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Fabrication of the pinhole aperture for AdaptiSPECT

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Abstract

AdaptiSPECT is a pre-clinical pinhole SPECT imaging system under final construction at the Center for Gamma-Ray Imaging. The system is designed to be able to autonomously change its imaging configuration. The system comprises 16 detectors mounted on translational stages to move radially away and towards the center of the field-of-view. The system also possesses an adaptive pinhole aperture with multiple collimator diameters and pinhole sizes, as well as the possibility to switch between multiplexed and non-multiplexed imaging configurations. In this paper, we describe the fabrication of the AdaptiSPECT pinhole aperture and its controllers.

Keywords

SPECT; adaptive imaging; small-animal imaging

1. INTRODUCTION

Conventional pinhole SPECT imaging systems have a fixed geometry and a resulting magnification, sensitivity, and field-of-view. They may therefore be well suited for one particular task, but are limited in their application to tasks with different geometry requirements. AdaptiSPECT, on the other hand, is a pinhole-SPECT system designed to be able to change its configuration autonomously in response to the data it is acquiring. The flexible geometry allows the magnification, sensitivity, and field of view to be varied during the imaging study.

In practice, adjusting the imaging properties means varying the detector-to-pinhole distance, the pinhole-to-object distance, the pinhole size, and the region of the object in the center of the field of view. Our new pre-clinical system, AdaptiSPECT, incorporates these features in a design based on an existing stationary system developed at the Center for Gamma-Ray Imaging: FastSPECT II.¹ The current system has 16 detectors arranged into 2 rings of 8 detectors, and a pinhole aperture with one pinhole per detector. Whereas FastSPECT II has a fixed aperture and detectors, the detectors in AdaptiSPECT are mounted on translational stages and can move radially relative to the pinhole aperture. The AdaptiSPECT aperture design includes three collimators of different diameters containing pinholes of varying diameters. The three collimators are mounted on the same axis, and selecting the appropriate ring of pinholes is accomplished by linear translation of the entire aperture to place the

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appropriate ring-of-pinholes in front of the detectors.² The dimension of the adaptive pinhole aperture are summarized in table 1, and the imaging properties of various system configurations are summarized in table 2. A rendering of the system and the aperture is shown in figure 1.

The adaptive aperture is supported on both ends in order to drive and guide the motion without obstructing the pinholes. On one end, it is connected to a linear stage that drives the translation motion that enables the selection of the ring of pinholes. On the other end, the aperture is supported by two ball bearings that translate on precision ground rails. One rail is flat and the other rail has a v-groove in it to achieve a kinematic support. A rendering of the motion components is shown in figure 2.

2. FABRICATION OF THE APERTURE

The aperture for AdaptiSPECT imposes challenging manufacturing requirements. In addition to the precise placement of the pinholes, the body of the aperture needs to be able to support its own weight while still allowing linear movement. We first designed the aperture to be cast in a tungsten-epoxy composite with pinhole inserts cast in platinum. We used this method successfully in a previous system,³ and have described this manufacturing method in detail.⁴ This technique, however, proved to be unsatisfactory when dealing with a large and moving aperture as the large molds created to cast the aperture deformed during the casting process. This led to imprecise pinhole placement, as well as surface imperfections. We have proposed a new manufacturing technique⁵ utilizing conventionally machined parts, but incorporating tungsten inserts created using additive manufacturing. We implemented this technique in 3 steps: first we manufactured the high-magnification part of the collimator. Because there is only one pinhole per detector, this is the smallest and easiest part to manufacture. Next, we are currently manufacturing one of the eight mid-magnification and low-magnification parts of the collimator to verify our pinhole designs. Finally, once the design and production have been validated, we will manufacture the rest of the aperture. This three-step approach enables us to limit our risks when manufacturing the aperture (i.e. if a design revision is required during stage 1 or 2, the cost is not as high as re-manufacturing the whole aperture).

Similarly, we first designed the shutters that enable the switch between the one- and five-pinhole-per-camera configurations on the mid- and low-magnification parts of the aperture to be manufactured using a 3D-printing approach. However, this soon proved to be impractical because the 3D-printed parts had an unacceptably high friction coefficient. We therefore re-designed the parts and manufactured them using low-friction materials.

