GOOGLE'S RANDOM VIBRATION TESTING METHODOLOGY, OPEN TEST DATA

Part 3.1: 3D DISPLACEMENT DATA OF A MACHINE DURING RACK LEVEL VIBRATION TESTING
REVISION A

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3D Displacement Data of Lenovo ThinkSystem SR650 V2 During Rack Level Transportation Vibration

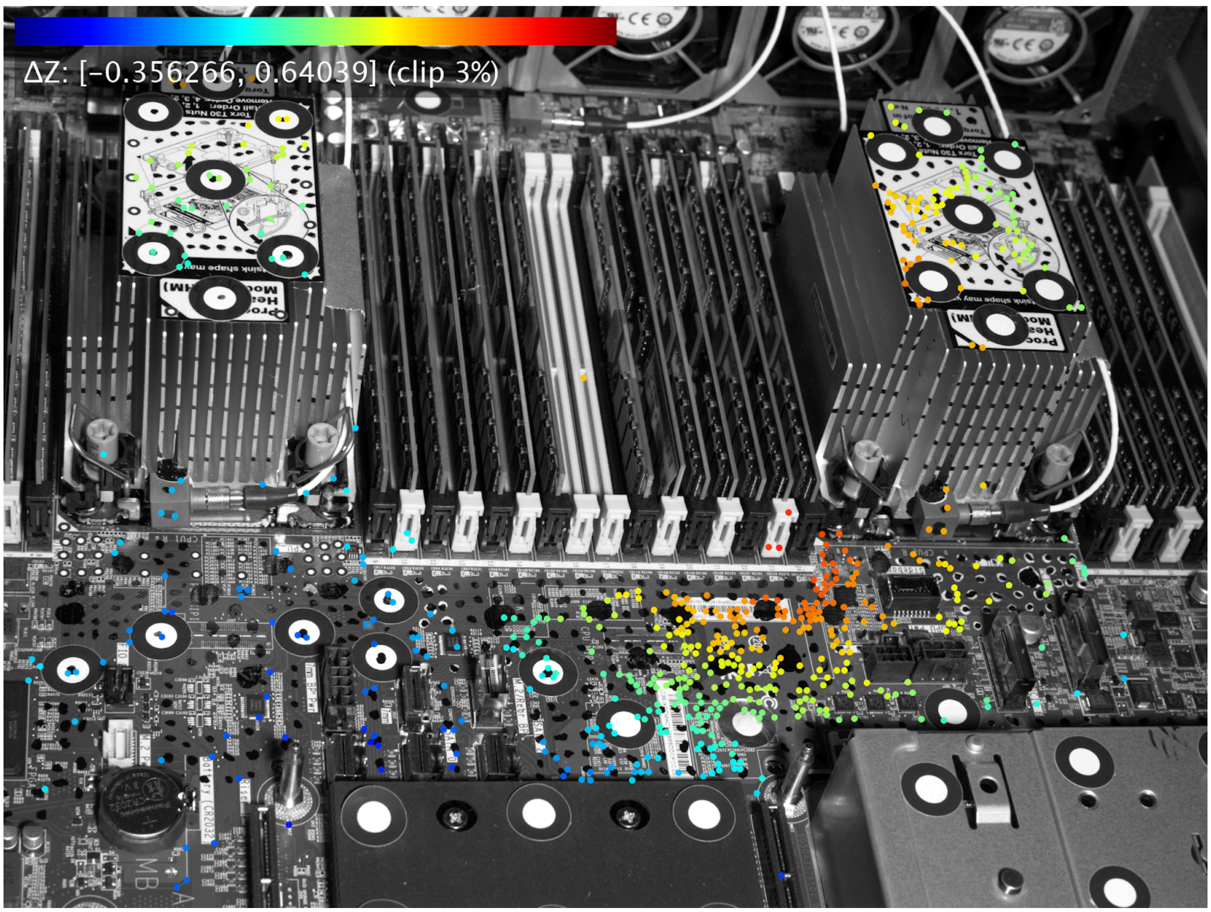


Figure 1.

3D Displacement Data Sharing Track

Since the first paper, we spent a lot of time describing various measurements and testing capabilities used during Google's vibration testing of data center hardware. We went over acceleration, strain, pressure, and 3D displacement measurements, and how they can be used to analyze a machine's dynamic behavior in different scenarios.

We are at a point in the project where actual data will be more meaningful than methods and techniques. **Methodology describes the overall architecture in broad strokes. Details of equipment enable methods and capabilities, and need to be provided up front. But actual data ground everything to reality, and feed into specific products to help understand behavior, assess risks, and improve design if necessary.**

Moving forward, we will spend a lot of time looking at 3D displacement and deformation data because there is a huge vacuum of such data in the testing world, which describes a system's **"Macro Dynamic Behavior"** during shock and vibration. There are numerous publication of accelerometer and strain data of PCB and chips, but it is difficult to visualize a complex machine's dynamic behavior, particularly when installed inside a populated rack:

1. How do the whole board displaced and deformed during specific sine vibration, random vibration, and shock scenario?
2. How does the overall test sample behave inside the rack?
3. What unexpected behaviors are missed by the classical mass-spring system that everyone assumes?
4. What can we learn from 3D data that cannot easily be described with traditional acceleration, strain, and pressure measurements?

We will find out as we deep dive into the rack and server test sample used previously in "PART 1.2: SINE VIBRATION OF A MACHINE INSIDE A RACK".

