ARTIFACTS IN STITCHED PANORAMAS FROM SEQUENTIAL MOVIE FRAMES

by

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Artifacts in Stitched Panoramas from Sequential Movie Frames

Thesis directed by Associate Professor Catalin Grigoras

ABSTRACT

This preliminary study examines artifacts in panoramic images created by stitching sequential frames extracted from panning-style cell phone videos. 159 videos were collected with multiple iOS and Android powered devices. 189 panoramas were generated using commercially available software on Windows and MacOS platforms. A structured workflow was developed to document data acquisition, image processing, and artifact evaluation. The observed artifacts were systematically categorized according to when they occurred during the workflow. Some were identified as input artifacts (introduced during capture) and some were identified as stitching artifacts (introduced during panorama assembly).

Artifact classification was performed using a keyword-based system developed in Adobe Lightroom Classic. Examples of input artifacts are motion blur and rolling shutter, while stitching artifacts included seams, misalignment and ghosting. Statistics were recorded, with motion blur (66 instances), seams (57) and misalignment (50) accounting for the artifacts most frequently observed.

Comparisons were conducted across processing platforms, including Microsoft Image Composite Editor and Adobe Photoshop on both Windows and macOS systems. While differences in output were found between the various software platforms, all artifact types occurred across multiple devices, platforms, and workflows providing evidence to support the author's hypothesis.

The results demonstrate that panoramic images created from panning-style videos may contain artifacts that could affect image reliability. These findings have direct implications for forensic practitioners, particularly when panoramic images are used in a legal setting. The study demonstrates the importance of understanding the capture process as well as the processing workflow. Due to the preliminary nature of this study, the Future Research section is heavily populated with ideas. There is ample opportunity for further research in this area.

The form and content of this abstract are approved. I recommend its publication.

Approved: Catalin Grigoras

DEDICATION

I dedicate this work to the memory of my father, Richard J. Fay. My dad was an automotive engineer and a pioneer in the field of Accident Reconstruction. I had the good fortune of being able to work alongside him in his business for over twenty years. He pursued the truth with unflagging integrity. On those occasions when the results of his investigation were unfavorable to his client, he prided himself on delivering “Scientifically accurate bad news”. I strive to carry on that integrity in my own work and life.

ACKNOWLEDGEMENTS

Many people helped me on this journey to achieve a masters degree in my late 50’s. Their patience and guidance was more valuable to me than they will ever know. To my wife Concha for encouraging me and helping make way for college in our family life. To Chuck Fox for giving me that push to find the best master’s program there is. To Benjamin Royall for being my boss and my biggest fan. To Catalin Grigoras for seeing the potential in my ideas and helping me find my direction for this thesis. To Cole Whitecotton for his matter-of-fact explanations. To Greg Wales for showing me what pure research can be. Thank you.

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I. INTRODUCTION

Panoramas

Panoramic images (referred to in this text as “Pans”) are a common part of today’s imagery. A modern panoramic image is one in which a wide view of the environment surrounding the camera is captured through the digital combination of a number of individual images. Individually captured images, each with a slightly different view of the scene, are stitched together to create one large composite image or panorama, with the image resolution of the panorama being equivalent to that of the individual images that make up the panorama. In this way, a panoramic image provides a substantially greater field of view compared to a standard photograph while maintaining the same resolution as the component images. [1] Because a panoramic image is made up of multiple images, it contains more visual information, accessible in a single construct, than that obtained in a single image or photograph of the same scene. [1]

Pans have found their way into everyday life. Cell phones most of us carry daily include built-in panorama features, and myriad software applications exist that automatically assemble panoramic images from existing content. Large-scale examples include platforms such as Google Earth, which relies on stitched imagery to create a continuous representation of the globe. In accident reconstruction, aerial photography of crash scenes in the form of digital orthomosaics is common. Dental imagery is also stitched together in a panoramic format such that an entire set of teeth can be seen in one image. These examples highlight how common and operationally important pans have become.

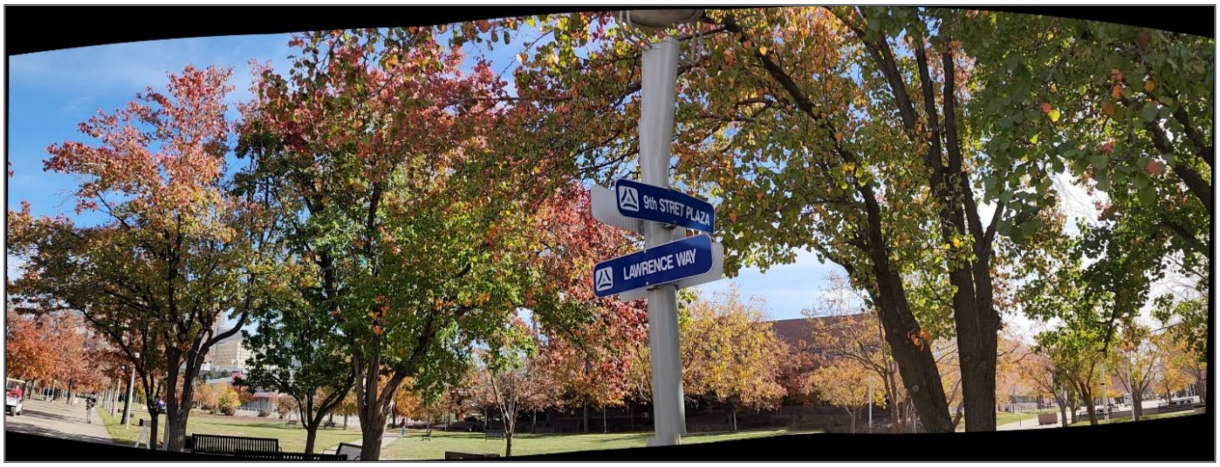


Figure 1. Panoramic Image with Visible Artifact

Despite their ubiquity, panoramic images are not always perfect representations of a scene. The stitching process can introduce visible artifacts such as misaligned edges, blurry regions, duplicated content, or missing characters. Figure 1 provides an example of this type of issue. To the casual observer, the street signs appear normal. But closer inspection reveals a stitching-induced error in the text, where "STREET" appears as "STRET." This type of artifact illustrates how small errors can affect the interpretation of an image.

Artifacts in pans are not merely curiosities. When panoramic images are used as part of an investigation or presented in court, their reliability becomes critical. An artifact represents a deviation from the original scene, and even subtle errors may influence how the pan is interpreted. As a result, it is not enough to evaluate the final image alone; it is also necessary to understand the process used to create it and the errors that may occur.

A series of still images is not the only type of source material for a pan. A video can be another potential source, especially if the video is taken by someone standing in one place and sweeping – or panning – the camera across the scene. Forensic practitioners may encounter panoramas made from videos recorded under less controlled conditions such as with body-worn cameras or when the mobile device was the only camera available. In these cases, individual frames from the video can be extracted and stitched together to produce a panoramic image. Although this workflow is less common, it has practical relevance in forensic contexts.

This study examines the artifacts that occur in panoramic images created from sequential frames originating from cell phone videos. The goal is to identify the types of errors that arise during panorama-generation and to better understand the conditions under which they occur. By studying these artifacts and comparing the results across devices, environments, and software platforms, the findings aim to support forensic practitioners in the collection, processing, and interpretation of panoramic imagery. Ultimately, this work seeks to improve the reliability of pans used as evidence in legal settings.

Hypothesis

Artifacts in panoramic images created by stitching consecutive frames from cell phone videos are consistent regardless of the cell phone model, stitching software, or processing hardware used. This hypothesis is based on the assumption that modern stitching algorithms rely on similar methods, such as feature detection, image matching, and geometric transformation. If these processes behave in comparable ways across platforms, then the types of artifacts they produce should also be similar, even when different devices or software are used.

Previous Research

Homography

Szeliski and Shum explain that cylindrical panoramas are commonly used because of their ease of construction. To build a cylindrical panorama, a sequence of images is taken by a camera mounted on a leveled tripod. If the camera focal length or field of view is known, each perspective image can be warped into cylindrical coordinates.[8] A homography is a transformation that maps points from one image plane to another assuming the scene is planar or the camera rotates about a fixed point. In the case of panoramas captured with cellphones while standing in one place, the homography is a cylindrical panorama. In other words the homography is the “bending plan” that allows images to be warped to match each other such that the panorama reflects the view from that single point.

Virtual Reality

Early work in panoramic images was done in pursuit of virtual reality applications as early as 1994. Szeliski writes that Panoramic Image Mosaicing involves rotating a camera around its optical center in order to create a full “viewing sphere” of images. When images are captured in this way, they can be related through two-dimensional projective transformations. This type of motion is well-suited for assembling a large scene from the individual images and being able to “look around” from a static viewpoint.[7]

Scale Invariant Feature Transform

Modern stitching methods rely heavily on feature-based matching. Lowe developed the Scale Invariant Feature Transform (SIFT) which transforms image data into scale-invariant coordinates relative to local features. [9] SIFT identifies image features that have many properties that make them suitable for matching differing images of an object or scene.The features can be well-identified regardless of changes in scaling and rotation, and somewhat well-identified with changes to lighting and camera position. This makes SIFT a good process for identifying corresponding points between overlapping images, such as those being used to generate pans. [9]

Transformations

Once features are identified, the next step is to determine how the images relate to each other geometrically. Szeliski explains the simplest transformations are pure translations, followed by translations and rotations (rigid transformations), plus scaling (similarity transformations), affine transformations, and full projective transformations. [7]

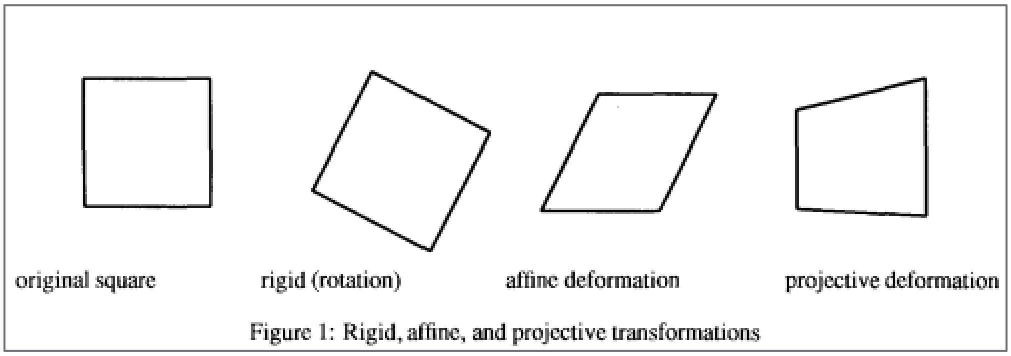


Figure 2. Rigid, Affine, and Projective Transformations [7]

Figure 2 demonstrates the types of transformations that may be performed to align images in a pan.

RANSAC

Fischler and Bolles introduced the Random Sample Consensus or RANSAC paradigm, which is capable of smoothing data that contain a significant percentage of gross errors. RANSAC is useful anywhere there is a lot of noise mixed in with the important data in a dataset. This paradigm is particularly applicable to scene analysis because local feature detectors, which often make mistakes, are the source of the data provided to the interpretation algorithms. [10] In the context of image stitching, it helps separate correct feature matches from incorrect ones, allowing for a more reliable estimation of the transformation between images.

