High resolution photography of Alcator C-Mod to develop compelling composite photos

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High resolution photography of Alcator C-Mod to develop compelling composite photos and virtual tours

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Abstract

A large set of photos of the interior of Alcator C-Mod were obtained at the end of the 2013 maintenance period. The purpose of the photos was to create realistic high resolution representations of the interior of Alcator C-Mod for display online and in print for distribution for public relation, outreach and engineering documentation. A novel camera mounting and movement system was developed to allow automated photography and a stable platform for long exposures. A high end fisheye lens was rented and photography settings were developed to optimize the end product. 1600+ photos were taken over three days and post processed thereafter. The photos were bracketed to allow for high dynamic range which was tone mapped for presentation. The photos were stitched together into a 92Megapixel image of 93% of the C-Mod outer C-Mod using open source software. Photos were stitched together to form nine 360deg x180deg projections at nine of the ten ports. These can then be used to drive virtual tours on a platform to be determined later. Composed single photos were also taken. The photo repository was used to derive movies and a 3D point cloud of the vessel. Ideas for future efforts are discussed.

General setup

The photos were taken just prior to the vacuum vessel being pumped down immediately before the LEDs (which are only used during maintenance periods) were removed. This was done over the evenings of September 16th, the day and evening of September 17th and the morning of September 18th. One of the ten large flanges (Gport) remained off to enable access, thus it is missing from the photographs. All the covers on delicate instrumentation were removed to enable photography of the system as close to operational as possible.

A Nikon D80 DSLR (10.2MP) with a Nikkor 10.5mm fisheye lens was used. This lens has a very large 180deg diagonal field of view enabling large portions of the vessel to be seen in a single photo, though with large distortion that was later removed. This very fast lens (f/2.8) was stopped down (f/4.5) to increase depth of field since features on the wall were ~20 – 150cm from the camera. We used low gain (ISO-100) to reduce graininess at the expense of long exposures which was tolerable since the camera and
scene was stationary. The lens was manually focused to best balance the focus of the various features and
the camera was controlled remotely to enable automated operation and a stable platform for bracketing.

Due to the weak lighting inside the tokamak and the many reflections from the metal components high
dynamic range (HDR) and mild tone-mapping were necessary to create an appealing photo for the web
and print. At each position a bracket of three photos were taken at three different shutter speeds (0.5s,
2.0s, 8.0s; -2EV, 0EV, +2EV;). These photos were then cross-registered and merged into a 32-bit depth
HDR TIFF and then tone mapped using Photomatrix Pro HDR software as shown in Figure 1.

![Figure 1: Tone mapping process to account for reflections and dark recesses.](image)

Note how the bright reflections are not blown out and the dark recesses of the port can be seen in the
tone-mapped result. All photos sets were tone mapped with the exact same settings as a batch in order to
enable stitching.

A camera positioning system was developed consisting of a flexible rail and a car that rides along it. The
rail was wrapped around the inside column of the tokamak like a band clamp. The flexibility and
lightness of the rail enabled it to be installed and repositioned with only one person invessel, an important
consideration due to the reduced vessel access. The car rolls around the tokamak center column carrying
various tripod heads which can hold camera in different orientations. An engineering diagram and photo
of the system is shown in Figure 2.
The car and camera are pulled around the tokamak pulled with fishing using a stepper-motor actuated reel, thus allowing the camera to be moved precisely. The camera is also remotely controllable, triggered via the same computer which controls its location. A MATLAB program synchronizes the movement and camera triggering. This allows a very large set of photos to be taken of the vessel automatically and precisely with minimal oversight.

**Composite photo of the outer wall**

To photograph the outerwall as if it was “unrolled” and laid flat the camera must observe it straight on. To do this the camera was mounted so it was looking straight out from the center column and with the camera placed as close to the center column as possible to enable the outer wall from top to bottom to be photographed in a single wide angle photo.

Since there are many items on the outer wall at different depths and the camera cannot be placed in the center of the torus due to the center column, parallax and perspective create problems as the camera moves. Therefore a very large number of photos are needed so only the center portion of each photo, where the camera is observing the wall most radially, is used in the final composite photo. To accomplish this, the camera was moved in very small increments; 1 inch along the track, ~3deg around the torus, taking the set of 3 bracketed photos at each stop. 92 sets of 3 photos were taken automatically over the course of ~1hr. A schematic of the process showing the field of view is shown in Figure 3.
Figure 3: The camera is moved around the torus capturing the outer wall (left). The wide field of view captures the outer wall and shelf (right).