<u>Typical rack level shock and vibration test profiles at Google</u>

Google's shock and vibration test profiles are straight forward, and should be familiar with most readers who work in this field:

Google's Typical Shock and Vibration Test Suite	
1.	Sine Sweep, 0.2G, 5Hz to 500Hz, 1 oct/min
2.	ASTM d4169-14 Truck Vibration, Assurance Level 2, 2 Hours
3.	ASTM d4169-14 Air Vibration, Assurance Level 2, 2 Hours
4.	ASTM d4169-14 Forklift Truck Handling Drop, Assurance Level 2, 4 corners, 4 edges, 1 flat bottom surface

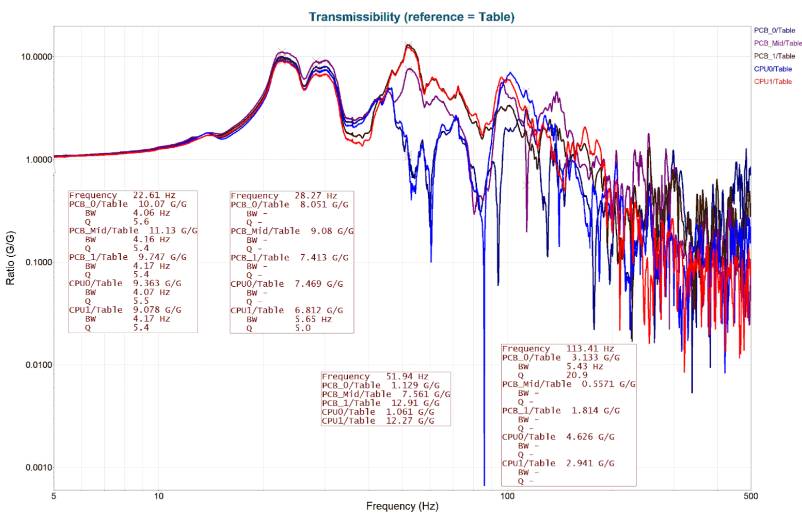
Sinesweep provide some basic information about the test sample's resonance frequency, **Truck and Air Vibration** stress any systems and components with design flaws missed during early phase of design (lack of sufficient constraints, insufficient fastener sizes, flimsy sheet metal parts), and the **6 inches Free Fall Shock Impact** at the end provide a level of stress most server racks will see during typical transportation and handling.

Historically, accelerometers are used at obvious locations during testing (heatsinks, middle of PCBA, critical components and interconnects, etc) and their values are shown in the final report, but it is difficult to understand what actually happened during testing. Racks and machines with complex structures are too complicated to explain with simple acceleration measurements. Let's look at what 3D displacement data can tell us that traditional accelerometers can't.

<u>3D displacement and deformation data during rack level vibration testing</u>

Recall the acceleration transmissibility plot shown in Part 1.2:

Lenovo SR650 V2 Rack Level Acceleration Transmissibility Profile, Rack Vibration



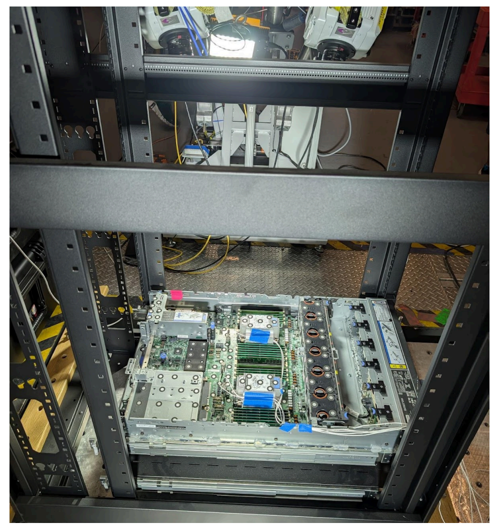


Figure 2.

The same rack and server was brought back for 3D displacement measurement. Every single test setup is slightly different. PCB samples fastened to aluminum fixtures, for example, are a lot more repeatable and generate much more consistent results. In this scenario, we weren't able to achieve the exact same resonance frequency as before. Resonance frequencies measured during the second round, 24Hz, 33Hz, 49Hz, 107Hz, are slightly different from frequencies during the first round, 22.61Hz, 28.27Hz, 51.94Hz, and 113.41Hz.

Sinesweep helps us to identify major resonance frequencies of the system, and understand what happens during random vibration when a whole range of frequencies are excited. But it is also very easy for accelerometer data to generate inconsistent results. 3D displacement measurements add an extra layer so that later, we can use them to decipher how a system behaves during ASTM random vibration profiles.

Integrating 3D Displacement Measurement into Traditional Vibration Testing Workflow

Figure 3.

Lenovo SR650 V2 High Speed Camera Video During Rack Level Test

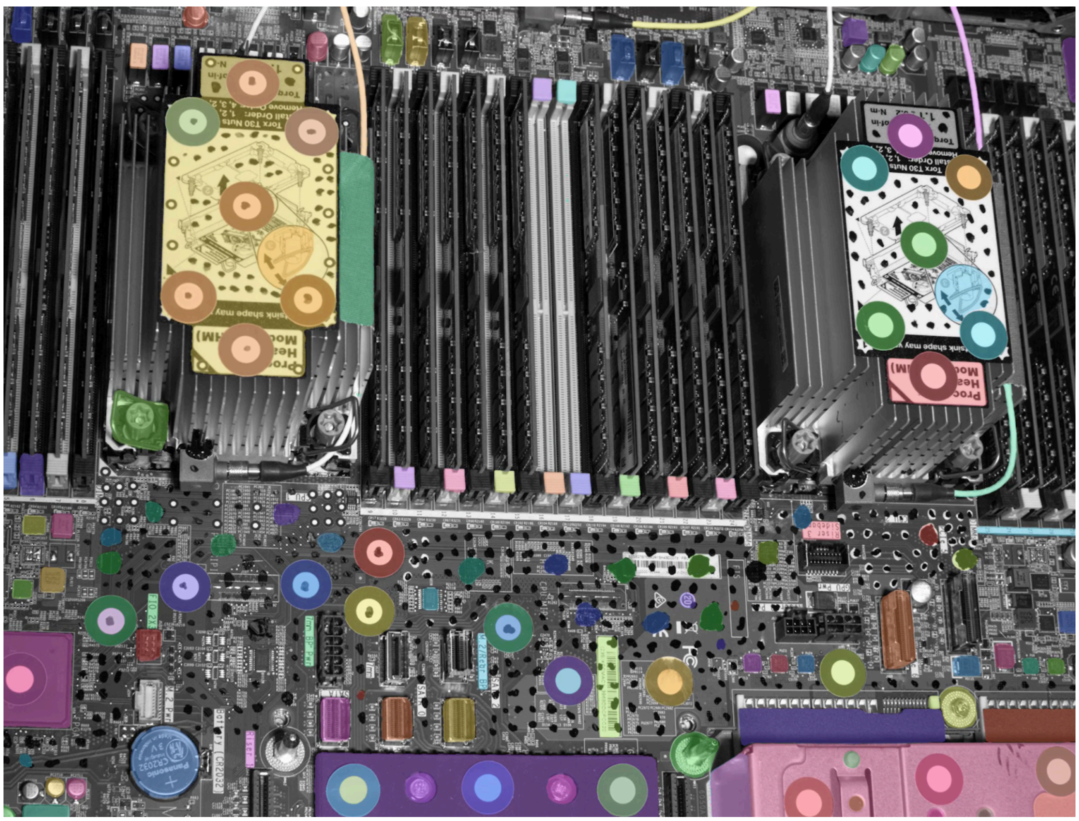


Figure 4.