Automatic Panoramic Image Stitching

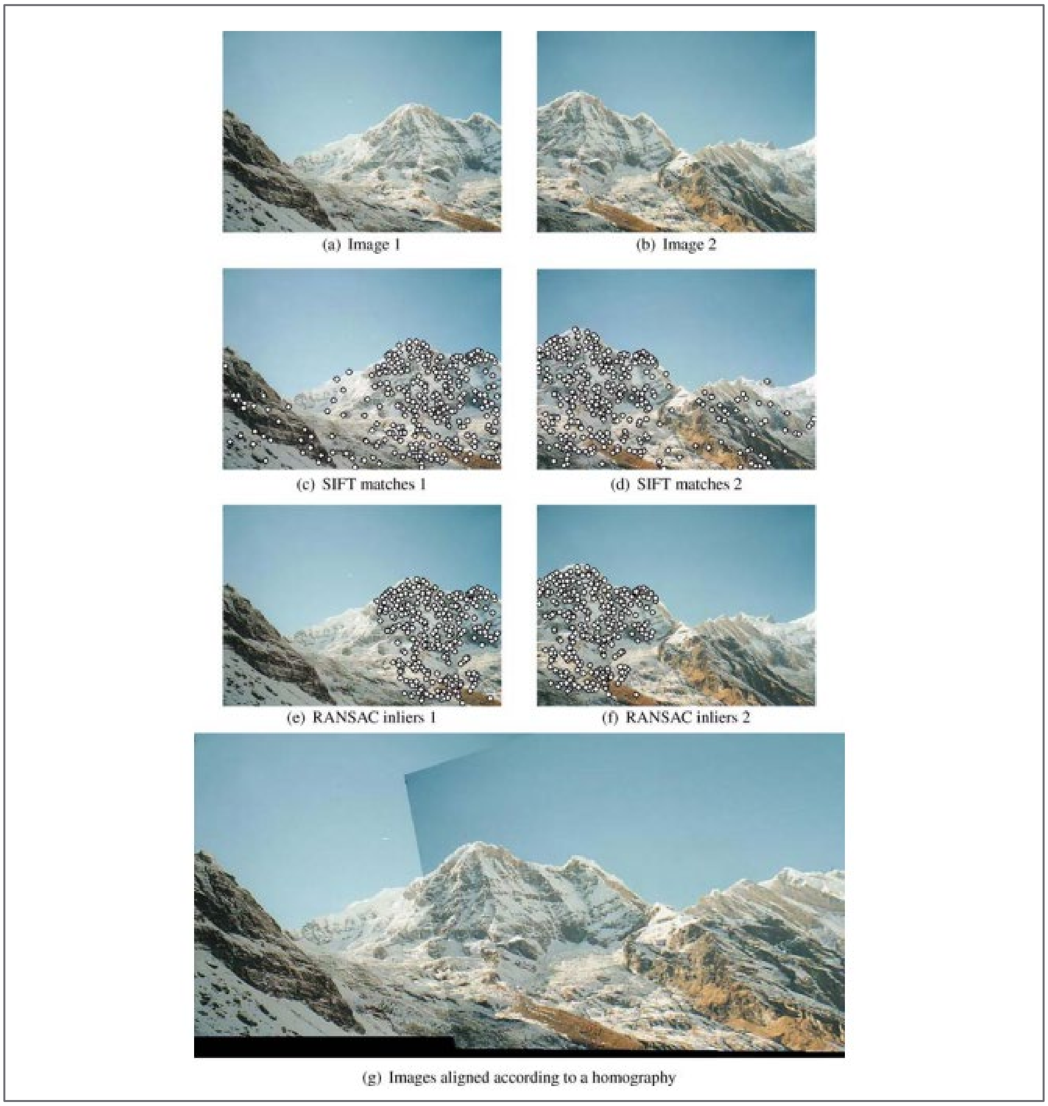


Figure 3. Brown and Lowe's SIFT + RANSAC Example [2]

Brown and Lowe ushered in the modern era of panoramic image creation by developing an invariant feature (SIFT) based approach to fully automatic panoramic image stitching. This had several advantages over previous approaches. First, they used invariant features to enable reliable matching of panoramic image sequences despite rotation, zoom and illumination change in the input images. Second, by viewing image stitching as a multi-image matching problem, they could automatically discover the matching relationships between the images and find panoramas in unordered datasets. Third, they used multi-band blending to render seamless output panoramas. [2] This became the foundation for many modern programs that assemble panoramas.

These underlying methods—homographies, feature detection, feature matching, transformation estimation, and blending—play a direct role in the types of artifacts that can appear in stitched panoramas. While the software used in this study automates these processes, understanding how they work provides important context for interpreting the artifacts observed in panoramas generated from panning-style cell phone videos.

II. MATERIALS

Recording Devices

Table 1. Phone Models and Operating Systems

Phone Model	Operating System
iPhone 7 32GB	iOS 13.4.1
iPhone SE 2nd Gen	iOS 14.4
iPhone SE 32 GB	iOS 15.8.4
iPhone SE	iOS 18.3.2
iPhone 16 Pro Max	iOS 18.3.2
iPhone 16 Pro Max	iOS 26.2
Moto g play 2023	Android 13
Samsung Galaxy S22 Ultra	Android 16

The phone models used are shown in Table 1. Apple iPhones with 6 versions of iOS were used along with two Android-powered phones with two versions of the Android operating system.

Panorama Processing Software

Table 2. Processing Software and Operating Systems

Panoramic Image Software	Version	OS
Microsoft Image Composite Editor (ICE)	2.0.3.0 64 bit built 2015-02-24 22:47:59	Win 11
Photoshop (PS) Author's Machine	26.11.3 20260216.r.121 3dbbc42 x64 (final, Release)	Win 11
Photoshop (PS) University's Machine	26.2.0 20241207.r.140 bc85906 x64	Win 11
Photoshop (PS)	27.4.0 20260218.r.15 6bd4063 x64 (final, Release)	Mac Sequoia

The software brands and version numbers, with their associated operating systems are shown in Table 2.

Data

Table 3. Video Locations and Dates

Location	Date	Contents
Downtown Denver	11/7/2025	3 videos, 4 pans
CU Denver Campus	11/8/2025	25 videos, 16 pans
Victor, CO	2/6/2026	12 videos, 10 pans
El Salvador, CA	12/19/2025	11 videos 4 pans
Swap Meet	2/10/2026	11 videos, 11 pans
AAFS New Orleans	2/14/2026	97 videos, 144 pans

Data collection occurred in November and December of 2025 and February of 2026. 159 videos were collected and 189 pans were generated.

III. METHODOLOGY

Original Idea

The original idea for this project came from an encounter with body-worn camera (BWC) footage captured by a police officer during an arrest. An individual was restrained by several police officers. Multiple officers had BWC recordings of the event, but they were all "too close to the action" for a viewer to see the overall scene. However, one officer's camera panned slowly across the scene by happenstance. The author realized the individual frames from this movie could be assembled into a panoramic image. This pan allowed the viewer to see the whole picture as if they had stepped back from the action, providing valuable insight into the event that wasn't available from the individual videos.

Police Use of Cell Phones

Using body-worn cameras as source devices for this project would have been truer to the original idea, but implementation would have proven difficult. The author chose cell phones instead because the panning motion of the officer's body could easily be mimicked by holding a cellphone in hand and sweeping it across a scene. In addition, it's conceivable, though perhaps unusual, that a police officer may sometime use a cell phone to record a panoramic scene. Chase Jarvis published a book in 2009 entitled, "The best camera is the one that's with you" **[4]** which fairly sums up the reason a panorama might be recorded with a cell phone and then used in some official capacity. With this in mind, SWGDE even produced a recommendation for mobile device photography for comparative analysis saying, "SWGDE recognizes there are instances where it may be necessary, in rare circumstances, to capture images on a mobile device camera and these images may still have limited acceptable uses. Examples of these circumstances include fleeting, or transient evidence or real-time investigative need due to an imminent public safety issue.” [3]

Artifacts Are Errors

Although stitching algorithms are robust there is still the potential for errors to occur. Kulscar et al, though talking about X-rays instead of photographs, sum up the errors succinctly: Proper identification of elements on a radiological image may also be difficult due to errors that may occur before, during or after the X-ray. These errors are called artifacts. [12]

Methods

The experimental design involved hand-capturing video footage in a panning motion with iOS- and Android-powered smartphones. Videos were recorded using different smartphones in a variety of locations, including the CU Denver campus, an auto parts swap meet, Victor and Cripple Creek, CO, El Salvador, CA, the New Orleans convention center, and Bourbon Street. The phones were held in both horizontal and vertical orientations and were panned both left to right and right to left. The motions were either slow throughout, fast throughout, or slow/fast/slow. The slow/fast/slow panning style was meant to mimic situations where a body worn camera moves quickly in the middle of an otherwise slow pan across the scene. The captured footage was processed with Microsoft Image Composite Editor (ICE) and Adobe Photoshop. The artifacts were categorized using Adobe Lightroom Classic.

Data Acquisition

Capture Device Attributes

On all phones, both iOS and Android, the default camera app provided with the operating system was used for capturing the panning movies.

Table 4. Device Resolution and Video Frame Rate

Phone Model	Resolution	Frame Rate
iPhone 7 32GB	1920x1080	30.00 Constant
iPhone SE 2nd Gen	1920x1080	30.00 Variable
iPhone SE 32 GB	1920x1080	29.97 Variable
iPhone SE	1920x1080	30.00 Constant
iPhone 16 Pro Max	1920x1080	30.00 Constant
Moto g play 2023	1920x1080	29.577 Variable
Samsung Galaxy S22 Ultra	1920x1080	59.859 Variable

Various phone models were used for capturing the panning movies, all having 1920x1080 resolution. Some variability was observed in the video frame rates as shown in Table 4 with the slowest frame rate being 29.577 Variable for the Moto g play 2023, and the fastest being 59.859 Variable in the Samsung Galaxy S22 Ultra.

Filming Strategy

The data acquisition effort was structured to capture panning-style videos mimicking the way a police officer's body worn camera might pass over a scene. Recognizing that police officers find themselves in varying situations from close contact with a single individual to wide-ranging contact with a large scene, the author chose scenes of varying degrees of complexity and depth of field.

The phones were held with both hands by the operators while capturing movies. No external stabilization equipment was used. The camera software's exposure mode, stabilization, and autofocus were left at the default setting in all captures. The phones were held horizontally in 98 of the movies, and vertically in 87. Phones panned left to right in 125 videos, and right to left in 57 videos. Two videos were panned from down to up. Pans were slow in 113 videos, fast in 38 videos, and slow-fast-slow in 27. The panning speed was not numerically specified or controlled, other than that the slow pans were intended to minimize blurring while fast pans were meant to induce it.

Image Processing

Panorama Software Choices and Settings

Microsoft ICE and Adobe Photoshop were chosen to create the pans due to their automated or semi-automated panorama-making processes, and their broad availability on Windows platforms. Adobe Photoshop is also available on the Apple MacOS platform. Cylindrical projection was used in all instances as it is the correct homography for a camera located at a central point and turning about that central point. Applying lens and exposure correction before stitching could have benefitted the assembly process, however this preliminary study was designed to capture a base level of panorama functionality. Future studies may include a pre-processing step to correct simple issues before panorama assembly. PNG formatted output files were chosen to minimize the effects of compression in the final products.