Each set of three bracketed photos was merged into an HDR image and then tonemapped. The photos were stitched together using the open source stitching software Hugin which identifies features in each photo that occur in neighboring photos and then rotates, stretches and morphs the photos to align them to each other. In order to create a good stitch, the photos were first cropped down into slices showing only the region in the center of the photo where the outer wall is viewed nearly radially. The software was instructed to only use the center portion of each cropped photo.

Figure 4: Photos were cropped into overlapping vertical slices (top) to create a seamless radial view (bottom).
The aligned photos were made horizontal using the row of bolts near the bottom of the photos. The stitching paths were modified so stitched did not disrupt geometric patterns such as the antenna screens and the lower hybrid grill because these would be very evident to the eye. It was also important to route stitching so it did not cut through diagnostics on the walls will be pointed out in future outreach uses of the photo. Generally the stitching was difficult because the items on the wall range in distance from the camera from 0.4m to nearly 2m and the lens distorts the top and bottom of the wall. The most difficult items were ones that have long paths radially and are thus subject to parallax errors, the tubes low in Fport and Hport are good examples. The seams were then blended along the stitching paths. The process is shown Figure 4. There are 91 vertical seams in the final photo, the worst one is at Jport where the tiles do not align, this was due to an operation error where several photos were missed, and thus the stitch had to use wider slices.

The end result is a stitched photo that is 24050 x 3845 pixels (92.5 Megapixels) covering approximately 93% of the outer wall, omitting Gport which was used for access. This yields an approximate resolution of 100dpi for features at the wall. The height of the photo encompasses both vertical surfaces and horizontal surfaces, thus tall items are distorted, as are items which extend radially. The view and dimensions are shown in Figure 5. Note the color changes from left to right due to the different LEDs used.

![Figure 5: The composite stitched photo covers 93% of the width of the wall, and the entire height and top and bottom shelves.](image)

**Projection photos for a virtual tour**

In order to form the views used for the virtual tour a special set of photos must be created which capture the sphere around the camera is if it was viewed from a single point. This differs from the previous long outer wall stitch photo because the camera should not move in space, only in angle.

To accomplish this, the camera was mounted on a gimbaled tripod head which rotates the camera about its entrance pupil (or zero parallax point) in two directions. In this fashion, as the camera rotates the relationship between objects at different distances stays constant because there is no parallax. The gimbaled tripod head was attached to the car on the track, placing the camera near the center of the plasma and allowing it to be pointed in arbitrary directions as shown in Figure 6.
Figure 6: A gimbal tripod head is attached to car to allow the camera to point in arbitrary directions about its no-parallax point.

The car was then moved to the center of each port and locked into place. 10 sets of 3 bracketed photos were taken, 8 viewing horizontally around 180deg, 1 upwards and one downwards thus encompassing the entire sphere around the camera. The camera was pivoted by one person operating the tripod head invessel while another person operated the camera remotely. These sets of three were then merged into HDR and tone mapped. The ten photos were then stitched onto the surface of a sphere using Hugin and the result was then projected onto a flat using a equirectangular projection at high resolution. The process is shown in Figure 7.
The process was repeated at each of the 9 ports, totaling 270 photos merged into nine tone mapped equirectangular projections.

The resulting equirectangular photos covers 360deg horizontally and 180deg vertically at each port, thus it shows the entire sphere around the camera. This format is a standardized format for interactive virtual reality viewers which take the image and reproject it back onto the surface of a sphere which can be navigated by the user by tilting, and panning the camera. Note that each of the nine photos contains the camera mount car and tripod head which appears to end in space due to how the stitching was done.

Commercial virtual tour software is then used to display the photos and links are added in the virtual sphere to navigate between the photos as if somebody was navigating through the space.

**Other products of the photos:**

The automated rail and car system allows for a variety of photos to be taken easily since it is automated. In addition to the view looking at the outer wall radially, sets of photos were taken observing the wall at
other angles. Thus an outer wall photo could be constructed but instead of looking radially, it would show everything in profile. Examples are shown in Figure 8.