Using open sourced vision based AI such as Meta's SAM2 (Segmentation Anything Model 2), objects and features can be easily identified so that specific data can be easily extracted during analysis, when specific information is needed. We will focus on the overall distribution and concentration of displacement at the moment, but there will be times when product designers and reliability engineers only require data of critical components such as heatsinks and specific areas of PCB.

The data captured are real time displacements (in mm) of critical points in three dimensions, ones identified by test operators or computer vision models. The 3D points are plotted over time, and a color mapping is applied (based on relative displacement in the vertical direction) to help understand shapes and distribution. Deformation only occurs when the PCB is moving relative to the shaker table’s displacement. That’s why the color mapping is based on relative displacement rather than absolute displacement.

24Hz, 2.0G Sine Vibration, Rack Level, 4000 Frames Per Second

Video link: https://www.youtube.com/watch?v=wu03SmzM5ew

The 2G amplitude was chosen through trial and error to make 3D displacements easy to detect. Such amplitudes are well within the typical range of G level seen in field vibration data.

These 3D displacement plots really need to be seen in high definition videos, so I encourage everyone to download them from the link above. For now, I will describe the motion with critical frames. Green represents zero relative displacement (in mm). Up to -3mm (downward, in blue) and +3mm (upward, in red) relative displacement are seen as the video advances forward. Upward relative displacements are more distributed on the left side, while downward ones more on the right.

These distributions aren't evenly symmetric around the middle. PCBs and server racks don't behave perfectly in the real world, particularly when subjected to shock and vibration.

Lenovo SR650 V2 3D Displacement During Rack Level Test, 24Hz, Frame 0, +/- 3mm

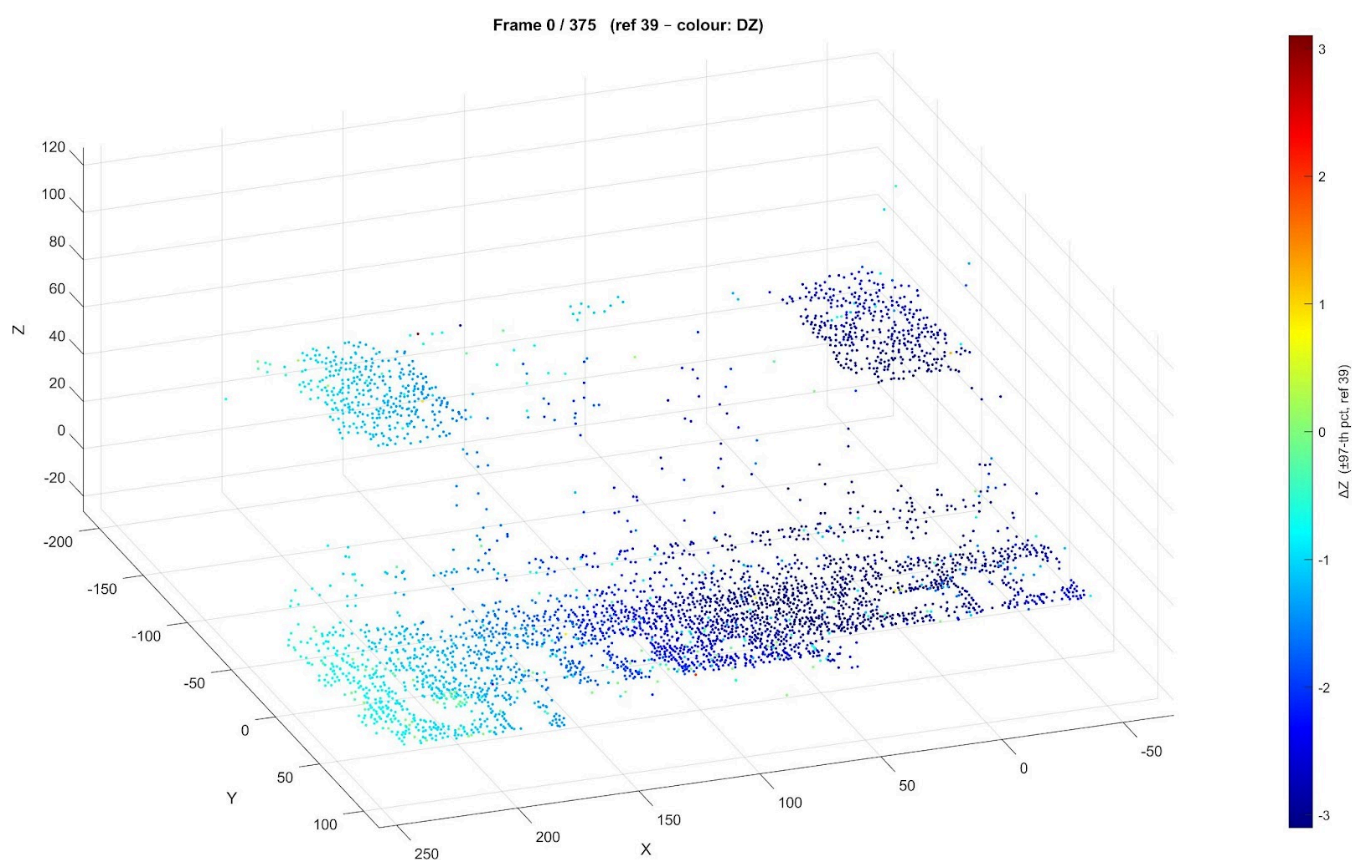


Figure 5.