Microsoft Image Composite Editor (ICE)

Microsoft ICE was developed in the mid 2000's. Development was halted in 2015 and no further versions were created. This final version remains popular.

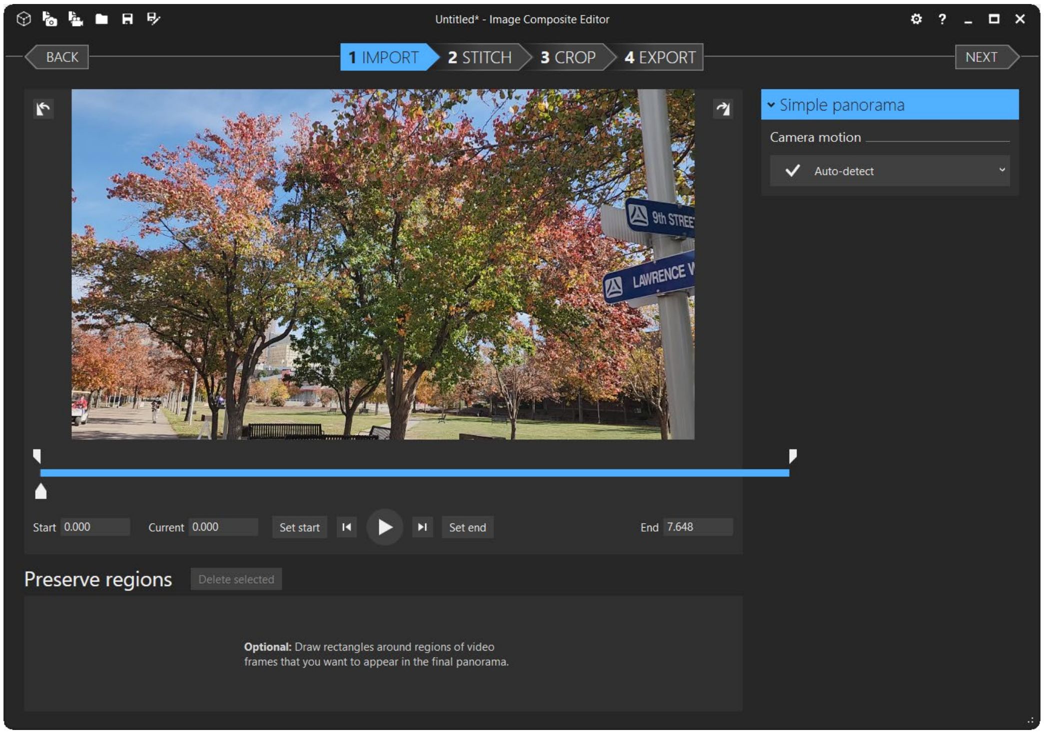


Figure 4. MS ICE Import Screen

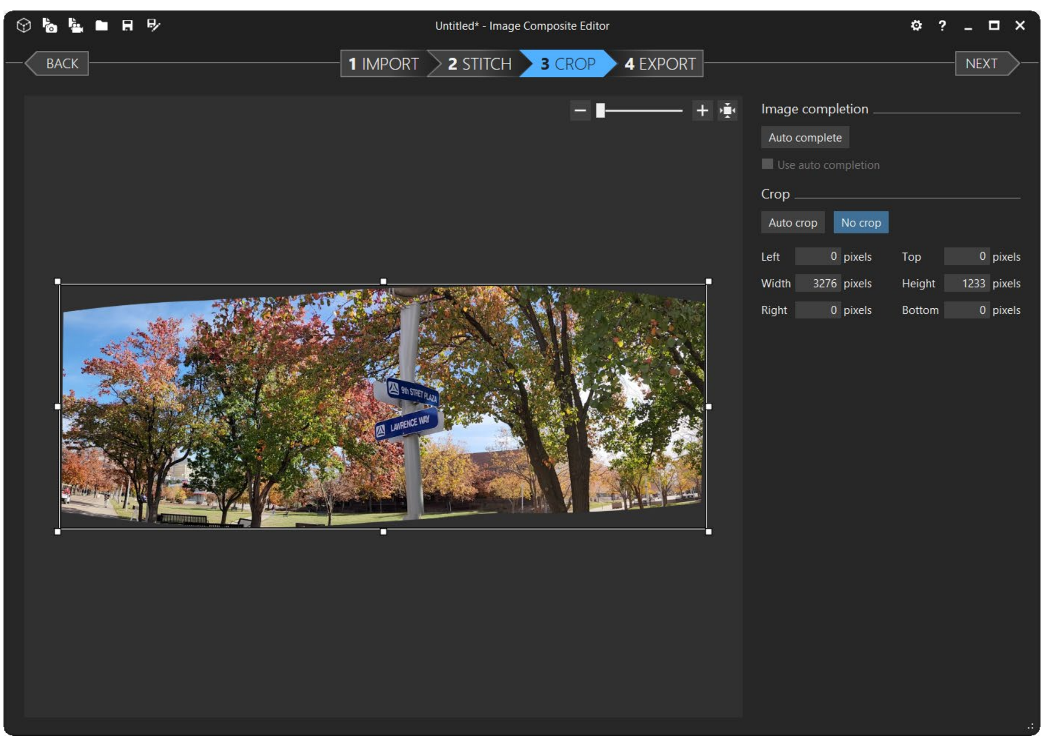


Figure 5. MS ICE Crop Screen (MS ICE Windows)

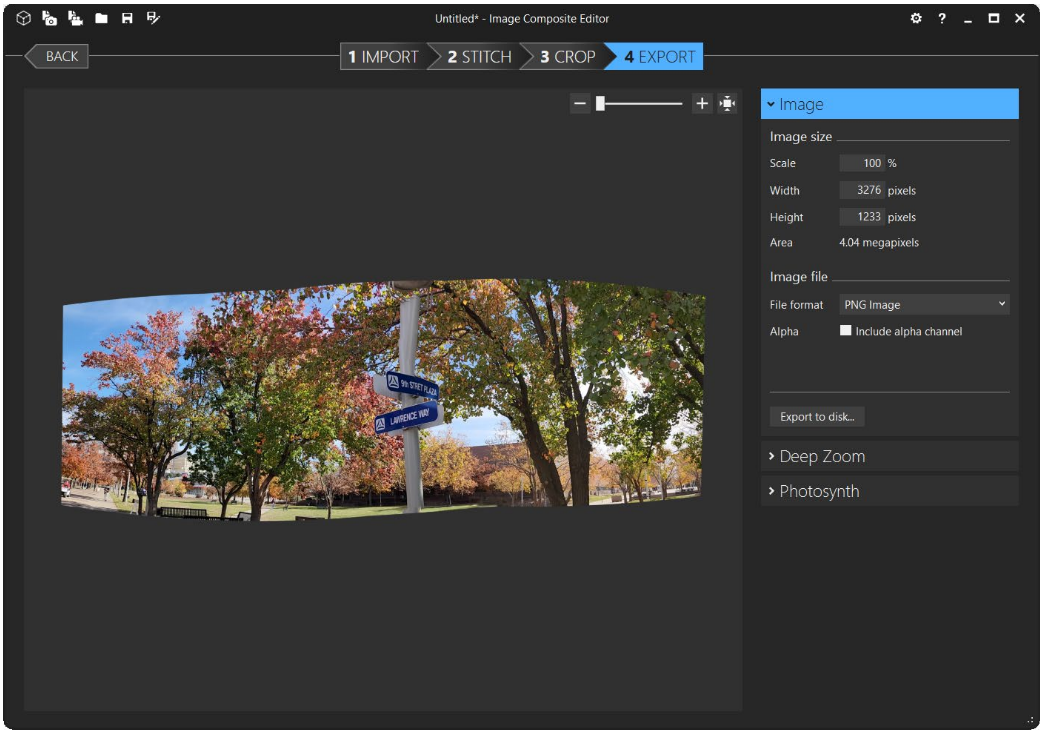


Figure 6. MS ICE Export Screen (MS ICE Windows)

MS ICE was used in its most default setup possible. The user interface is very simple, offering three options to get started. the “New Panorama From Video” was the workflow used. The main processing window is also quite sparse. The only options allow the user to preserve regions by highlighting them before stitching, and to crop the length of the movie to use as shown in Figure 4. For this study, “Preserve Regions” was not selected. It may be a worthy option for future research. Each movie was used in its entirety without cropping, shown in Figure 5. Similarly, the resultant pan was not cropped; again because this was the default condition. Note that there was no choice of “every Nth frame” in this MS ICE workflow while such a feature was utilized in the Photoshop workflow.

Adobe Photoshop (PS)

Adobe Photoshop (PS) is a popular program for editing images, and it has many tools built in. Though it does not offer a button-push solution like MS ICE, it can produce similar results. If the user performs series of steps, Photoshop will produce a panoramic image.

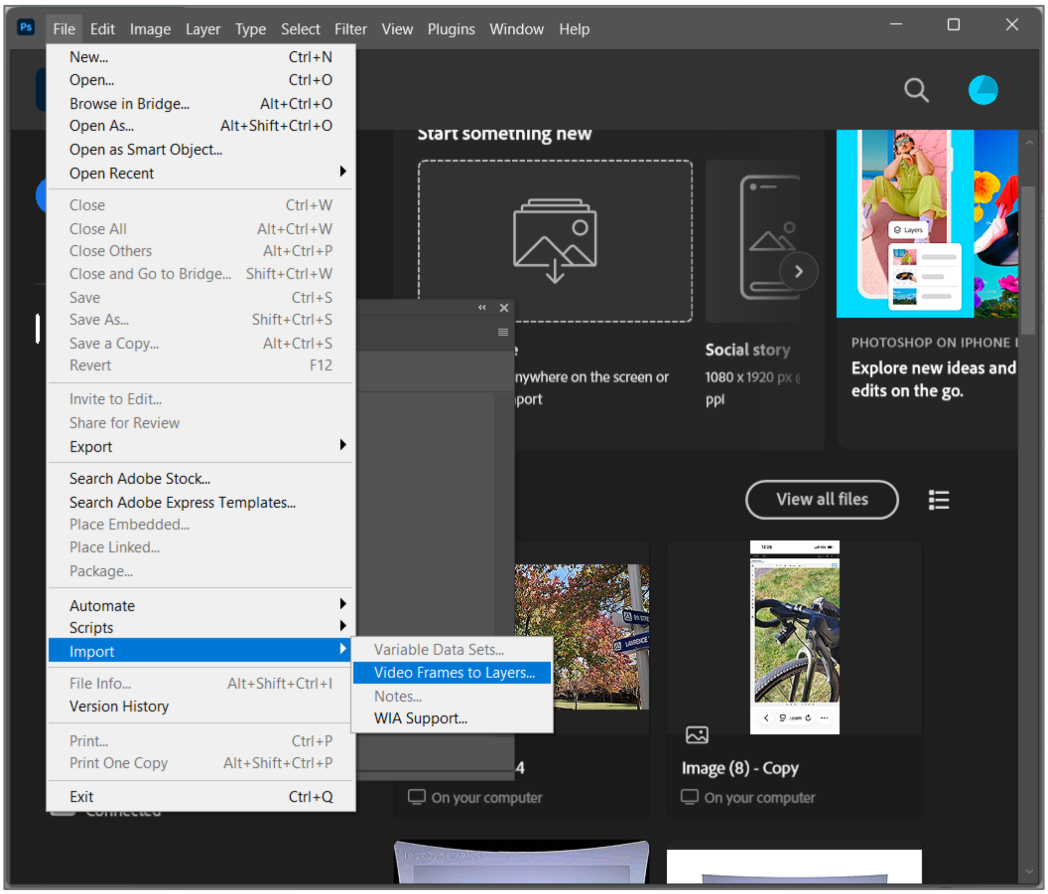


Figure 7. Photoshop Import Video Frames to Layers (Photoshop Windows)

In Photoshop, the workflow is to add frames from the video to individual layers, then create a pan from the layers. A video can be imported to layers as shown in Figure 7. Some types of videos could not be opened in Photoshop. To process some of the videos into pans, the frames were first extracted using ffmpeg and then loaded into layers using a stack. The appendix contains the script used for extracting the frames.

