https://doi.org/10.2352/ISSN.2470-1173.2021.6.IRIACV-333

Experiments and Analysis for Measuring Mechanical Motion with Event Cameras

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Abstract

Event cameras—which detect pixelized, spatiotemporal changes asynchronously as opposed to frame-based triggered cameras—are commercially available and the topic of considerable research recently for computer vision and robotics applications. We hypothesize that these novel devices can be of utility in understanding mechanical motion by performing functions similar to high speed cameras, but with reduced bandwidth and simpler processing. To test this hypothesis, we applied multiple measurement modalities to a simple high-speed mechanical tool, including accelerometer, acoustic, and event-camera images. We also explore the utility of onboard inertial measurement units which are often integrated into these devices. Our analysis shows that these measurements are possible and consistent across modalities, possibly leading to novel new architectures for image and sensor based measurements.

Keywords: *Novel vision systems, Event camera, Mechanical measurements, Scene understanding*

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Introduction

Multiple methods exist for measuring mechanical motion, including contact methods, such as accelerometers, and noncontact methods based on lasers or imagery. These methods are widely used in machine diagnostics and are important for maintaining quality control as well as for other machine dynamics applications. We explore the utility of event cameras for noncontact measurements, possibly in harsh environments, through a simple set of experiments.

Detection of Frequency of Rotating Cutter

Motivation

We performed a sequence of three experiments to determine the feasibility of event cameras for mechanical measurements. We compared the event camera data and analysis to direct methods to compare and contrast their effectiveness. In all cases, we used a data acquisition phase followed by an analysis phase to perform the proof-of-principle measurements. Note, one important benefit of event cameras are their ability to focus attention only on pixels with some level of brightness changes, allowing for higher temporal resolution than a conventional frame-by-frame camera, but they still allow a potential wide angle view of the object under test, which could allow capturing of more dynamic and spatially distributed motions for more complex devices. Ultimately, we would like to use real-time processing for objects instead of data collection followed by analysis. For the purposes of this work, we sought to establish the proof-of-concept; therefore, we defer real-time processing (including potential benefits of inline "edge" processing and interpretation) for future work. We also sought to establish the proof-of-concept with simple laboratory instruments and test articles to bound the problem.

Method

A variable-speed mechanical cutter, rotating up to 35,000 RPM (approximately 583 Hz) was used as the test device. The device was chosen for its availability and its high-speed which we hoped would test the event camera capabilities. The mechanical cutter was adjustable, albeit with limited precision, and therefore we hoped we could adjust the cutter as needed to understand the maximum frequencies obtained by the different methods available. The cutter is shown in Figure 1. The device frequency was measured at different speed settings using acoustic methods (a smartphone recorder), an accelerometer, and a pair of commercially available event cameras that included integrated IMUs. Experiments were performed with the cutter and camera mechanically coupled and isolated, and in natural and artificial light (the latter was used because of sensitivity of the event camera to fluctuations in lighting sources). We compared the simple time series spectra from the first two methods with the event camera captured events, which were spatially processed to estimate the fundamental motion of the cutter. We performed the estimation of motion using simple short-term fast Fourier transform methods, including temporal integration. We also performed measurements using the event camera's inertial measurement units (IMUs), which were extracted and available in the standard data stream. A final experiment focused on correction for motion by IMU and was conducted by placing the event camera on a vibration table and imaging a fixed target. Note, in all event camera work, we used standard software available from the vendors to acquire the event camera data; we recognize that more sophisticated software may be desired, but as stated earlier, we seek to keep the scope of the work to establishing proof-of-concept.

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Figure 1 Cutter unit used for experiments. The cutter is adjustable with speeds up to 35,000 RPM based on the description of the unit. We used a battery-powered device. A mounted corner target is visible near the middle of the device, just to the right of the blue switch and almost in the exact center of the image.