Lenovo SR650 V2 3D Displacement During Rack Level Test, 24Hz, Frame 18, +/- 3mm

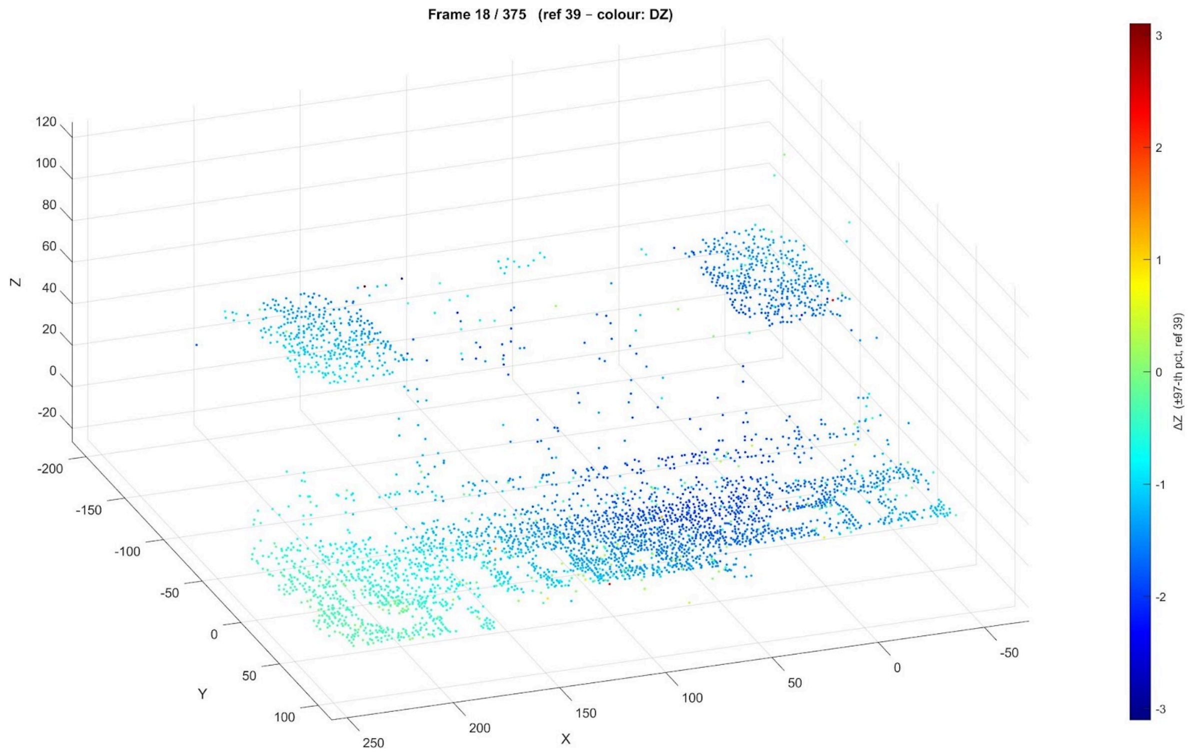


Figure 6.

Lenovo SR650 V2 3D Displacement During Rack Level Test, 24Hz, Frame 39, +/- 3mm

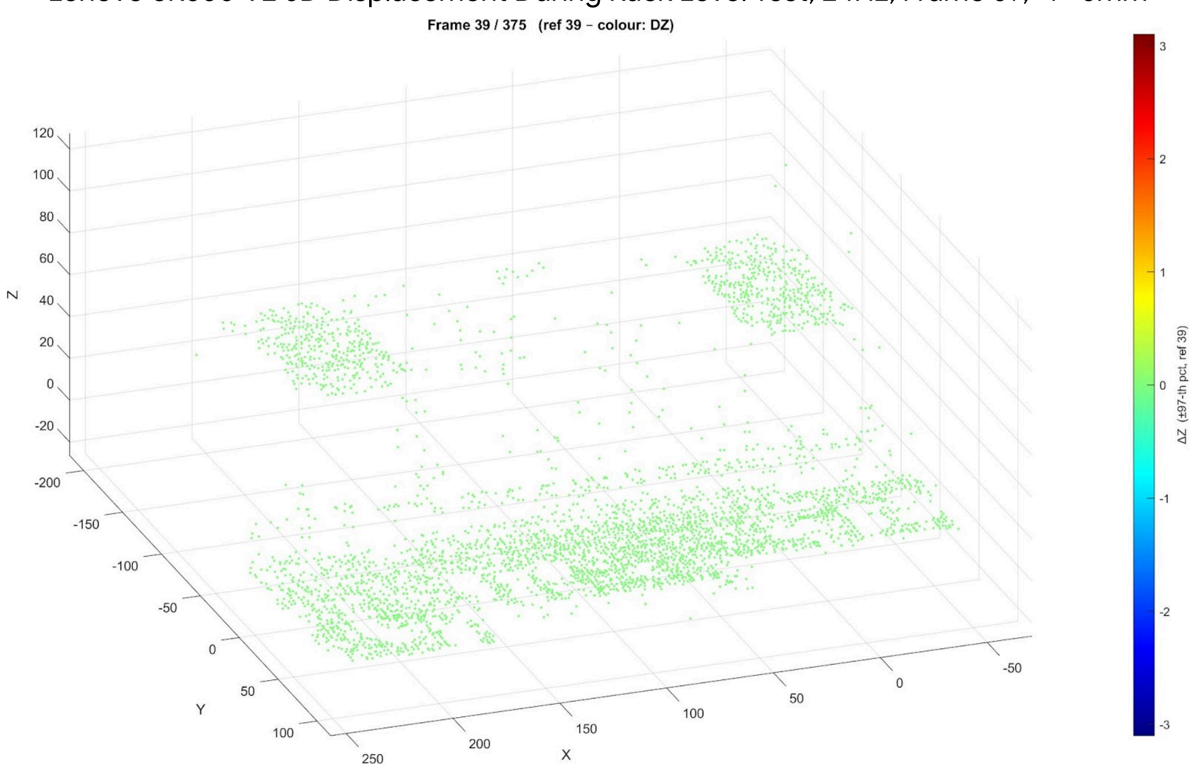


Figure 7.