![Viewed radially](image1)  ![Panned 45deg from radial](image2)  ![Panned 90deg from radial](image3)

Figure 8: In addition to radial views of the wall, it was also photographed in profile and downward (not shown).

Also, the rail was used to photograph the divertor looking straight downward.

The spacing between the photos was larger (30 for the panned and downward vs 92 for the radial) which would make the stitching more complex but likely still doable.

In all there are 278 high quality tone-mapped photos of the vessel available with many different angles. These have been used as frames to make movies as well as composite photos.

With so many photos available it is conceivable to use open source 3D mapping software to construct a 3D model of the vessel and project the photos back onto it. This was attempted using the tutorial located at: [http://wedidstuff.heavyimage.com/index.php/2013/07/12/open-source-photogrammetry-workflow/](http://wedidstuff.heavyimage.com/index.php/2013/07/12/open-source-photogrammetry-workflow/)

A few screenshots of the process using the 92 radial photos are shown in Figure 9:
Photos used to create sparse point cloud  Dense point cloud reconstructed, used to create mesh

Figure 9: Photos were used to create a 3D point cloud of the vessel wall.

If this is to be successful the photos need to have the fisheye projection mapped to rectilinear prior to analysis and to use the entire set of 278 photos. Note the above point cloud is inverted (ie. cameras solved looking inward at wall instead of outward at wall.

Another thing that can be accomplished with the existing photoset is a Photosynth which maps the photos together and allows you to navigate them online. I attempted one which can be found here: http://photosynth.net/view.aspx?cid=6b948a0c-8942-4ed8-9569-9abd54332565

Improvements for next time

If more photos were to be taken, here is what I’d do:

- Do more gimbaled shots in the cell, power room and control room to expand virtual tour outside of vessel.
- Rent a higher quality full frame camera. This would increase the resolution per photo. The D80 is fairly antiquated.
- Modify the rail to allow the car to travel around 360deg, currently limited to ~330deg due to gap in rail where clamp is.
- Use a rectilinear lens and take more photos at different heights for the outerwall stitch which would allow higher resolution. Also consider focus stacking to capture details at different distances.
- Consider temporarily installing Gport (maybe just position it) to show the entire vessel.
- On the gimbaled shots, take an 11th one with the tripod head rotated to mask the black arm out.
- Take more scans in different direction to try to build an accurate 3D model.
- Do a panned 90deg from radial view but with very small steps. This can be used to make a very high resolution “fly through” movie where the viewer is transported around the vessel at the center of the plasma. Probably need >400 steps to make it smooth.
• Do a large set entering the vessel to make a nice movie going through the ports.
• Take a few high quality ones with people in vessel (posed) for human interest.

A key thing to note is that the photo taking process is automated, thus increasing the number of photos by a factor of 10 requires marginal more work, just more time to have the system in vessel. Also, the tone-mapping, processing and stitching processes are all batch driven so the workflow is fairly insensitive to the number of photos involved, aside from computation time, which was not a limiting factor for this work. (note: Hugin is parallelized)

Software used:

To control the camera: Camera Control Pro V1.3 http://www.nikonusa.com (commercial)

To automate the motion: MATLAB R2012b www.mathworks.com/products/matlab/ (commercial)

To combine the brackets and tonemap: Photomatrix Pro 4.2.7 www.hdrsoft.com (commercial)

To stitch the photos: Hugin 2012 http://hugin.sourceforge.net/ (open source)

To batch crop and convert: IrfanView v4.36 www.irfanview.com (open source)

To crop/rotate and edit levels/curves: GIMP 2.8.6 www.gimp.org (open source)

To create the 3D point cloud: VisualSFM http://ccwu.me/vsfm/ (open source)

Location of the photo products:

The finalized jpeg photos: \psfc\psfcfiles\Engineering Drawings\Engineering\EngImages\C-Mod_Interior_2013\finalized

Derived videos: : \psfc\psfcfiles\Engineering Drawings\Engineering\EngImages\C-Mod_Interior_2013\finalized\movies

Repository for good photos: : \psfc\psfcfiles\Engineering Drawings\Engineering\EngImages\C-Mod_Interior_2013\tone_mapped