Procedure

We obtained three different commercially available state-of-the-art event cameras from Inivation® (the DAVIS 346, DVXplorer, and DVS 240) [1]. The DAVIS 346 features a 346 × 260 pixel dynamic vision sensor (DVS) with 18.5 µm pixel size. The unit features 12 mega-events per second (MEvents/s) temporal resolution and 120 dB dynamic range. The DAVIS 346 also provides a gray level standard camera frame image at up to 40 frames per second, also at 346 × 260 pixels and spatially aligned with the DVS. The DVS 240 is similar but with a smaller number of pixels (240 × 180). The DVS sensor is also rated at 120 dB dynamic range. The DVS 240 also features a conventional frame-based camera image but it is provided "for calibration only," meaning the frame is not temporally aligned with the event data stream. We used a variable focal length with both units, estimated to be at 10–12 mm. The DVXplorer unit features a 640 × 480 pixel sensor, with dynamic range between 90 and 110 dB depending on the overall scene contrast. The device features much higher event throughput, rated at 165 MEvents/s. However, the DVXplorer does not include a conventional frame camera output although it is possible to reconstruct a comparable image using the software provided with the devices. All three units include a six-axis IMU with temporal sampling at various rates for motion measurements.

In all cases, the data stream is stored in ".aedat4" (Address Event DATa) [2] format, which uses Google Flatbuffers to serialize data.

As described earlier, we used a low-cost, low-power variable-speed battery operated mechanical cutter as the test device. Although precision speed control was not available with the cutter, we compared other measurement modalities (acoustic and vibration) to establish understanding of the capabilities of the event cameras. We mounted a corner pattern on the device to provide better understanding of the signals obtained. Three sets of experiments were performed: 1) calculation of speed by comparing the results using the video function on a smartphone to capture an audio track for processing, a set of accelerometers attached to the cutter, and the IMU on the event camera, 2) calculation of time series spectra vs event camera captured events spatially processed to estimate the motion of the cutter, and 3) calculation of camera IMU motion using a laboratory shaker. Each experiment is described in the following sections.

First Experiment

The first experiment included three different measuring techniques for acquiring the frequency of the cutter: 1) accelerometers mounted to the cutter, 2) a smartphone with video, and 3) an event camera mechanically coupled with the cutter to leverage the onboard IMU of the event camera. We collected all data with a Linux laptop running a variant of Ubuntu for data acquisition and/or processing of all technologies.

The first test consisted of running the cutter at near full speed and measuring the frequency of the rotation. Two PCB Piezotronics Inc. J352C68 accelerometers with calibrations of approximately 100 mV/g were mounted on the cutter. The accelerometers were attached to a PCB Digital ICP® 485B39 signal conditioner and input into the computer via a USB port. Figure 2*Figure 2* shows the experimental setup.

Figure 2 Cutter with accelerometers attached to signal conditioner. The event camera is shown on the bench to the left of the cutter wheel, which also has a corner target mounted on the cutting wheel. In the first experiment, we used the IMU of the event camera to estimate the cutter speed.

The "arecord" command was used to acquire the data, which was processed using functions in Matlab®. The peak frequency of 542 Hz was computed from the accelerometer with results shown in Figure 3*Figure 3*. Both accelerometers gave essentially identical results.

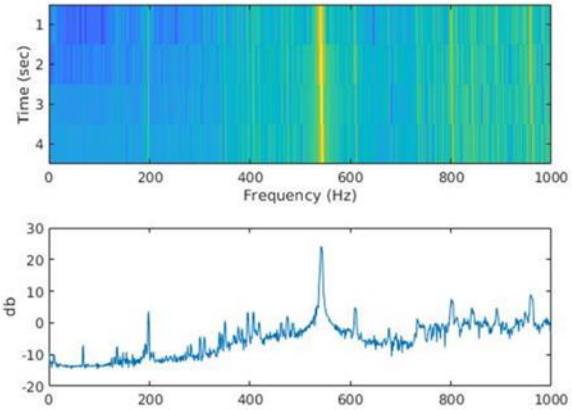

Figure 3 Accelerometer peak frequency of 542 Hz. Above, spectrogram with time on the y axis, at 1 s resolution obtained with Hamming window with no redundancy. The image is rendered with logarithmic scaling of intensity values. Below, integrated signal from top spectrogram.