Lenovo SR650 V2 3D Displacement During Rack Level Test, 24Hz, Frame 57, +/- 3mm

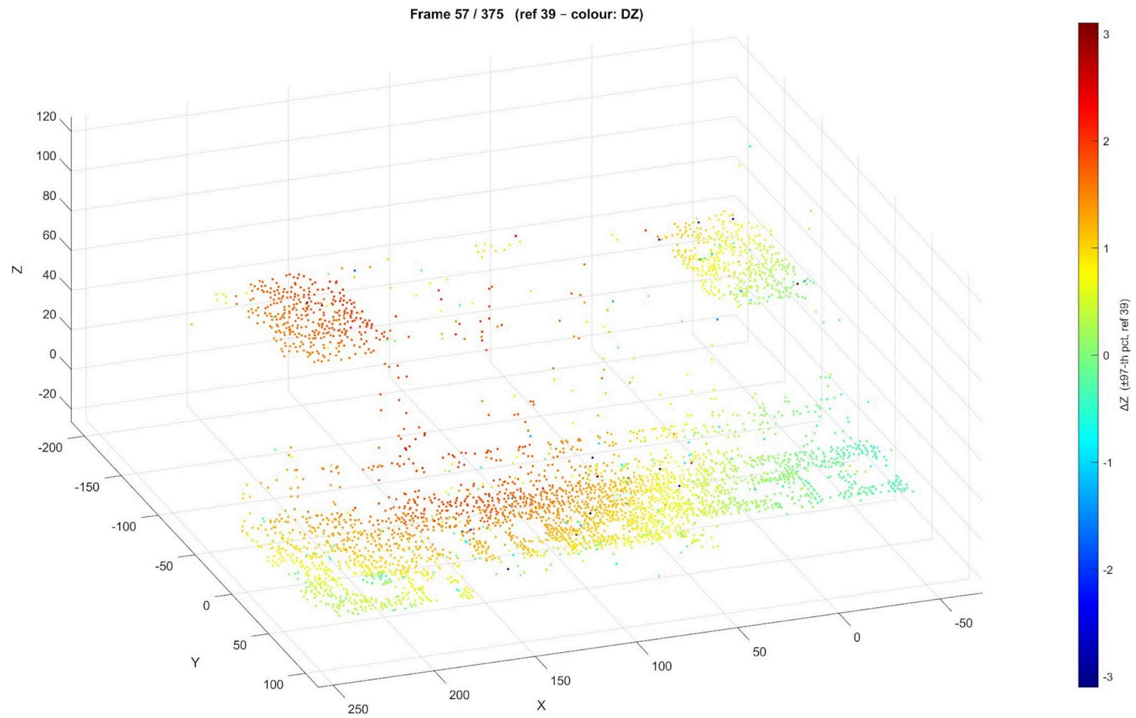


Figure 8.

Lenovo SR650 V2 3D Displacement During Rack Level Test, 24Hz, Frame 76, +/- 3mm

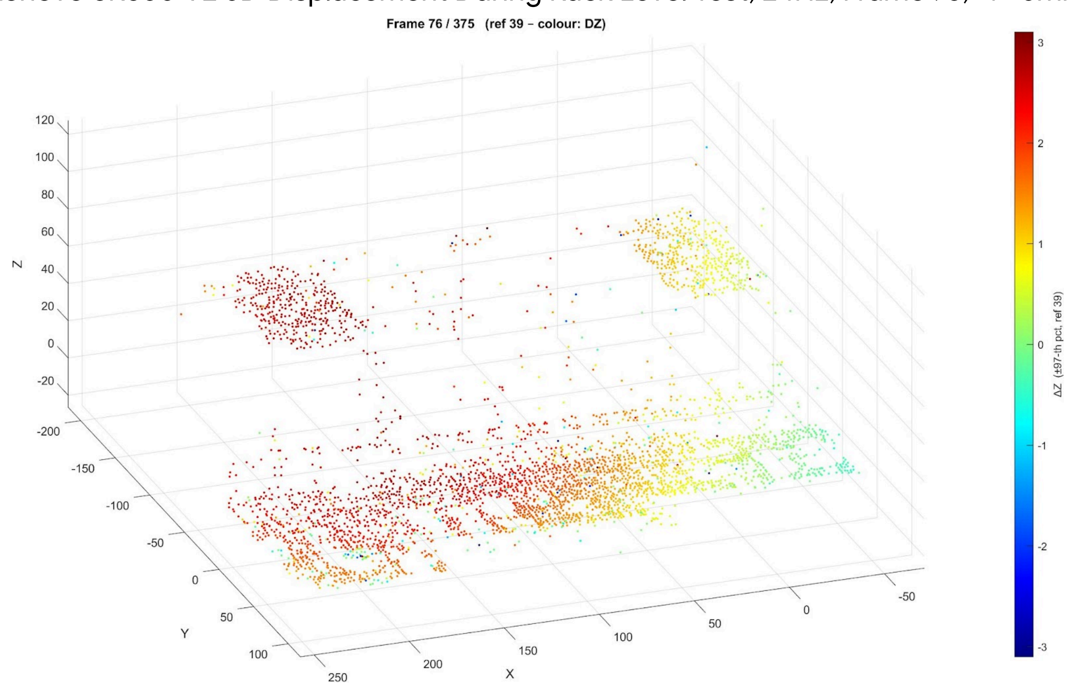


Figure 9.

33Hz, 2.0G Sine Vibration, Rack Level, 4000 Frames Per Second

Video link: https://www.youtube.com/watch?v=-T_lkCDuNpw

During machine level vibration, we saw a single resonance at 28.5Hz (Part 1.1). At rack level, we saw them at 22.6Hz and 28.3Hz (Part 1.2). At the time, we didn't know where the extra resonance came from, but guessed that the lower mode came from flexing of the shelf. With 3D displacement, it's easy to see the 2nd mode is more inline with machine level resonance, in terms of shape (more centered) and amplitude (+/- 1.25mm).