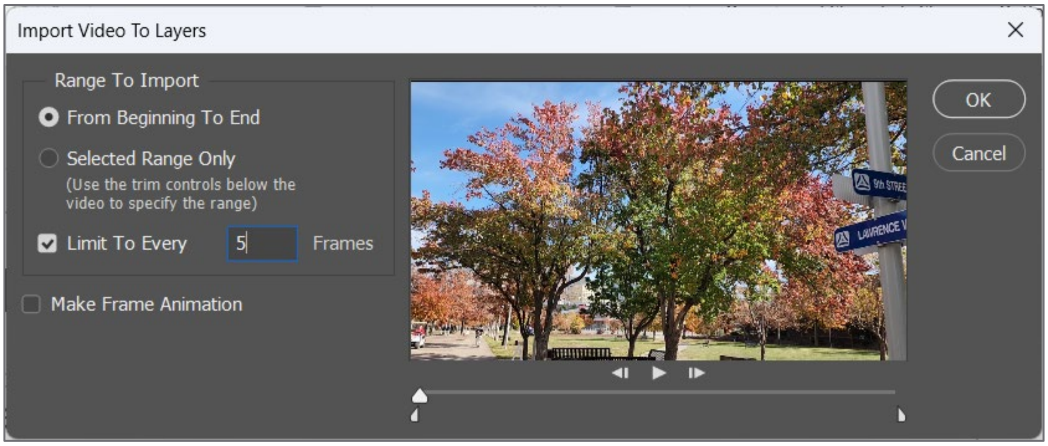


Figure 8. Range and Limit Selection (Photoshop Windows)

In Photoshop as in MS ICE, the intent was to capture a base level of panorama functionality so wherever possible, default values were used and no pre-processing was performed. Once a video is selected, the user can set up the range and frame limit. As noted above, this step was done externally for some files, but in all cases every 10th frame was extracted.

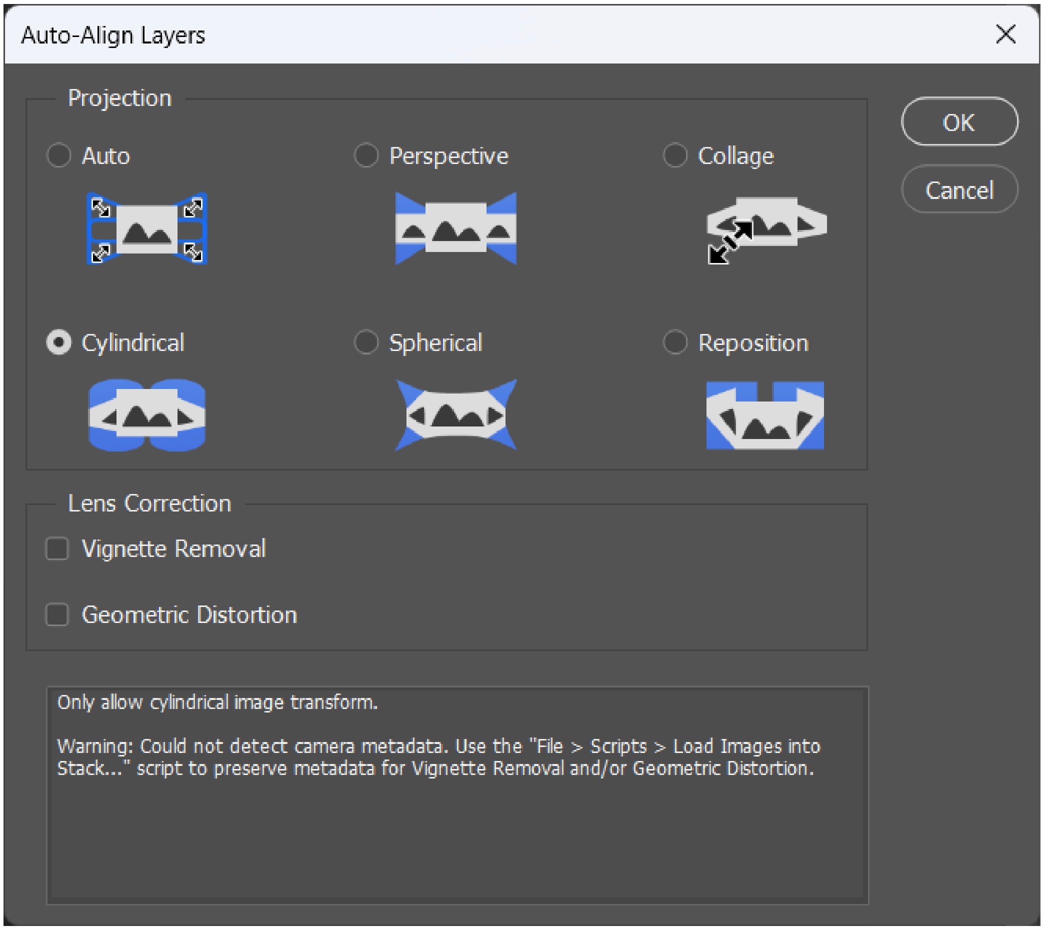


Figure 9. Projection Choice, AKA Homography (Photoshop Windows)

Figure 10. Completed Panorama (Photoshop Windows)

Once images were saved in layers, they could be aligned. As shown in Figure 9, only cylindrical projection was used, and no lens correction was selected, in compliance with the base functionality intent. As in the MS ICE workflow, completed panoramas were exported as PNG files.

Artifact Evaluation

The author identified visible artifacts through observations of the completed pans and defined a system for categorizing artifacts based on when they were created during the process. Artifacts fell into two categories; they were either input (pre-stitching) artifacts or stitching-induced artifacts. Input artifacts were those created by either the operator while handling the device or by the camera itself during the capture. Examples of input artifacts are lens distortion, exposure, motion blur, and rolling shutter. Stitching-induced artifacts occurred during the stitching process after the data was collected. Stitching artifacts include misalignment, ghosting, seams, warping, and character deformation.

Adobe Lightroom Classic

Adobe Lightroom Classic (LRC) was used to categorize the artifacts found during the project. LRC is a powerful photograph cataloging program that offers tools for organizing and evaluating images.

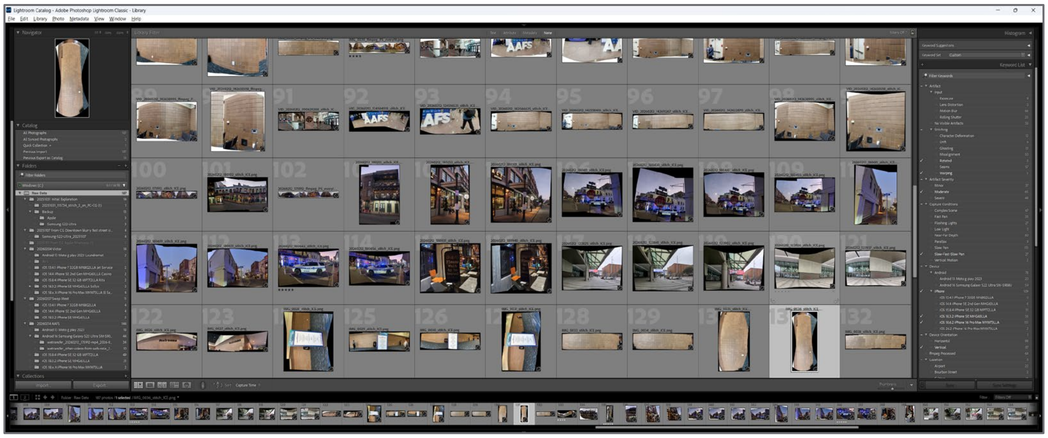


Figure 11. Adobe Lightroom Classic User Interface

The pans were loaded into LRC and categorized with keywords, as shown in Tables 5 through 11 below. This effort produced a searchable database allowing the user to quickly observe all attributes for each pan while also allowing the user to search for pans having particular attributes. In addition, LRC allowed development of statistics around the frequency and severity of each artifact, along with the conditions under which the image was captured.

Input Artifacts

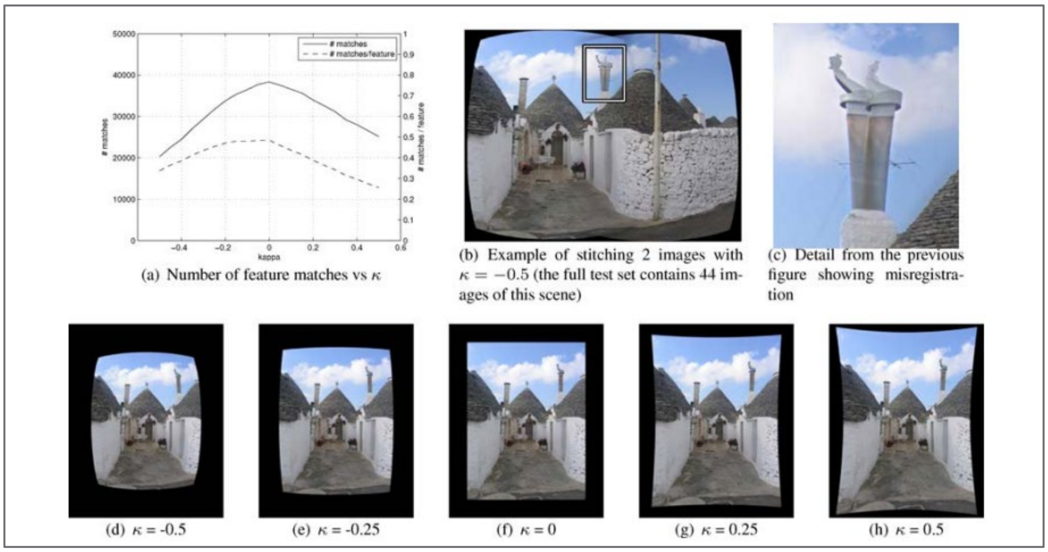
Since artifacts such as geometric distortion are generated within the recording device, they may carry through to the finished pan. It may be possible to reduce their influence on the final product by pre-processing the source images before stitching.

Frame Rate

Videos captured in the panning style defined by this project naturally feature substantial overlap from frame to frame, especially when a slow panning motion is used during filming. This produces sets of images containing sufficient overlap for SIFT-style image alignment regardless of the frame rate used, from 29.597 through 59.859. Video frame rates near 60 frames per second (FPS) may produce less blurring than those at 30 FPS.