A smartphone was used to record a video (.MOV) file while the cutter was rotating. The phone was located approximately 1 ft away from the cutter. The resulting file audio was manipulated in Matlab to generate fast Fourier transform (FFT) results for comparison. The results show a peak frequency of 542 Hz, which agrees with the accelerometer data. The FFT results are shown in Figure 4.

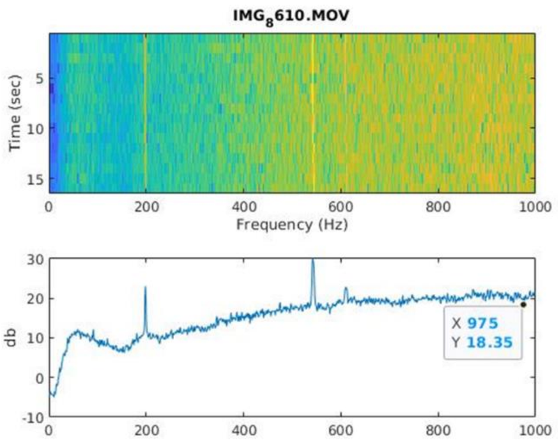

Figure 4 Smartphone video results show peak frequency of 542 Hz.

For this test the Inivation® DAVIS 346 event camera was used. The experimental setup is shown in Figure 5.*Figure 5*

Figure 5 Experimental setup of event camera.

Data from the event camera is stored in ".aedat4" format. The data was translated from ".aedat4" to ".mat" (Matlab) format using a Python [3] program. Matlab was used to find the peak frequency using the FFT. The results that are shown in Figure 6. The results show a frequency of 463 Hz, which is lower than the results from the other tests (542 Hz). After examination, we determined the sample rate of the DAVIS 346 IMU is not user definable, at least with the version of the software and firmware we used, and appears to be roughly 1,000 samples/s. This suggests that care must be taken to avoid mechanical coupling of the event camera for high speed measurements. Another alternative approach would be accounting for the limited sample rate when comparing event measurements with IMU measurements with this version of the event camera.

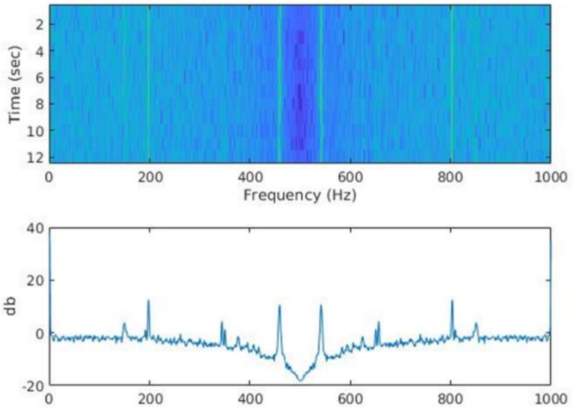

Figure 6 DAVIS 346 IMU shows frequency of 463 Hz.

The cutter was then adjusted to a lower speed and tested with each technology. The accelerometer showed a peak frequency of 387 Hz as shown in Figure 7.

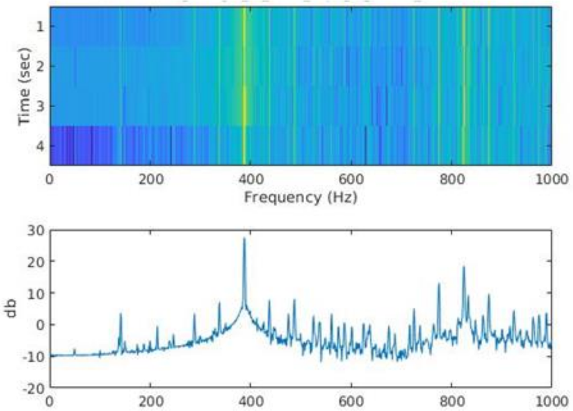

Figure 7 Accelerometers attached to cutter show frequency of 387 Hz

The smartphone peak frequency matched the frequency of the accelerometer. The results are shown in Figure 8.