Lenovo SR650 V2 3D Displacement During Rack Level Test, 33Hz, Frame 0 Thru 60, +/- 1.5mm
(Last Figure - Same Tray Under Machine Level Sine Vibration in Part 1.1, +/- 1.3mm)

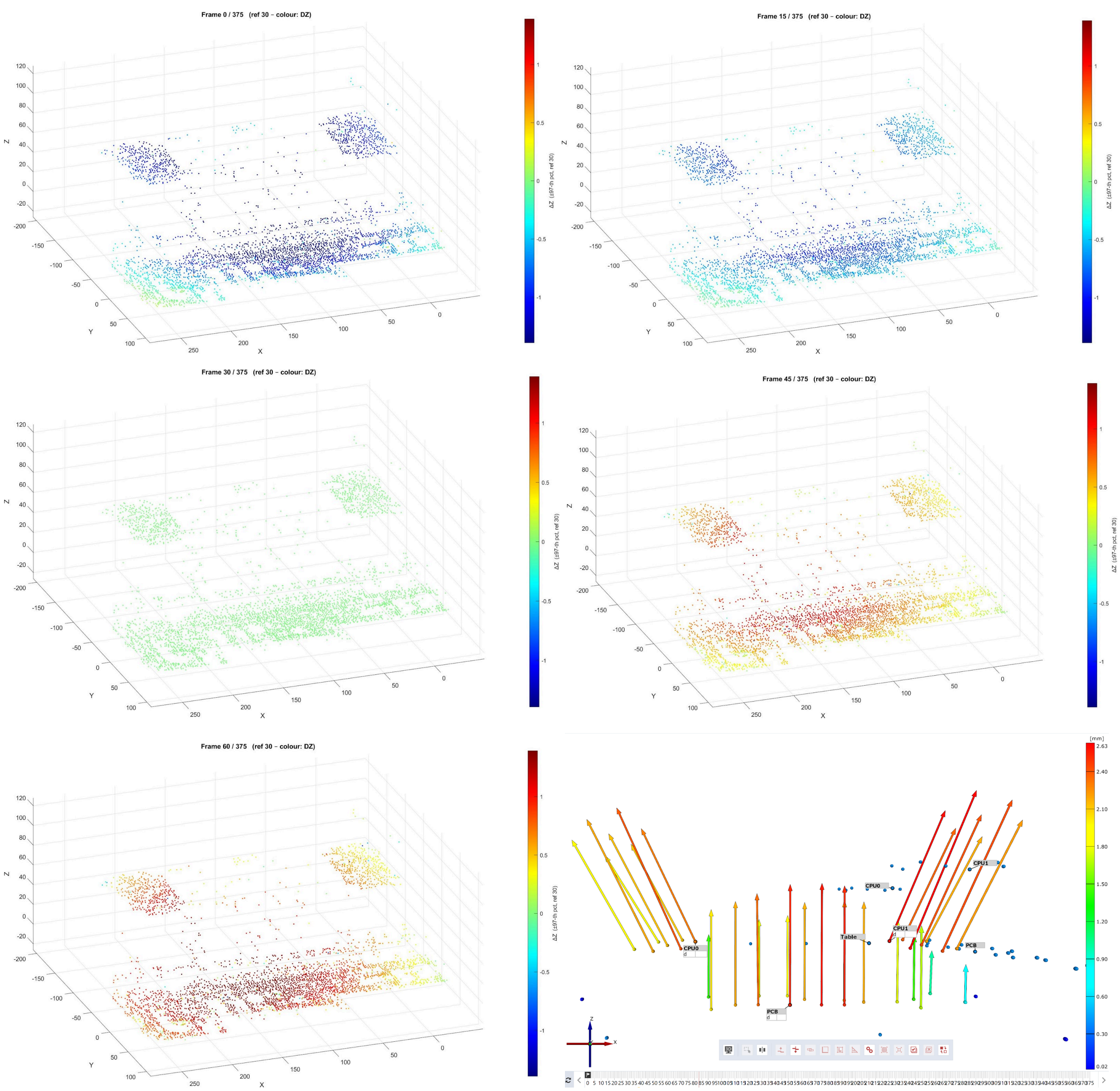


Figure 10.

49Hz, 2.0G Sine Vibration, Rack Level, 4000 Frames Per Second

Video link: https://www.youtube.com/watch?v=GqtJm9s86Js

Lenovo SR650 V2 3D Displacement During Rack Level Test, 49Hz, Frame 0 Thru 154, +/- 1mm