Barrel Distortion

Barrel/pincushion distortion produces curved lines in things that are known to be straight such as windowsills and edges of buildings. It varies based on the focal length of the lens. A wide-angle lens will produce more barrel distortion in an image than a 50 mm lens, for example. These distortions may contribute to misalignment during stitching.



(a) Number of feature matches vs κ

(b) Example of stitching 2 images with $\kappa = -0.5$ (the full test set contains 44 images of this scene)

(c) Detail from the previous figure showing misregistration

(d) κ = -0.5 (e) κ = -0.25 (f) κ = 0 (g) κ = 0.25 (h) κ = 0.5

Figure 12. Brown and Lowe Discuss Radial Distortion [2]

Brown and Lowe discussed artifacts associated with radial distortion. Radial distortion causes visible artifacts in rendering as shown in figures (b)–(c) and they noted that correcting for this in the bundle adjustment and rendering stages would be important for high quality panorama stitching. [2]

Exposure and Time of Day

Figure 13. Bands/Seams from Exposure Differences (Photoshop Windows)

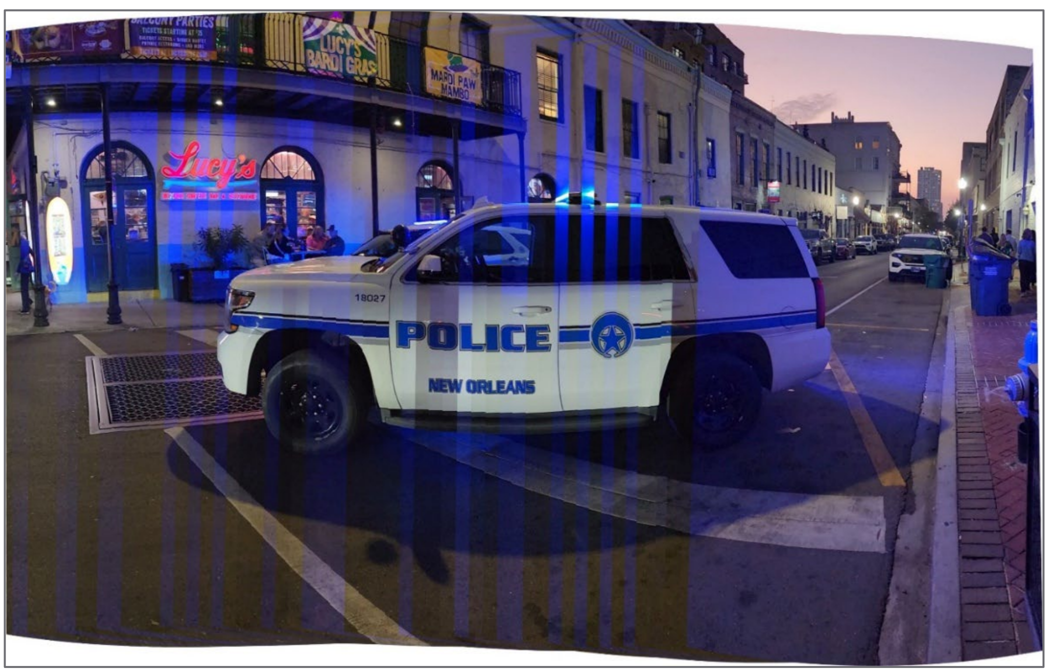


Figure 14. Bands/Seams in Panorama (Photoshop MacOS)

Brightness and color shifts between images can influence the overall smoothness of the panoramic image. This can manifest as bands of color or visible seams. Changes in lighting can be gradual if the individual images are separated in time. For example, if some outdoor pictures are taken in the morning and some in the afternoon, the lighting and shadows will have changed in the interim. Short-term lighting changes can also have an impact on the resulting pan. Figure 13 and Figure 14 demonstrate bands resulting from police car lights flashing as the source movie (20260212_180643.mp4) was recorded.

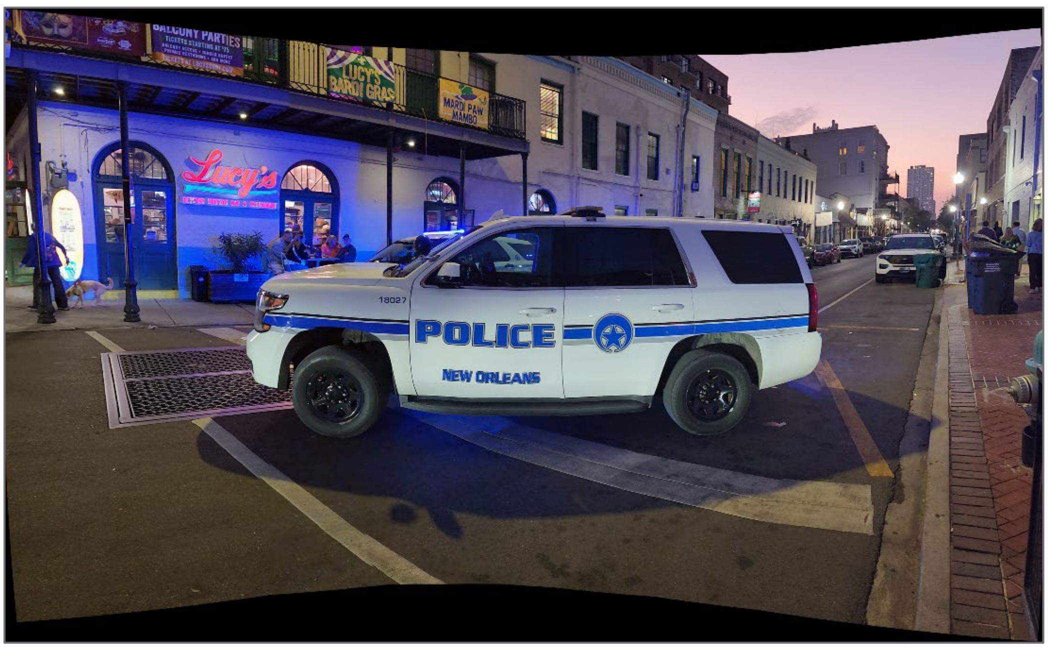


Figure 15. Clean Panoramic Image (MS ICE Windows)

Some algorithms do a better job than others in certain circumstances. While the Photoshop process on Windows and macOS computers produced images with bands, Microsoft ICE, using the same source movie, arrived at a solution without bands, as shown in Figure 15.

Motion Blur

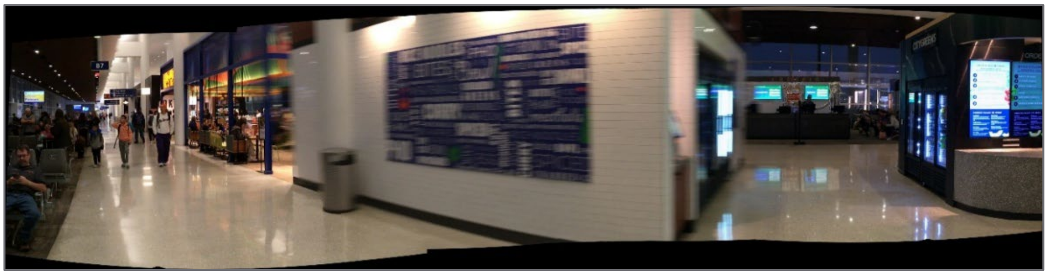


Figure 16. Slow/Fast/Slow Panning Produces Blurry Artifact (MS ICE Windows)

Camera motion affects the panoramic image if the camera moves too fast across the scene. If the individual frames of a movie contain motion blur, the resultant panorama will as well. Thinking back to the body-worn cameras, the recording is continuous; it contains some moments of fast camera motion and some relatively slow. Those moments without fast motion will be candidates for useful pans. Figure 16 demonstrates a pan with a blurry middle and clear outer edges when slow/fast/slow panning style is used. A possible mitigation strategy is to pre-process the blurry frames for motion blur.

Rolling Shutter

Rolling shutter artifacts occur when images are recorded by the chip in a raster-style line by line rather than all at once. Since the image is recorded one line at a time, if things change in the view between the start of one frame and the start of the next, a slight error occurs. This is most visible in recordings of rotating objects such as airplane propellers and car wheels in motion.

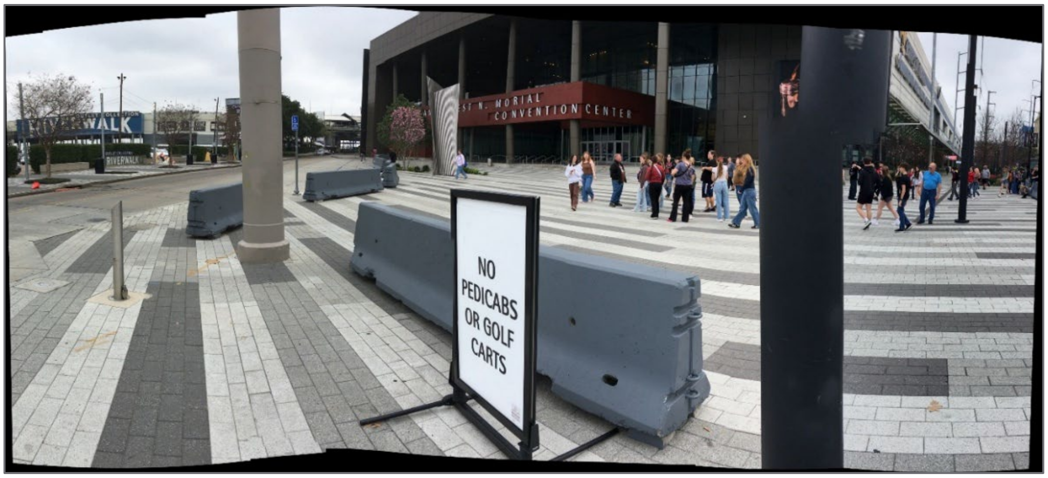


Figure 17. Rolling Shutter Artifact (MS ICE Windows)

Figure 17 shows a broken vertical pole close to the camera at the right side of the image in an otherwise artifact free pan. The pole being the closest item to the camera and thus moving the most within the viewport from frame to frame, makes it a good example of the rolling shutter artifact.

Stitching Artifacts

Stitching Artifacts are created during the process of aligning photographs into a panorama. These errors are heavily influenced by the stitching algorithm used by the software. Some stitching artifacts may be able to be mitigated by choices the user makes before starting the alignment, if such options are offered by the software.

Misalignment

Figure 18. Severe Misalignment Artifact from IMG_0157.MOV (Photoshop Windows)

Stitching artifacts such as misalignment can range from benign to severe. Figure 18 shows a severe misalignment from Photoshop on Windows resulting in an image that has, among other artifacts, one part of the pan placed upside-down.