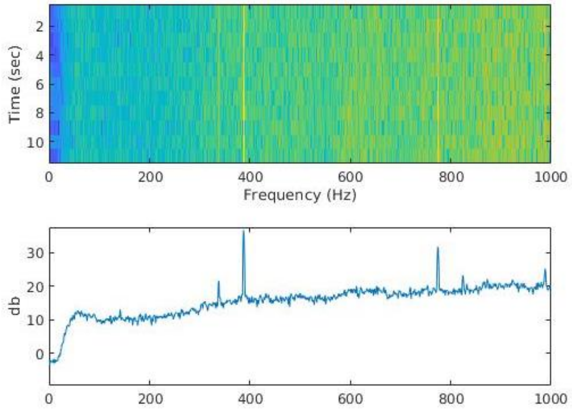

Figure 8 Smartphone shows peak frequency of 387 Hz.

The DAVIS 346 camera also showed a peak frequency of 387 Hz as shown in Figure 9. The IMU sample rate was high enough to detect 387 Hz.

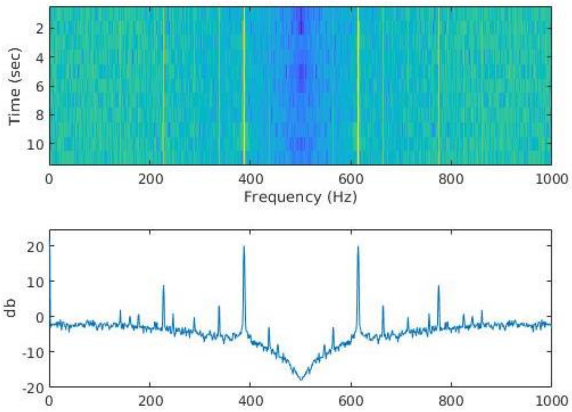

Figure 9 DAVIS 346 showed peak frequency of 387 Hz

Because of the limitations of the DAVIS 346, we next tested a more advanced event camera, the Inivation® DVXplorer, which includes additional user settings; the onboard accelerometer sample rate is user-definable up to 1600 Hz. An additional test was performed with the cutter with measurements performed using the accelerometer, smartphone, and DVXplorer with a 1,600 Hz sample rate. The accelerometer showed a peak frequency of 438 Hz as shown in Figure 10.

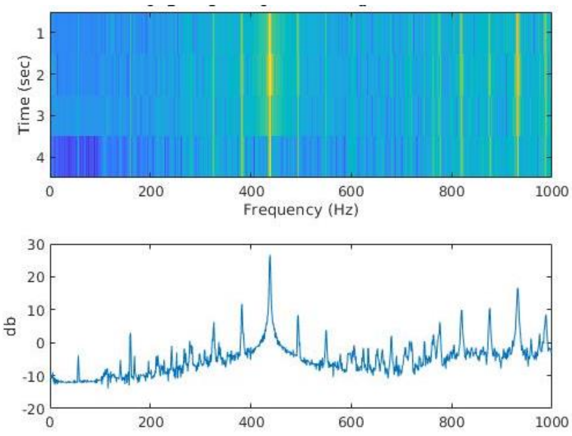

Figure 10 Accelerometer results show peak frequency of 438 Hz.

Again, the smartphone video frequency showed a peak frequency of 438 Hz as well and is shown in Figure 11.

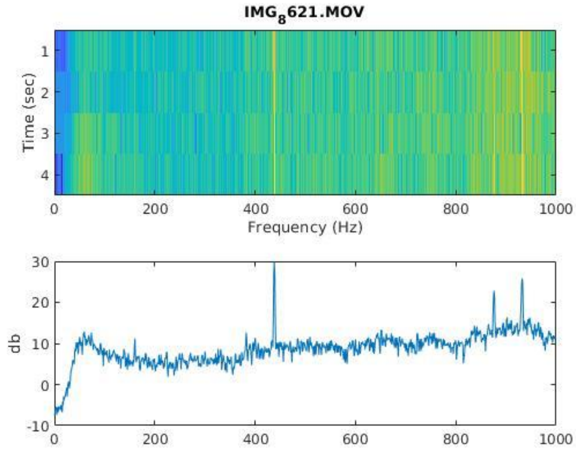

Figure 11 Smartphone shows peak frequency of 438 Hz.