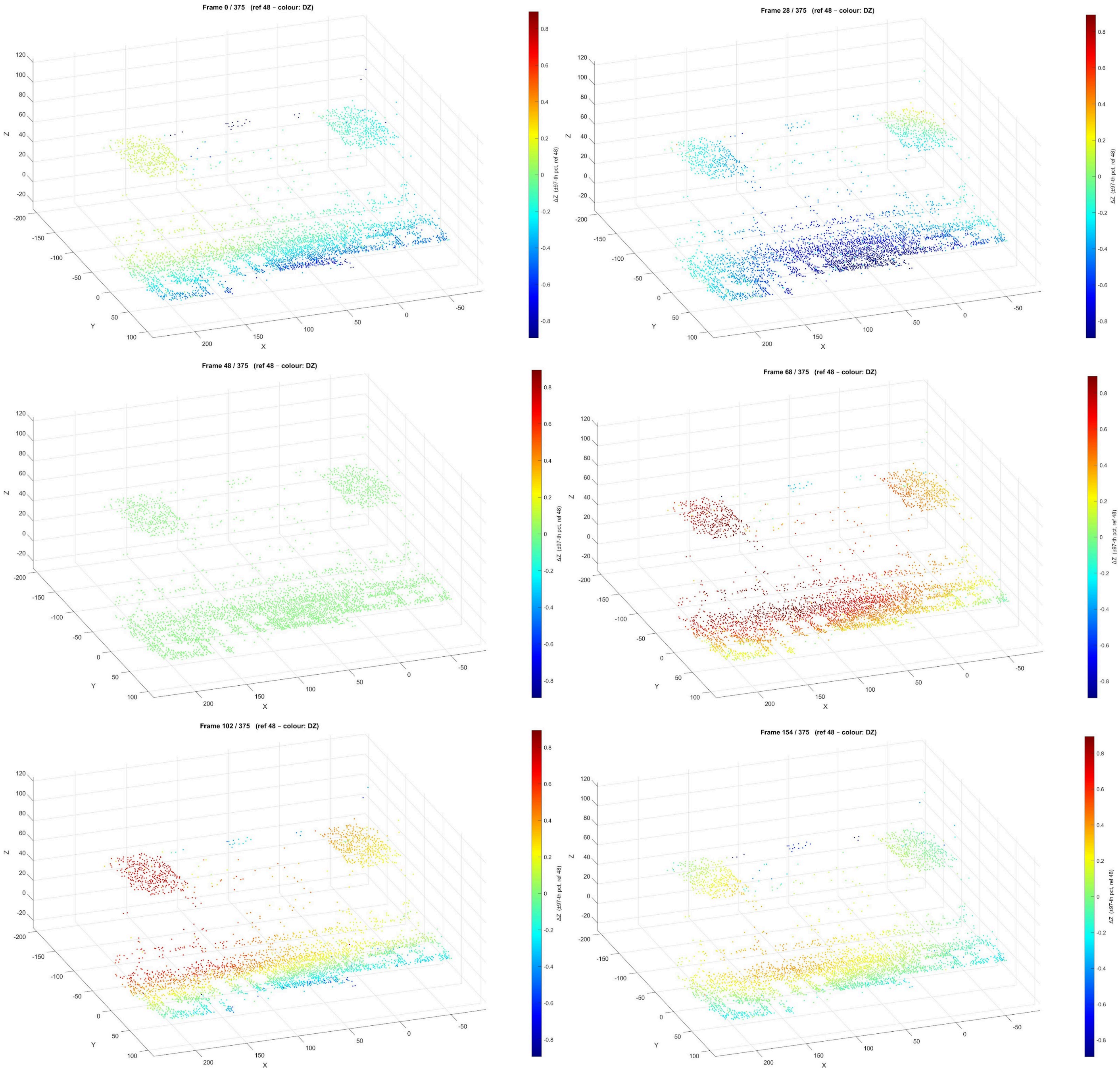


Figure 11.

By 49Hz, the motion becomes more complex. The distribution isn't always even across the whole PCB, and in this case increases in the front right to back left direction. It is much easier and more intuitive to visualize what's happening when watching the motion through multiple loops of HD video.

Lenovo SR650 V2 3D Displacement During Rack Level Test, 49Hz, Frame 170 Thru 230, +/- 1mm

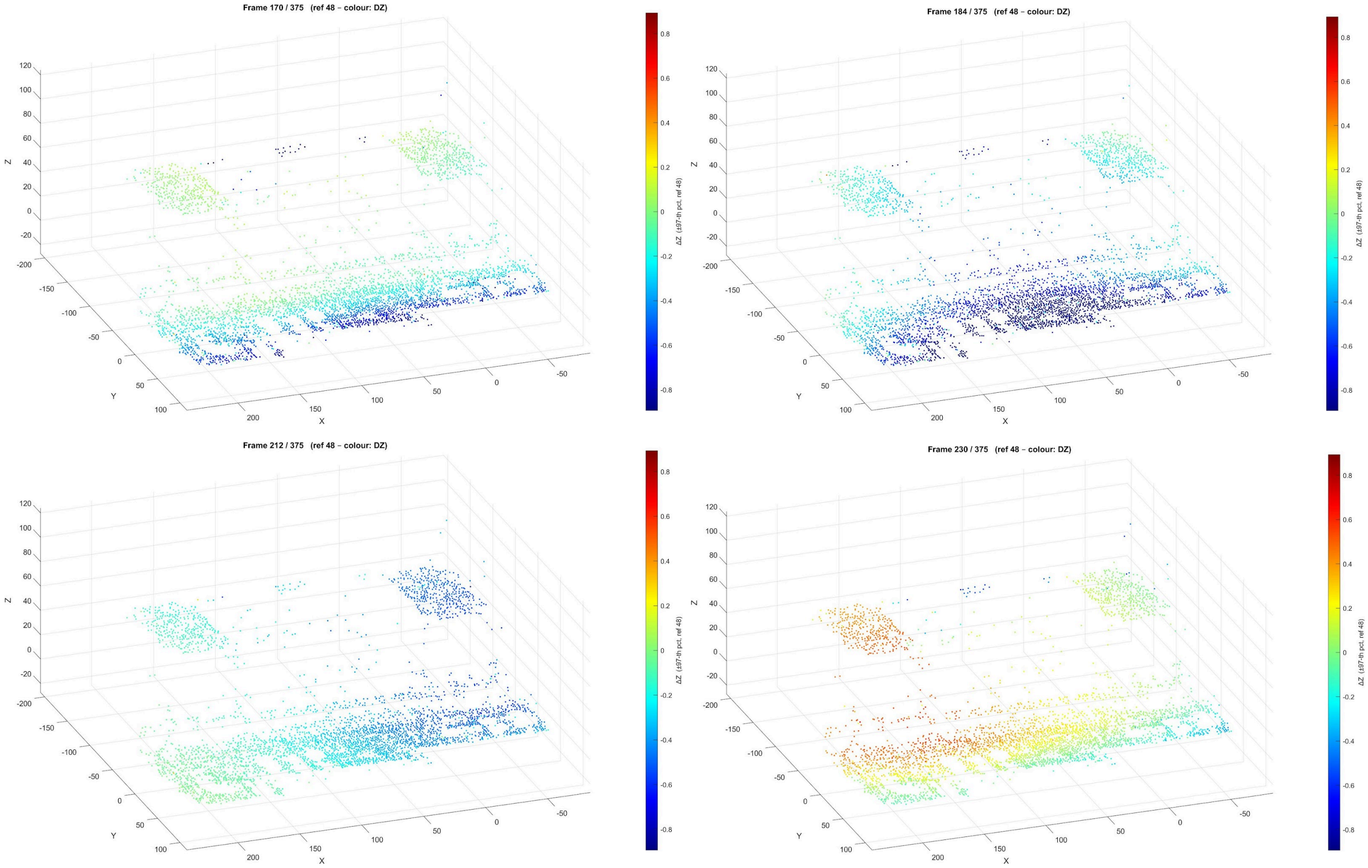
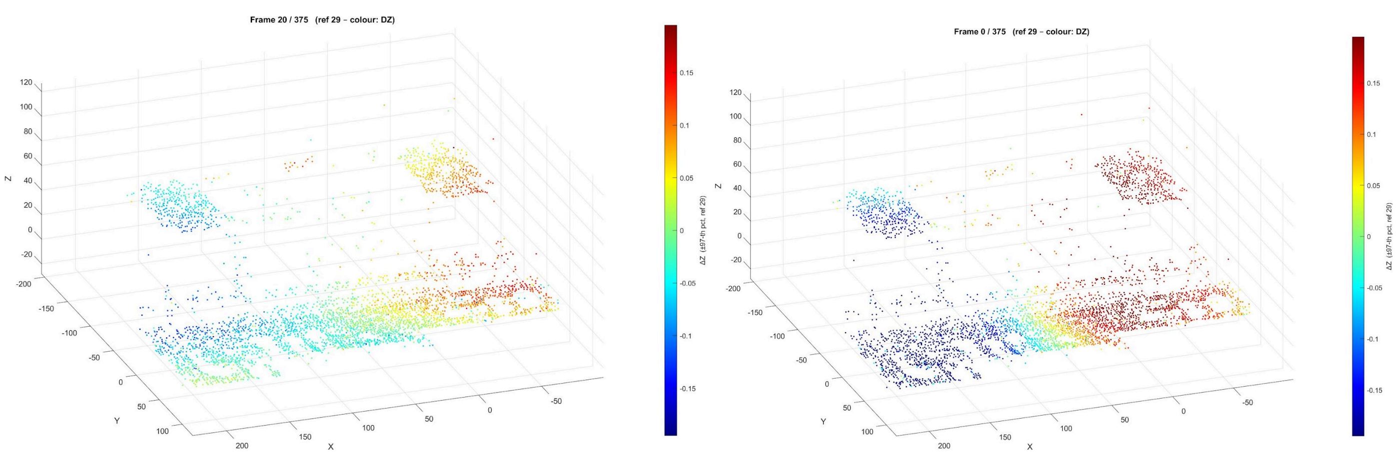


