, M. F. Smith, V. H. Tran, B. Welch J. Baba, J. Goddard, M. Pomper, and B. Tsui, “Instrumentation Development of a SPECT-CT System to Image Awake Mice,” Proc. IEEE Medical Imaging Conference, San Diego, November 2006.

[2] S. S. Gleason, J. S. Goddard, M. J. Paulus, J. S. Baba, S. Majewski, M. Smith, T. Tran, A. Weisenberger, B. Welch, R. Wojcik “Real-time, high-accuracy 3D tracking of small animals for motion-corrected SPECT imaging,” Proc. IEEE Nuclear Science Symposium and Medical Imaging Conference, Rome, Italy, October, 2004.

[3] A. G. Weisenberger, B. Kross, S. Majewski, V. Popov, M. F. Smith, B. Welch R. Wojcik, S. Gleason, J. Goddard, M. Paulus, and S. R. Meikle, “Development and Testing of a Restraint Free Small Animal SPECT Imaging System with Infrared Based Motion Tracking,” Proc. IEEE Medical Imaging Conference, Portland, November 2003.

[4] J. S. Goddard, S. S. Gleason, M. J. Paulus, S. Majewski, V. Popov, M. Smith, A. Weisenberger, B. Welch, R. Wojcik, “Pose measurement and tracking system for motion-correction of unrestrained small animal PET/SPECT imaging,” Proc. IEEE Medical Imaging Conference, Portland, November 2003.

[5] R. Hartley and A. Zisserman, *Multiple View Geometry in Computer Vision*, Cambridge: Cambridge University Press, 2000.

[6] A. G. Weisenberger, J. S. Baba, B. Kross, S. Gleason, J. S. Goddard, S. Majewski, S. R. Meikle, M. Paulus, M. Pomper, V. Popov, M. F. Smith, B. Welch, and R. Wojcik,, "Dual Low Profile Detector Heads for a Restraint Free Small Animal SPECT Imaging System,” Proc. IEEE Nuclear Science Symposium and Medical Imaging Conference, Rome, Italy, October 2004.

[7] B. Horn, "Closed-form solution of absolute orientation using unit quaternions," Journal of the Optical Society of America, 4, pp. 629-642, April 1987.

[8] O. Faugeras and Q-T. Luong, *The Geometry of Multiple Images*, Cambridge: The MIT Press, 2001.