The DVXplorer results also show a peak frequency of 437 Hz as shown in Figure 12.

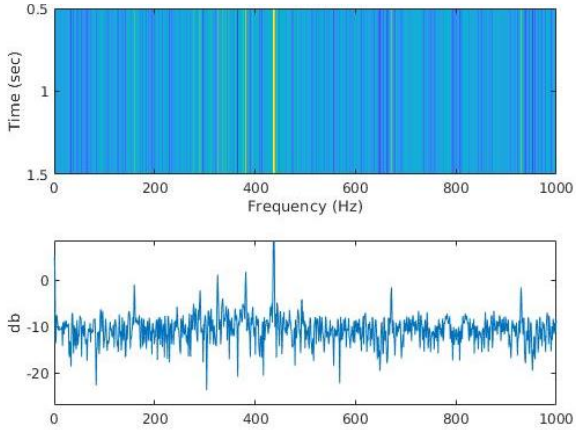

Figure 12 DVXplorer shows frequency of 437 Hz.

The results show a difference between the smartphone/accelerometer and the camera of 1 Hz. The camera accelerometer sample rate was set at 1,600 Hz. When calculating the sample rate based on the accelerometer start and end timestamps and the number of events, the sample rate was calculated at 1,595 samples/s.

Second Experiment

The second experiment compared the time series spectra and the DVXplorer event camera events measured spatially. Events were recorded using artificial light as well as natural light. Results showed that natural light provided better results while using the event camera, so natural light results will be presented. We believe this may be due to the either temporal interference from the artificial light sources, which were not controlled, or simply due to illumination levels overall. Initially, the camera was positioned within 2 in. of the rotating wheel of the cutter. The close distance caused the vendor-provided software to miss events due to the large number of events as the cutter was rotating. The camera was moved to approximately 1 ft from the event camera. The setup showing the cutter with the disc and the event camera is shown in Figure 13.

Figure 13 Cutter with disc and event camera setup.

Accelerometers were mounted on the cutter similar to the first experiment. The peak frequency from the first cutter speed setting was calculated to be 182 Hz and is shown in Figure 14.

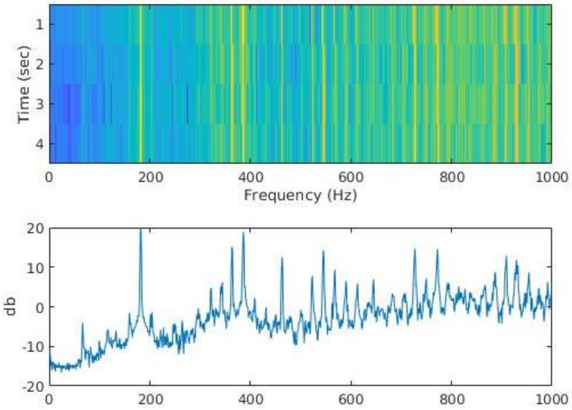

Figure 14 Accelerometer peak frequency of 182 Hz.

The output format of the vendor supplied software ".aedat4" was translated to a Matlab ".mat" file using the Python software discussed previously. We wrote additional analysis software in Matlab to focus on a small spatial region to count events and estimate the cutter frequency. Each event is coded as positive or negative based on the change in pixel values. Our analysis selected a spatial region with high activity and monitored the positive and negative events as the cutter wheel moved. The transition between event positives and negatives were captured. The event occurrences were accumulated and used to estimate the frequency which was then assumed to be identical to the cutter frequency. Our analysis estimated the frequency as 182 Hz.