Figure 19. No Alignment Issue with macOS Version (PS MacOS)

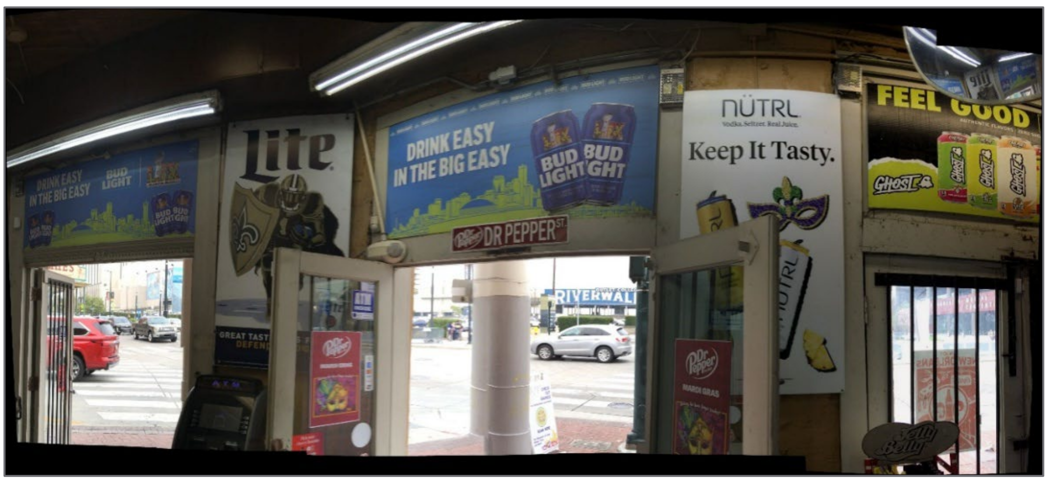


Figure 20. IMG_0157.MOV Pan from MS ICE (MS ICE Windows)

The same movie (IMG_0157.MOV) processed by both MS ICE and Photoshop for macOS produced more usable pans with minor input artifacts such as blurring and rolling shutter as shown in Figure 19 and Figure 20.

Ghosting

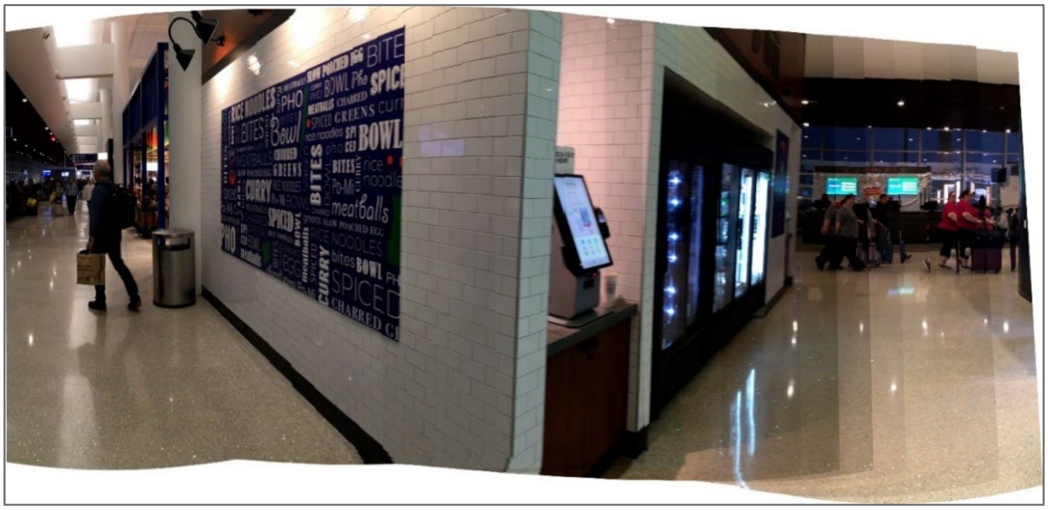


Figure 21. Examples of Ghosting and Seams (Photoshop Windows)

The ghosting artifact duplicates portions of the source image in the finished pan. People at the right side of the pan in Figure 21 from IMG_0181.MOV are duplicated as they walk.

Seams

Figure 21 is also a good example of seams. This artifact appears similar to the bands artifact discussed earlier due to changing lighting conditions. However, the seams appear under normal lighting conditions in this example. Mitigation may be possible here by adjusting levels on the individual layers.

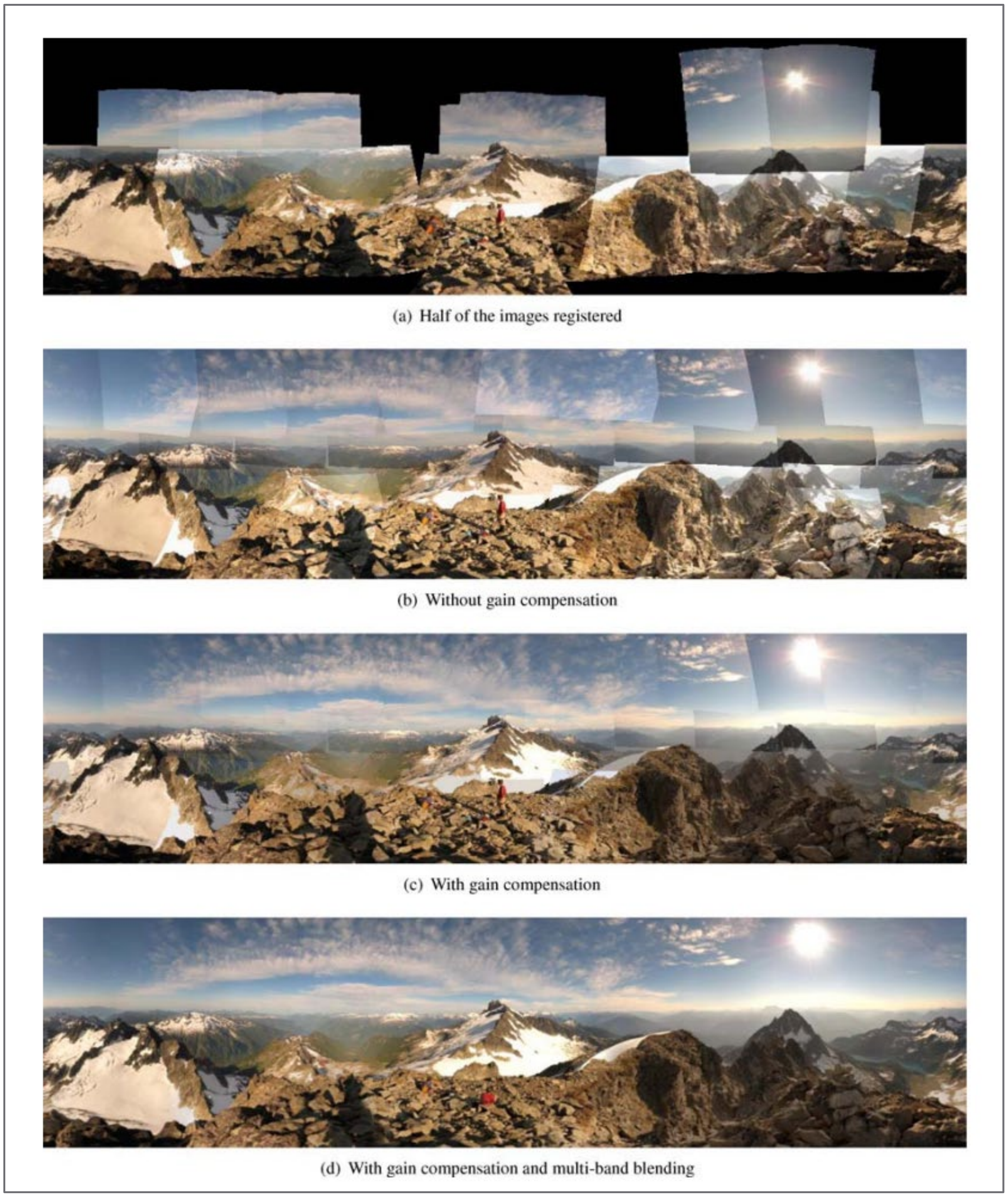


Figure 22. Brown and Lowe Discuss Multi-Band Blending [2]

Brown and Lowe handled seams with Multi-Band Blending. Note that large changes in brightness between the images are visible if gain compensation is not applied (a)–(b).After gain compensation, some image edges are still visible due to unmodelled effects such as vignetting (c). These can be effectively smoothed out using multi-band blending (d). The idea behind multi-band blending is to blend low frequencies over a large spatial range, and high frequencies over a short range. [2]

Drift/Warping

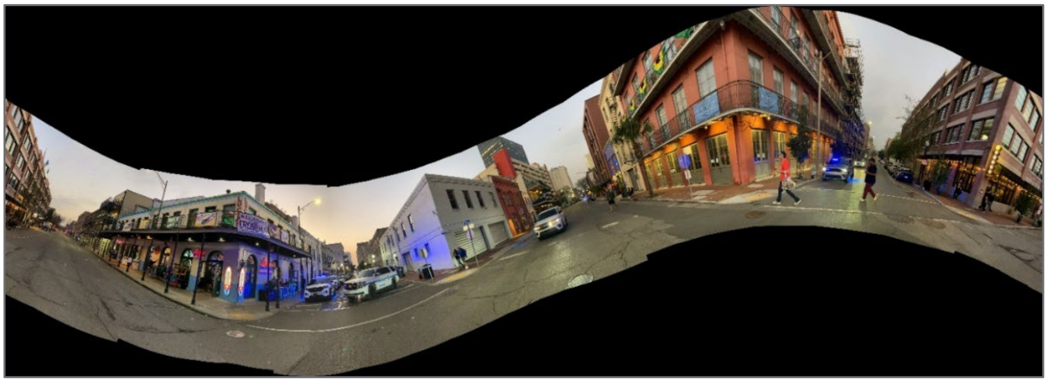


Figure 23. Drift (MS ICE Windows)

Drift is a progressive error that occurs when small misalignments from source image to source image accumulate to create a warped panoramic image, as in Figure 23.

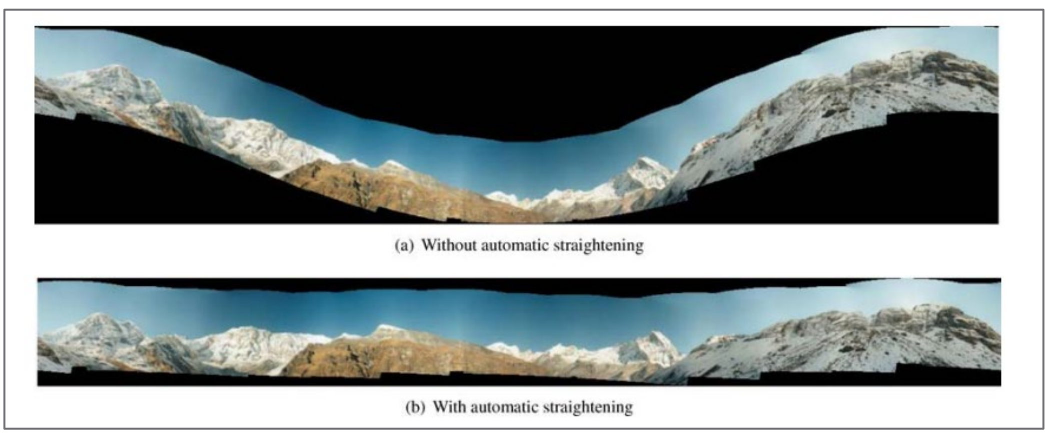


Figure 24. Brown and Lowe Discuss Automatic Straightening [2]

Brown and Lowe discussed wavy panorama artifacts and their solution. Using the heuristic that users rarely twist the camera relative to the horizon allows us to straighten wavy panoramas by computing the up-vector (perpendicular to the plane containing the horizon and the camera center). [2]

Character Deformation

Character deformation tends to be the result of one or more of the other artifacts, and so is not a standalone artifact. Character deformations appear in conjunction with seams, misalignment or rolling shutter. Figure 1 is a good example of a character deformation artifact. Though they can be the most subtle of artifacts, their detection is usually made easier by being related to others.