2.1 Aperture

In the new manufacturing technique, the body of the aperture is machined using a tungsten alloy while the pinholes are 3D-printed in tungsten. Since it would be very expensive to machine the aperture from a single block, we designed it as an ensemble of plates that are bolted together in a barrel-like fashion around a cylindric core. By using circular end plates of different diameters, it is very easy to switch from one diameter of aperture to another. Furthermore, by designing parts of the aperture as an ensemble of plates, machining

becomes simple and efficient. In fact, most of the aperture plates can be manufactured in a single pass on a CNC, reducing the time and cost of fabrication. The design of the plates is also simplified: we only need to design two plates per aperture section, one for the cameras in the front ring, and one for the cameras in the back ring. Finally, by having a barrel-like structure with overlapping tungsten plates, we ensure that there are no seams with direct lines of sight in the aperture, and therefore reduce the risk of gamma-ray leakage.

Figure 3 shows the plate manufactured for the high-magnification part of the collimator along with the pinholes. The pinholes were manufactured by 3D Systems LayerWise⁶ using additive manufacturing technique. The plates were machined on a CNC using a machinable tungsten alloy with 90% tungsten. The screws used to bolt the plates on the cylindric holder were also machined in a tungsten alloy. In figure 4 we show the assembly of the high-magnification part of the collimator. The barrel-like arrangement of the machined plates is clearly visible. Also visible is the circular disk on which the mid-magnification part of the aperture will be bolted once completed.

In the new manufacturing technique described here, there are two main risks for leakage: first there is a chance of leakage where the plates are joined together, and second, there is a chance of leakage where the pinholes are inserted. We conducted two leakage tests on the aperture. In the first test, we joined together three adjacent plates and placed a pinhole in the central one. We acquired a planar x-ray image of this assembly and compared the attenuation from a part with no pinhole and a part with a pinhole. No leakage was detected at the place where the plates are joined. In the second test, we used the completed high-magnification part of the aperture with its pinholes inserted and placed a ^{99m}Tc point source at the center of the collimator. We then recorded counts coming out of a pinhole using one of our detectors. No leakage was found from the places where the plates join nor from the places where the pinholes are inserted. The results of these leakage tests are shown in figure 5.

These leakage tests along with mechanical tests to verify the rigidity of the collimator proved that this new manufacturing technique is suitable for the adaptive aperture. We are currently in the second stage of our manufacturing process and will soon perform similar leakage tests on the mid- and low-magnification sections.

2.2 Shutters

The shutters enable autonomous switching between single- and multiple-pinhole configurations. Each shutter consists of a fixed base mounted to the aperture and a rotating ring on which tungsten blocks are attached. The blocks cover the 4 peripheral pinholes when the shutter is closed. The shutter is opened by a miniature pneumatic air piston and has a spring-loaded return.

To manufacture the shutters, we selected a polymer used in plastic bearings, called Igus[®] J.⁷ This material is easy to machine, robust, and has a very low coefficient of friction when used in contact with anodized aluminum. We therefore manufactured the fixed part of the shutter in aluminum and the rotating part using the Igus[®] J material. This combination allows the rotating ring of the shutter to act as its own bearing. The tungsten blocks were

again manufactured by 3D Systems Layerwise using 3D-printing. This enables us to use a complex design for the blocks, with large radii on the edges and a step in the height, so that the manufacturing of the shutter ring can be easily accomplished on the CNC. Figure 6 shows pictures of the mid-magnification shutters in both the opened and closed states.

We are currently performing durability tests on the shutters to assess the number of times the shutter can be actuated before parts need to be replaced (e.g. the spring). Also, tests will be performed to demonstrate that no leakage is observed from the mid- and low-magnification parts of the aperture when the shutter mechanism is closed.

3. INTEGRATION AND ALIGNMENT OF THE APERTURE

The axis of translation for the aperture is defined by a linear stage, as well as the v-groove in which one of the ball bearings supporting the aperture translates. For stress-free operation of the system, it is important that the v-groove and the aperture stage axis are aligned properly. Furthermore, the axis on which the aperture translates needs to coincide with the central axis of the system so that the pinholes will be placed symmetrically in front of the detectors. The alignment process of AdaptiSPECT and its aperture comprises 3 stages: first a central axis is determined by alignment of the detectors, second, the aperture stage is aligned on this central axis, and finally, the aperture v-groove is parallel to this same axis.

3.1 Alignment of the system detectors

The detector mounts themselves define the central axis of the system. Since the detectors in AdaptiSPECT are arranged into two rings of eight, there are two detector planes. By defining a center point on each plane, we establish an axis. To do this, we 3D-print a reference template that we affix to the detector mounts. The detector mounts are then aligned two at a time using a cross-hair laser, as shown in figure 7. Once the 16 detector mounts are aligned, we can affix another 3D-printed reference on the mounts to mark a pinhole in each detector plane. Thus, we have created two pinholes in two different planes, and therefore defined the axis.