Tests were also performed at 275, 364, 446, and 523 Hz. The software used for counting events accurately counted the 275 and 364 Hz events, but the accuracy started to degrade at 446 Hz. The counting software counted events of only 435 for the 446 Hz peak frequency. The counting events detected less than half of the rotations at 523 Hz. We suspect events were missed as the cutter rotated at higher frequencies. Note, there is a trade-off between the event camera maximum events allowed, the spatial region of interest, and event thresholds. At first glance, the frequency of interest should be well below the event bandwidth of the camera. However, when events occur across multiple pixels, the event camera bandwidth is shared across multiple pixels, and consequently the actual measurement speed is reduced, presumably proportionally to the inspection area. As an example, in Figure 15 we show the trade-off between the inspection area and the maximum events detected based on the bandwidth of 12 MEvents/s. We assume an intensity change here is both positive and negative, which reduces the detectable frequency by a factor of 2.

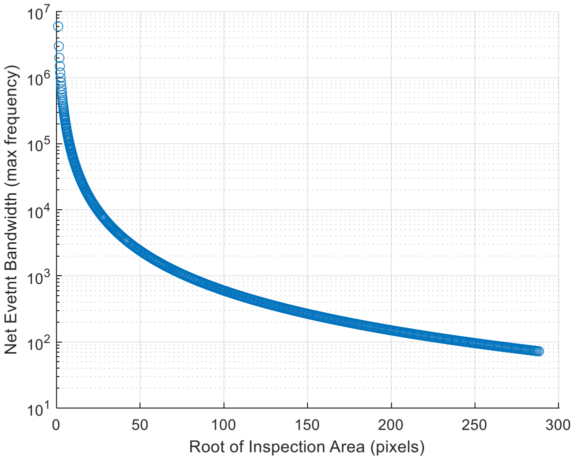

Figure 15 Estimated trade-off between inspection area and events (assumed to be proportional to maximum frequency detected).

Third Experiment

We used two event cameras (the DVS240 and the DVXplorer) for this test. We attached the cameras to a Modal Shop Inc. model 2075 E shaker, which was used for this test. The shaker setup is illustrated in Figure 16.

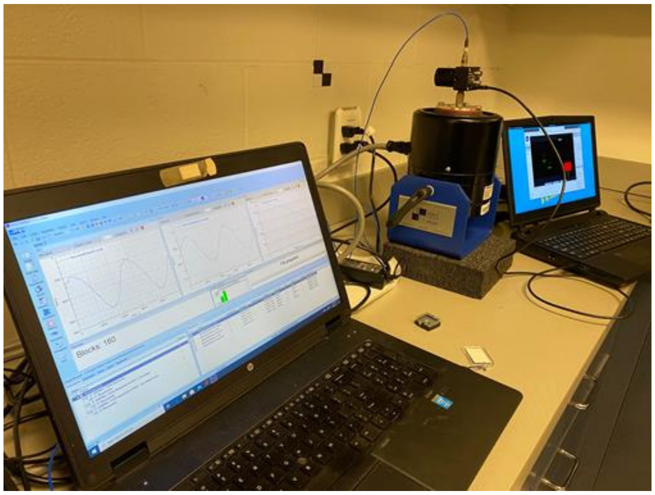

Figure 16 Shaker experimental setup.

A closer view of the shaker with the vendor-supplied event camera software is given in Figure 17.

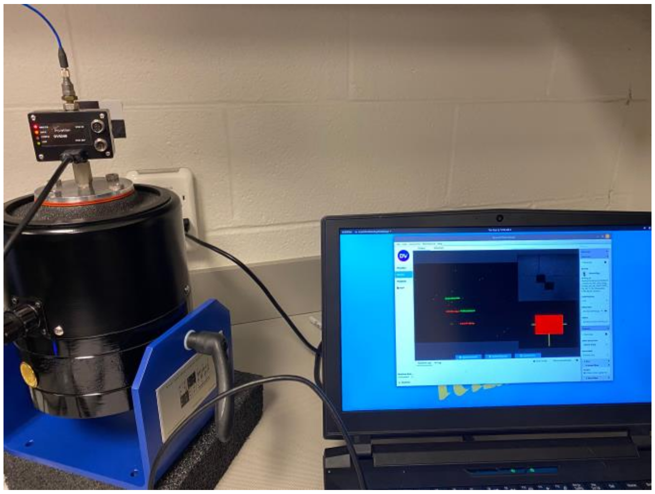

Figure 17 Shaker and vendor-supplied camera software.