IV. RESULTS

Hypothesis

During this project, the author found no artifact that was isolated to a single camera, processing software, or workflow. In other words, all artifact types were observed across the multiple devices, software, and workflows studied. These observations were consistent with the hypothesis.

Many panoramas worked out as expected, though some slow pans turned out slightly blurry in the middle. Slow/Fast/Slow pans were usually blurry in the middle. Artifacts tended to be influenced greatly by the filming style and the complexity of the scene. Fast panning motion usually produced blurry or unusable pans, but not always. When scenes contained objects in both the near ground and far ground, the algorithms sometimes struggled. In general, MS ICE produced better pans than Photoshop. 38 pans came out with no visible artifacts.

Figure 25. An MS ICE Pan with No Visible Artifacts (MS ICE Windows)

Artifact Results

Frame Rate

Differences in video recording frame rate were not observed to have any appreciable effect in the results. Further study could reveal more impact from frame rate differences, but this preliminary study was unaffected by the differing frame rates between capture devices.

Project Statistics

Tables 5 through 11 below demonstrate the counts and statistics categorized with Adobe Lightroom Classic. Statistics were developed for the artifacts, severity, capture conditions, device orientation, capture locations, panning direction, and software usage.

Table 5. Artifact Counts

Input Artifacts	Count	Stitching Artifacts	Count
Exposure	9	Character Deformation	12
Lens Distortion	0	Drift	6
Motion Blur	66	Ghosting	13
Rolling Shutter	23	Misalignment	50
No Visible Artifacts	38	Rotated	8
		Seams	57
		Warping	5

Table 6. Artifact Severity Counts

Minor	Moderate	Severe
37	65	44

Table 7. Capture Conditions Counts

Condition	Count	Condition	Count
Complex Scene	67	Fast Pan	38
Flashing Lights	27	Low Light	0
Near-Far Depth	80	Parallax	9
Slow Pan	113	Slow-Fast-Slow Pan	27
Vertical Motion	2		

Table 8. Device Orientation Counts

Horizontal	Vertical
98	87

Table 9. Capture Location Counts

Location	Count	Location	Count
Airport	22	Bourbon Street	2
C Store	14	Campus	9
Classroom	6	Convention Center Inside	46
Convention Cetner Outside	18	Downtown	3
El Salvador	4	Restaurant Inside	4
Restaurant Outside	38	Swap Meet	11
Victor, CO	10		

Table 10. Panning Direction Counts

Down to Up	Left to Right	Right to Left
2	125	57

Table 11. Software Counts

Software	Count	Software	Count
Photoshop Windows	69	CU Photoshop Windows	2
MS ICE	113	CU MS ICE	2
Photoshop macOS	3		

Input Artifacts

Barrel Distortion

Though barrel distortion is an obvious candidate to be a source of visible artifacts, no pure barrel distortion artifacts were observed. However, they may have played a part in several types of stitching artifacts such as misalignment, ghosting, and drift. In addition, pans with no visible artifacts may still have been influenced by barrel distortion. Further study with controlled conditions and measured control points could reveal that images with no visible artifacts are in fact flawed while appearing to represent the original scene faithfully.

Exposure and Time of Day

No panoramas were filmed over long periods of time such that the effects of changes in sunlight on panoramas could be studied. Also, no pans were categorized as having been affected by low light. Exposure played the biggest part in panorama creation for the project when the scene included flashing lights on police cars. 27 pans showing some influence from flashing police lights were created. Ten of the 57 images showing seams had flashing police lights.

Motion Blur

The motion blur artifact was observed in 66 pans. Blurring tended to occur at the middle of the pan, especially but not exclusively in fast pans. There were fast pans that did not feature any blurring, however they may have had other artifacts. Motion blur at the center of the image could be related to relatively smaller image overlaps at the center of the panning motion as compared to the edges.

Rolling Shutter

23 pans exhibited artifacts attributed to rolling shutter. These artifacts typically appeared as misaligned vertical objects like poles. These artifacts occurred in otherwise coherent pans; however they sometimes accompanied other artifacts such as character deformation. The misalignments frequently occurred with objects that were close to the camera.

Stitching Artifacts

Misalignment

A significant number of pans exhibited misalignment, with 50 in all. Six were minor, 22 were moderate, and 22 were severe. Severe misalignments tended to occur in pans that were created by Photoshop. Some pre-processing by hand alignment could have improved Photoshop's results in some cases. Minor misalignments could potentially be related to rolling shutter.

Ghosting

Ghosting was observed in thirteen pans. This artifact was associated with items such as cars and people moving while the panning video was being filmed. Ghosting could be considered an input artifact but combating it at the input stage would be unrealistic since it would involve having people stand still or closing streets so moving cars would not be filmed.

Seams

Seams were visible in 57 pans. Twelve were minor, 34 were moderate, and eleven were severe. Some seams presented as differences in color, while some showed minor displacement and appeared alongside misalignments in the same image.

Drift/Warping

Warping occurred in five pans. In its purest form the warping produced a wandering image similar to those handled by Brown and Lowe's up-vector heuristic [2]. Other warping turned out in the form of a misshapen pan having severe vertical deviations and incorrect overall width. One of the warped pans may have occurred because the cylindrical homography was applied to the pan in its rotated format.

Rotated Pan

Eight pans came out rotated 90 degrees to the original capture. Each of these was captured with the phone in a vertical orientation, however 79 other pans from videos captured in the vertical orientation did not suffer the same fate. For the most part, rotation was easily corrected by post-processing the image with a 90-degree rotation. The exception was the single warped pan IMG_0036_Stitch_ICE.PNG which appeared to have cylindrical homography applied after the rotation occurred.

Character Deformation

Figure 26. Deformed Character from IMG_0156.MOV (MS ICE Windows)

Character deformation occurred in twelve pans. The deformations ranged from slight malformations to entirely missing characters. Some character deformations occurred along with seams. Twice, the study found deformed characters in street signs. Figure 1 and Figure 26 are good examples of these subtle artifacts. Figure 26 is nearly artifact free despite the challenging scene being filmed. The “DR PEPPER” sign in the center of the image is missing one letter P and the other one is malformed. This image is evidence that artifacts can be small and barely noticeable, yet critically important to the integrity of the image. This kind of artifact could also give rise to an argument that Artificial Intelligence was involved in the creation of the image, since LLM-generated images can have trouble rendering legible text.

Curiously, both subtle artifacts having to do with missing or malformed letters occurred in a street sign with doubled letters. Figure 1 has an artifact at the location of a “EE” in “STREET”. Figure 26’s artifact is at the location of the “PP” in “PEPPER”. Thinking back to the SIFT + RANSAC method, the author wonders if the doubled characters can trick the algorithm into thinking they’re duplicates and cause it to eliminate one.

Analysis

Comparison of MS ICE and Adobe Photoshop

The hypothesis was intended to determine if artifacts were the same across different hardware and software, and no contradictory cases were found. However, each panoramic stitching software produced slightly different results from the same source video – regardless of if the device was iOS or Android-powered – with one exception. As an example, MS ICE was used to process IMG_0040.MOV on the author's Windows 11 computer and the university's Windows 11 computer. These two pans turned out identical.

Differences Between Photoshop Algorithms

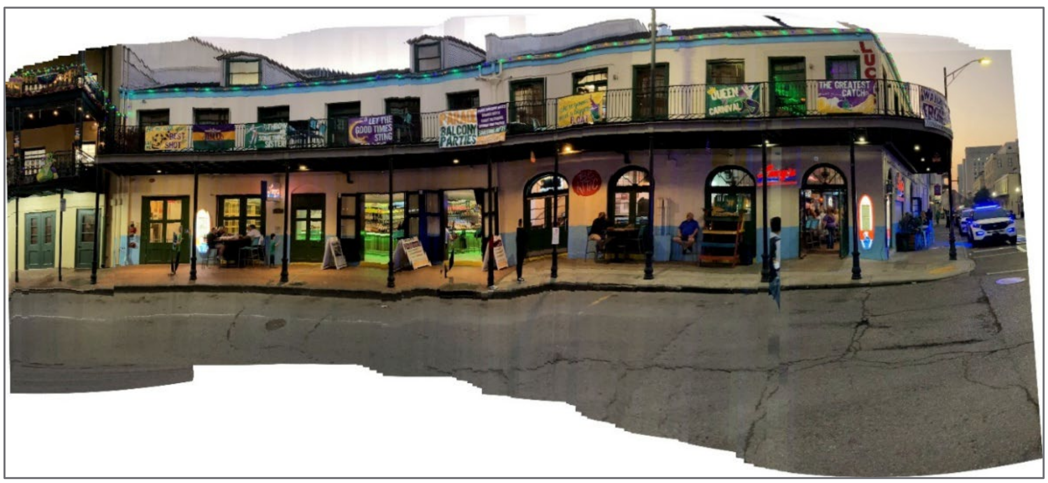


Figure 27. Parallax Video with Cylindrical Homography (Photoshop Windows)

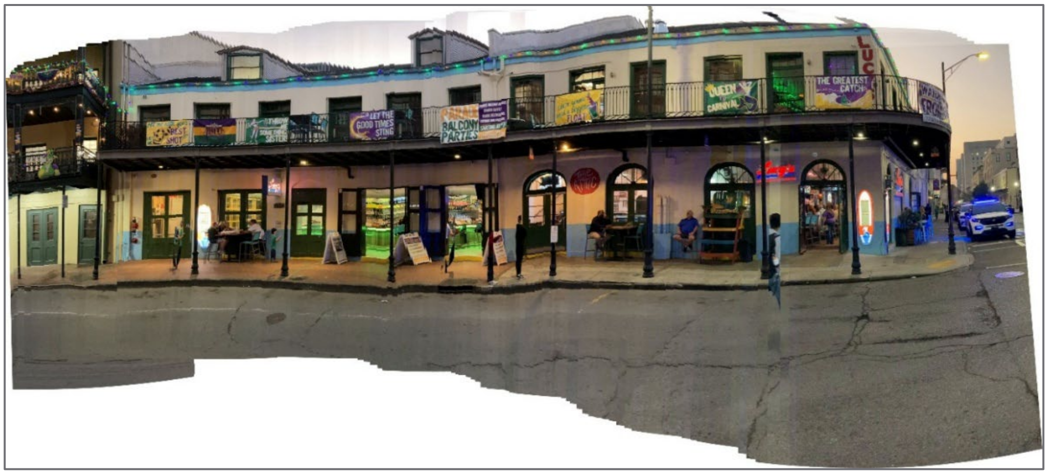


Figure 28. Parallax Video with Cylindrical Homography (Photoshop CU Windows)