3.2 Alignment of the aperture

We align a laser with the pinholes described in the previous section to mark the central axis of the system. Our next step is to align the aperture translation stage. To do this, we have permanently attached a mirror inside the aperture holder. We mount the holder on the translation stage and align the stage by autocollimation using this mirror. Once the aperture is complete, we bolt it to the holder, and align the v-groove, using autocollimation again. Stress from any residual misalignment is relieved in a spring tensioned connector.

4. APERTURE CONTROLLERS

AdaptiSPECT is designed to autonomously change its imaging configuration: the control software can be loaded with an adaptation rule that sends various commands to the system such as “switch to mid-magnification”, “open shutter #12”, or “close shutter #5”. To ensure the timely execution of these commands, we have designed a set of controllers to execute the commands from the software in the hardware. In addition to transmitting commands, we

also designed some of these controllers to provide feedback related to aperture position and camera positions to the software.

4.1 Aperture positioning controllers

In addition to the mechanical controllers for the stage motor, we have designed a custom circuit board using a position sensitive detector manufactured by Hamamatsu⁸. The circuit board is shown in figure 8 with the 12 mm×1 mm detector shown in a yellow box. The detector has two photodiodes connected to a common cathode (see schematic in Figure 9). The detector outputs two currents, I_1 and I_2 . When a light-emitting source is aligned with the center of the detector, the two currents are equal. Thus, alignment is accomplished by finding where $I_2 - I_1 = 0$. To provide a uniform illumination pattern, we coupled 910 nm LEDs with condenser lenses and 1-mm diameter pinholes at multiple locations. This ensures that all possible positions for the aperture have the same spot size, and provide the same sensor response.

To position the aperture properly, we mount LEDs on the side of the aperture motion stage that are at a fixed position relative to the aperture. The custom printed circuit board with the position sensor is mounted on the aperture holder and moves with the aperture during the translation. Since there are only 3 primary positions for the aperture corresponding to the three pinhole rings, we need to place LEDs at only 3 locations. For each, we used two LEDs: one is used to mark the position of the aperture and the other one is placed a few millimeters ahead of the first to signal to the control computer that the aperture is approaching the correct position, and that a deceleration should start. This positioning scheme is summarized in Figure 10.

Adding this controller to the existing mechanical controller of the linear stage enables two capabilities: first, it improves the reproducibility of the positioning of the aperture. The linear motor has a cited accuracy of $5\mu\text{m}$, whereas the position device has a theoretical positioning accuracy of $0.2\mu\text{m}$. This repeatability is crucial for the correct operation of the system, because the aperture positioning configuration with which a dataset is acquired needs to be known relative to the configurations used to calibrate the system. Second, the stage controller only gives a relative position. The independent LEDs provide the system with the ability of homing to a known configuration after a power outage, without user intervention.

4.2 Shutter controllers

The shutters are opened and closed using miniature compressed air pistons that are controlled by electronic valves. We have designed a custom printed circuit board to control the actuation of the shutters. For each electronic valve, we use an FET switch triggered by a signal generated by a National Instruments DAQ USB 6009. Each custom electronic board monitors the opening and closing of 8 shutters independently from each other. In addition to the transistor switch, each circuit has logic that shows the open/closed status of each shutter. All four controllers for the shutters are mounted on the AdaptiSPECT gantry directly below the aperture drive stage. This minimizes the amount of air tubing necessary to connect the compressed air source with each shutter. This also places all of the controllers and air tubing

away from the entrance of the imaging system where the operator will be handling animals and related equipment (anesthesia, heart rate monitor, etc.). Figure 11 shows a single shutter and the associated control components (a) unmounted and (b) mounted in final position on the gantry.

5. CONCLUSION

In this paper, we have described the on-going fabrication of the pinhole aperture for AdaptiSPECT. We have identified a suitable manufacturing technique for the complex aperture using interlocking plates machined in a tungsten alloy on a CNC and arranged in a barrel-like fashion. Pinholes are produced using additive manufacturing and inserted in the plates. We have also validated a machining technique for the shutters for the system, using anodized aluminum, a polymer carrier that forms its own bearing, and 3D-printed tungsten blocks. Finally, we have produced and validated the controllers necessary to drive the adaptive features of the aperture.

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(a) Rendering of the complete system

(b) Rendering of the aperture

Figure 1.
Rendering of the system and of the aperture

Figure 2.