The shaker was set up to shake the camera from 2 to 7 Hz. A four-square checkerboard was mounted on the wall with the camera pointed at the checkerboard. The camera IMUs were used to measure the vibration of the camera. The frequency results from the DVXplorer camera accelerometer is given in Figure 18.

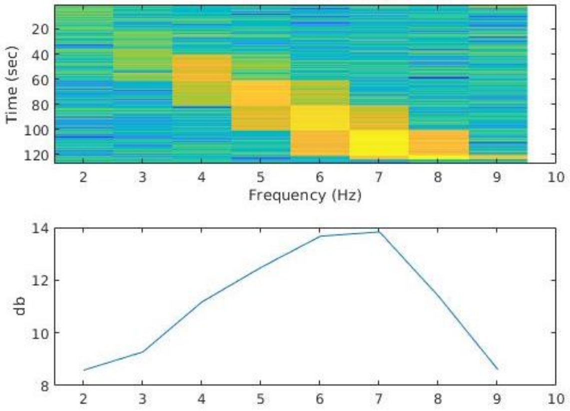

Figure 18 DVXplorer event camera accelerometer IMU frequency.

The frequencies detected using the accelerometer shows 2–8 Hz. The motion of the shaker was also computed by focusing on a small special region, counting the events, and averaging them over a 3 s time period using software programmed in Matlab. The results of the counted events are given in Figure 19.

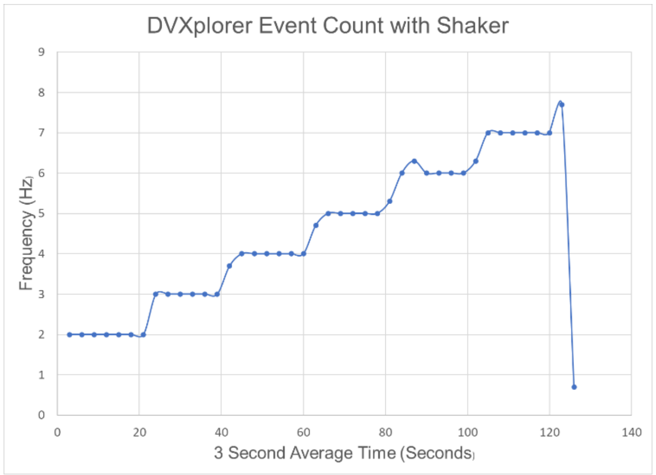

Figure 19 DVXplorer event camera computed shaker frequencies

The same test was performed with the Inivation® DVS 240 camera. The results are similar and are given in Figure 20. The motion of the shaker determined using the software to count the events is given in Figure 21.

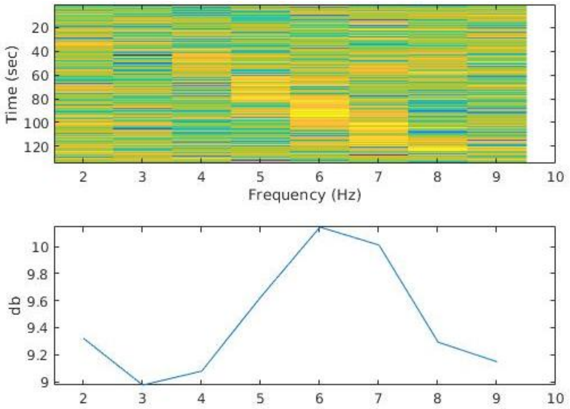

Figure 20 DVS 240 event camera accelerometer IMU frequency.