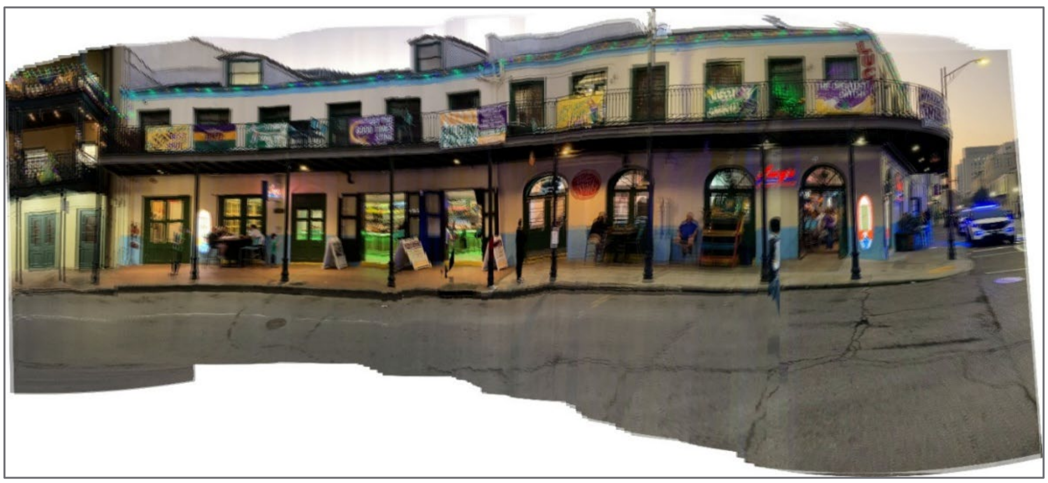


Figure 29. Photoshop Windows Comparison (Photoshop Windows CU Windows)

Figure 29 demonstrates the slight difference between the results from the author's Windows 11 computer with Photoshop 26.11 and the university's Windows 11 computer with Photoshop 26.2. The images were overlaid and one made partially transparent. The mis-registration is slight but unmistakable.

Figure 30. Parallax Video with Cylindrical Homography (Photoshop MacOS)

The MacOS version of Photoshop produced a substantially different pan than either of the Windows versions.

MS ICE Versions Identical

Figure 31. Parallax Video with Cylindrical Homography (MS ICE Windows)

Figure 32. Parallax Video with Cylindrical Homography (MS ICE CU Windows)

Figure 31 and Figure 32 demonstrate identical pans produced by the author's Windows 11 computer with MS ICE 2.0.3.0 and the university's computer with MS ICE 2.0.3.0.

Figure 27, Figure 28, Figure 30, Figure 31, and Figure 32 are all pans created from IMG_0040.MOV, taken with an Apple iPhone SE. These pans share many similarities, but the artifacts are not consistent between the Windows MS ICE, Windows Photoshop, and MacOS Photoshop versions.

Figure 13, Figure 14, and Figure 15 (above) are all pans created from the video 20260212_180643.mp4, taken with a Samsung Galaxy S22 Ultra. Like the pans created from an iOS device, inconsistencies can be found between the pans created by different software, even though they were produced from the same source video. As before, MS ICE on both Windows 11 computers produced identical files.

Photoshop's Method

Due to the stepwise workflow in Photoshop it's possible to observe the method it uses to construct panoramic images.

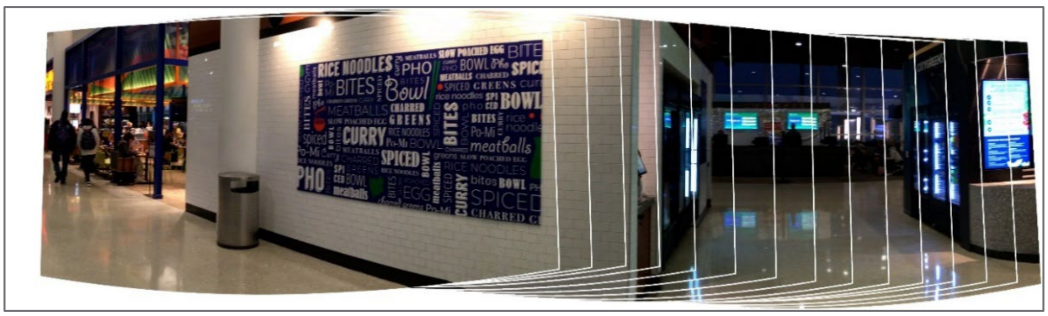


Figure 33. Photoshop Layers Demonstrating Method (Photoshop Windows)

Figure 33 is a pan with the individual layers highlighted. It shows the locations where bands would appear and helps explain why bands may trail off at an angle toward the top or bottom of a pan.

Artificial Intelligence

Since MS ICE development was terminated in 2015, it's safe to say it does not use AI to create panoramic images. However, since this study used modern versions of Photoshop, we are right to question whether AI has a place in its workflow. The Adobe documentation does not describe any AI in the "Auto-Align Images" documentation on its Help Center website. [11] Although a negative as proof is a weak argument, the fact that Adobe makes no mention of AI combined with well-documented high quality panorama generation algorithms that have existed for decades, the author finds no evidence that AI is involved in Adobe's panorama creation workflow.

Practical Implications

Practitioners must be vigilant when creating pans for use as evidence. Mitigation of some of these artifacts is possible. As in all forms of photography, preparation is crucial for producing excellent results. The scene should be as well-lit as possible and the filming technique should be slow and steady. For best results, follow the SWGDE best practices. Be aware that artifacts may be subtle, and that they could appear as if they were created with Artificial Intelligence.

When preparing to process videos into panoramas, practitioners should look for opportunities to take care of pre-stitching artifacts ahead of time. For example, consider removing barrel/pincushion distortion beforehand. Also, check the exposure of the images; if there are ways to improve the exposure while maintaining the integrity of the images, do this step before stitching. Be aware that multiple types of artifacts may show up in a single pan, and the order of operations could be important.

V. CONCLUSIONS

This preliminary study explored the artifacts created when cell phone videos are processed into panoramas. The hypothesis was, "Artifacts in panoramic images that are created through the process of stitching together consecutive frames from cell phone videos are consistent regardless of what cell phone, stitching software, or processing hardware is used." No contradictory evidence was found. This means that artifacts—effectively errors—may occur in any pan created with this workflow regardless of the cell phone or processing software used.

The process of creating pans from source data was documented for both Adobe Photoshop and Microsoft Image Composite Editor. The results from the software were compared and discussed relative to each other and to the hypothesis. Photoshop's method for creating panoramic images was covered briefly as a way of understanding the algorithm it uses.

Artifacts fell into two broad categories. They were either classified as Input Artifacts that were influenced by the device attributes and the filming strategy when data were collected, or Stitching Artifacts that were a result of the panorama assembly process encoded in the software used.

Input Artifacts were divided into subcategories Frame Rate, Barrel Distortion, Exposure and Time of Day, Motion Blur, and Rolling Shutter. Stitching Artifacts were divided into subcategories Misalignment, Ghosting, Seams, Drift/Warping, and Character Deformation. Each artifact was defined and described through examples. Discussions explored how these artifacts could be mitigated and how the input artifacts may have influenced the stitching artifacts.

One unique observation was that pans containing street signs with doubled characters were observed to have artifacts of swallowing or deforming one of the pair while leaving the other untouched.

Future Research

Input Variables

Recording Devices and Frame Rates

This study used cell phone cameras; however, many other recording devices exist in the market. Future research could evaluate the same workflow using these other devices, including DSLR cameras, GoPro systems, and body-worn cameras. Also, the effect of differing frame rates on panorama generation and artifact formation warrants systematic investigation.

In-Device Panoramas

The present study relied exclusively on PC-based panorama software. Further research could examine artifacts created by the cameras' own panorama generation algorithms compared with those produced by external software.

Artifacts in h.264 vs h.265 Compression

Future work could investigate differences in artifacts between videos encoded using H.264 and H.265 compression standards.

Processing Variables

Software Configuration and Tuning

Microsoft ICE (MS ICE) was operated in video-to-panorama mode. Greater control over output could be achieved by first extracting individual frames, as performed for select Photoshop inputs, and subsequently generating panoramas using the MS ICE image-to-panorama workflow. This would enable direct comparison between panoramas from video streams and panoramas made from images.

Within Adobe Photoshop, the geometric distortion and vignette removal settings were not used. Comparing panoramas generated with and without these corrections would be valuable.

The operating systems and software environments used in this study were simply those available to the author and were not standardized. Future studies could control system configuration and software versions to isolate processing-related variability.

Artifact Mitigation

This study briefly evaluated potential artifact mitigation techniques. A more rigorous investigation should compare panoramas generated with and without mitigation, including barrel distortion correction, motion blur reduction, and exposure normalization.

The flashing emergency vehicle lights produced an unusual exposure condition. Given the relevance to body-worn camera applications, further study of panorama generation under dynamic lighting conditions is recommended.

Post-processing within Photoshop offers additional opportunities for artifact reduction. Features such as seam blending and banding correction could be evaluated for their effectiveness.

Double Character Artifacts

Character deformation artifacts observed in this study were associated with repeated characters (e.g., “EE” in “STREET”). Future research could investigate how stitching algorithms handle repetitive visual elements within a scene.

Control Points

In aerial orthomosaics, accuracy is enhanced using ground control points. A related line of inquiry would examine using control points for aligning panoramas in a similar fashion.

Usage Variables

Panoramic Images in Legal Contexts

This study touched on the use of pans in the courtroom. Future research could analyze case law to determine pans' admissibility, with particular attention to Federal Rule of Evidence 702. Establishing error rates associated with specific workflows would bolster admissibility.

AI-Based Panorama Generation

Advancements in artificial intelligence may significantly alter the way panoramas are created. Emerging methods may synthesize panoramic images using source images as prompts, potentially without preserving any original pixel data. Future studies could evaluate these developments and their implications for accuracy and evidentiary reliability.

In-Camera AI Processing

Modern mobile devices increasingly incorporate automated image enhancement through AI. Future research could determine the extent such processing is applied without first asking the user, and assess its impact on both the panoramas created and the artifacts observed.

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APPENDIX

ExtractFrames.ps1 – this script was built to extract every 10^{th} frame from a movie file. It was needed in some cases where Photoshop couldn't process .MOV files. Where it was used, the pan filename contains "_every10".

```
$Dir = (Get-Location).Path
Write-Host "Working directory: $Dir"
$VideoExtensions = @(".mp4",".mov",".avi",".mkv",".wmv",".m4v")
$videos = Get-ChildItem -Path $Dir -File | Where-Object {
    $VideoExtensions -contains $_.Extension.ToLower()
}
Write-Host ("Found {0} video file(s)." -f $videos.Count)
foreach ($v in $videos) {
    $baseName = $v.BaseName
    $fullPath = $v.FullName
    $movieOutputDir = Join-Path $v.DirectoryName $baseName
    New-Item -ItemType Directory -Force -Path $movieOutputDir | Out-Null
    $outPattern = Join-Path $movieOutputDir ("{0}_{1}.png" -f $baseName, "%06d")
    Write-Host "Processing $($v.Name) -> $movieOutputDir"
    # Write-Host "Output pattern: $outPattern"   # uncomment if you want to verify
    ffmpeg -hide_banner -loglevel error `
        -i "$fullPath" `
        -vf "select='not(mod(n\,10))'" `
        -vsync vfr `
        "$outPattern"
}
```