(a) Rendering of the aperture on the low-magnification end. The two ball-bearings supporting the aperture along with the two rails are visible. One rail is flat, and the other rail has a v-groove to guide the translation of the aperture. (b) Rendering of the aperture on the high-magnification end of the aperture. The holder connecting the aperture to the translation stage, as well as the stage are visible.

Figure 3.

(a) Pinholes manufactured for the high-magnification part of the aperture are shown. The pinholes are manufactured by 3d Systems Layerwise, using an additive manufacturing technique. The pinholes then inserts in the plates shown in (b). The plates are machined using a machinable tungsten alloy, along with screws that will be used to bolt the plates together on cylindrical holders.

Figure 4.

(a) Photo of the assembled collimator. The plates are bolted together using tungsten screws and the pinholes are inserted and glued on them. At the right end of the collimator, the screw holes to bolt the mid-magnification part of the collimator are visible. (b) Front view of the collimator showing the barrel-like arrangement of the plates to prevent leakage.

Figure 5.

(a) Results of the leakage test performed using an x-ray source. Leakage is measured by joining three adjacent plates and placing a pinhole in the central plate. A planar x-ray projection is taken and the intensity along a line passing through the pinhole is compared to a line through all the material. No leakage was observed at the place where the plates are joined nor at the place where the pinhole is inserted. (b) Result of the test performed using a ^{99m}Tc point source showing no leakage.

Figure 6.

Shutters manufactured for the mid-magnification ring segment. The base (black) is in aluminum and has been hard anodized. The circular plate (yellow) is manufactured using the Iigus[®] J material. The 4 tungsten blocks are manufactured using additive manufacturing and glued on the circular plate. In (a) the piston is not actuated and the four peripheral pinholes are covered by tungsten blocks yielding single-pinhole projections. In (b) the actuated piston rotates the circular plate and opens the peripheral pinholes yielding a five pinhole-per-camera configuration. The spring is extended and will bring the circular plate back in place once the piston retracts.

Figure 7.

Alignment of the system detectors: we use a cross-hair laser source to project two lines at 90 degree angles on the system. We first align the detector mounts that are vertical and horizontal using a 3D-printed reference mounted on the detector mounts. Once the 4 detectors are aligned, we rotate the laser source 45 degrees and align the next 4 detectors. We use the same alignment method on the detectors situated on the other side of the gantry.

Figure 8.

Custom printed circuit board for controlling the aperture positioning. The sensor is a position sensitive detector, manufactured by Hamamatsu (S3932).

Figure 9.

Functional schematic of the Hamamatsu position sensitive detector S3932. The sensor is made of two photodiodes connected to a common cathode. When the light source (in this case an LED) is positioned above the center of the sensor as shown in (a), the two currents coming from the photodiodes are equal. (b) When the light source is not positioned above the center of the sensor, the two currents are different. Alignment of the positioning LED and the detector is accomplished by simply measuring the difference between I_1 and I_2 .

Figure 10.

Three groups of LEDs and their corresponding optical elements are used to position the aperture. This figure shows the sensor positioning scheme: the LEDs are placed along the aperture stage and remain fixed. The printed circuit board with its sensor is mounted on the aperture holder and moves with the aperture, translating in front of the positioning

Figure 11.

(a) Mid-magnification shutter and control elements including the custom electronics, pneumatic valves, and National Instruments DAQ system. (b) All the shutter controllers mounted on the gantry. 4 boards control the 32 shutters of the aperture. The boards and valves are mounted directly under the stage driving the selection of the adaptive aperture configuration.

Table 1

Aperture dimensions. The pinhole aperture consists of three ring-segments: low-magnification, mid-magnification and high-magnification.

	Low-M	Mid-M	High-M
pinhole distance (mm)	76.2	50.8	26.1
pinhole diameter (mm)	1.5	1	0.6
total length (mm)	140	315	140

System Properties of AdaptiSPECT. Since the detector distance to the central axis is also variable, from 165.1 mm to 317.5 mm, each pinhole-ring has a range of magnifications, resolutions, and fields of view.

Table 2

Imager Configuration	Low-Mag		Mid-Mag		High-Mag	
detector distance (mm)	165.1	317.5	165.1	317.5	165.1	317.5
magnification	1.2	3.2	1.7	4.2	5.3	11.1
resolution (mm)	3.48	1.95	2.40	1.60	0.8	0.7
transaxial FOV (mm)	90	37.5	48	24	20	10.5