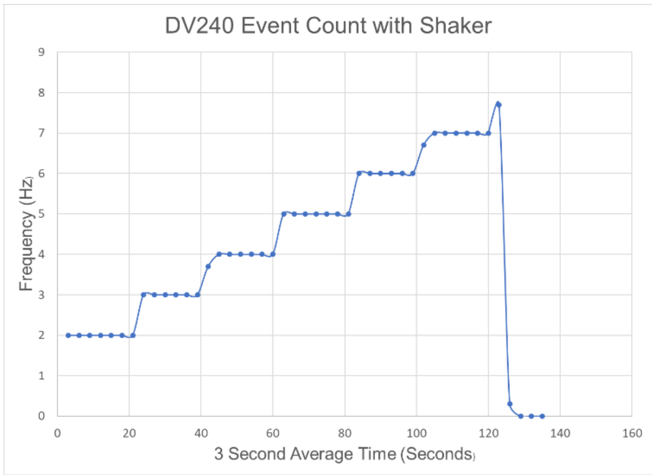

Figure 21 DVXplorer event camera computed shaker frequencies.

The 8 Hz data is believed to be the data detected as the shaker was ending its shaking sequence.

Conclusions

This work is, to our knowledge, the first time event cameras have been combined with multiple measurement modes to rapidly moving objects to determine fundamental frequencies of motion and vibration. Although our work is a first step and is highly laboratory based, we believe the work is significant because we hypothesize that event cameras can offer improved methods for these measurements with reduced bandwidth and simplicity. Our explorations revealed some strengths and weaknesses of the method, in particular the high sensitivity requires tight control over parameters, such as detection area to stay within the camera bandwidth. We also found some limitations to motion compensation depending on the specifications of the cameras utilized.

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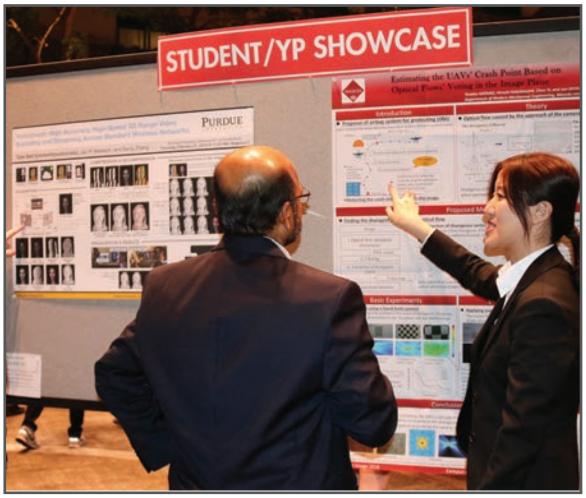

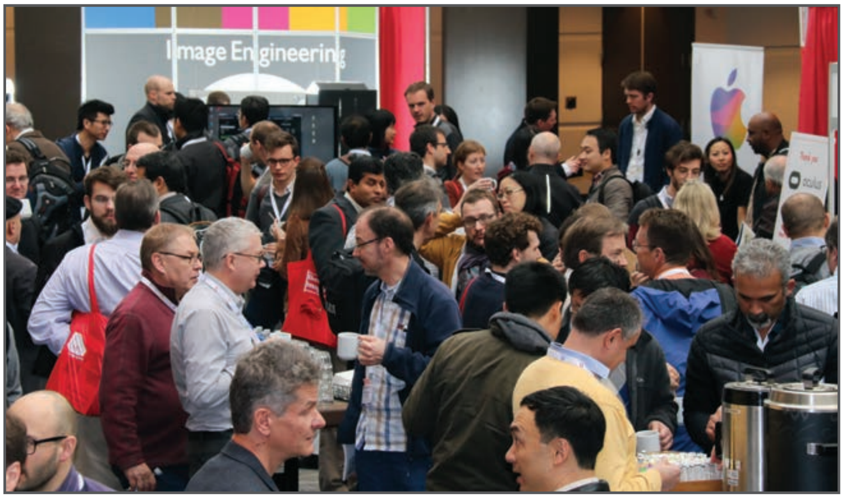

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