Figure 12.

<u>107Hz, 2.0G Sine Vibration, Rack Level, 4000 Frames Per Second</u>

Video link: https://www.youtube.com/watch?v=VgOVQxYrHs8

Lenovo SR650 V2 3D Displacement During Rack Level Test, 107Hz, Frame 0 Thru 102, +/- 0.2mm



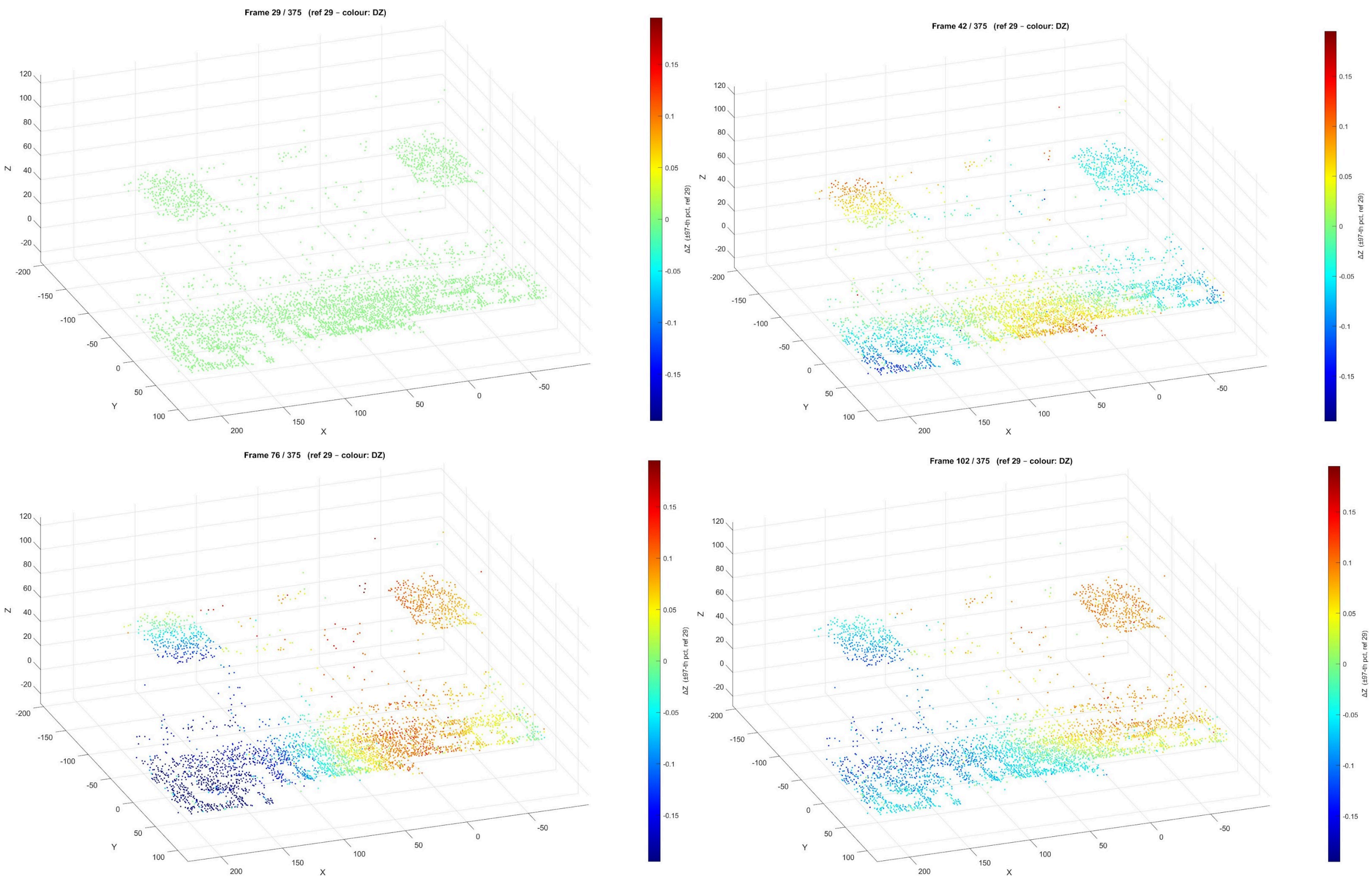


Figure 13.

107Hz is interesting because it is mostly focused on the right side. It also only shows +/- 0.2mm of relative displacement, which is significantly smaller than lower frequency resonance. The higher the frequency, the lower the amplitude. This mode is potentially less stressful to the components on board due to the lowered amplitude. The other consideration is how concentrated the stress is. If the stress is really concentrated, there might be a lot more localized stress underneath the component above it.

ASTM d4169-14 Truck Profile, Assurance Level 2, Rack Level, 4000 Frames Per Second
Video link: https://youtu.be/0C2t9vNmBXU

The best part about 3D data is its ability to communicate stress distribution and concentration with simple pictures. Very little training or experience is needed to look at high speed videos with 3D data to understand whether modes identified during sine vibration are re-occuring during random vibration.

Lenovo SR650 V2 3D Displacement During Rack Level Test, Truck Transportation

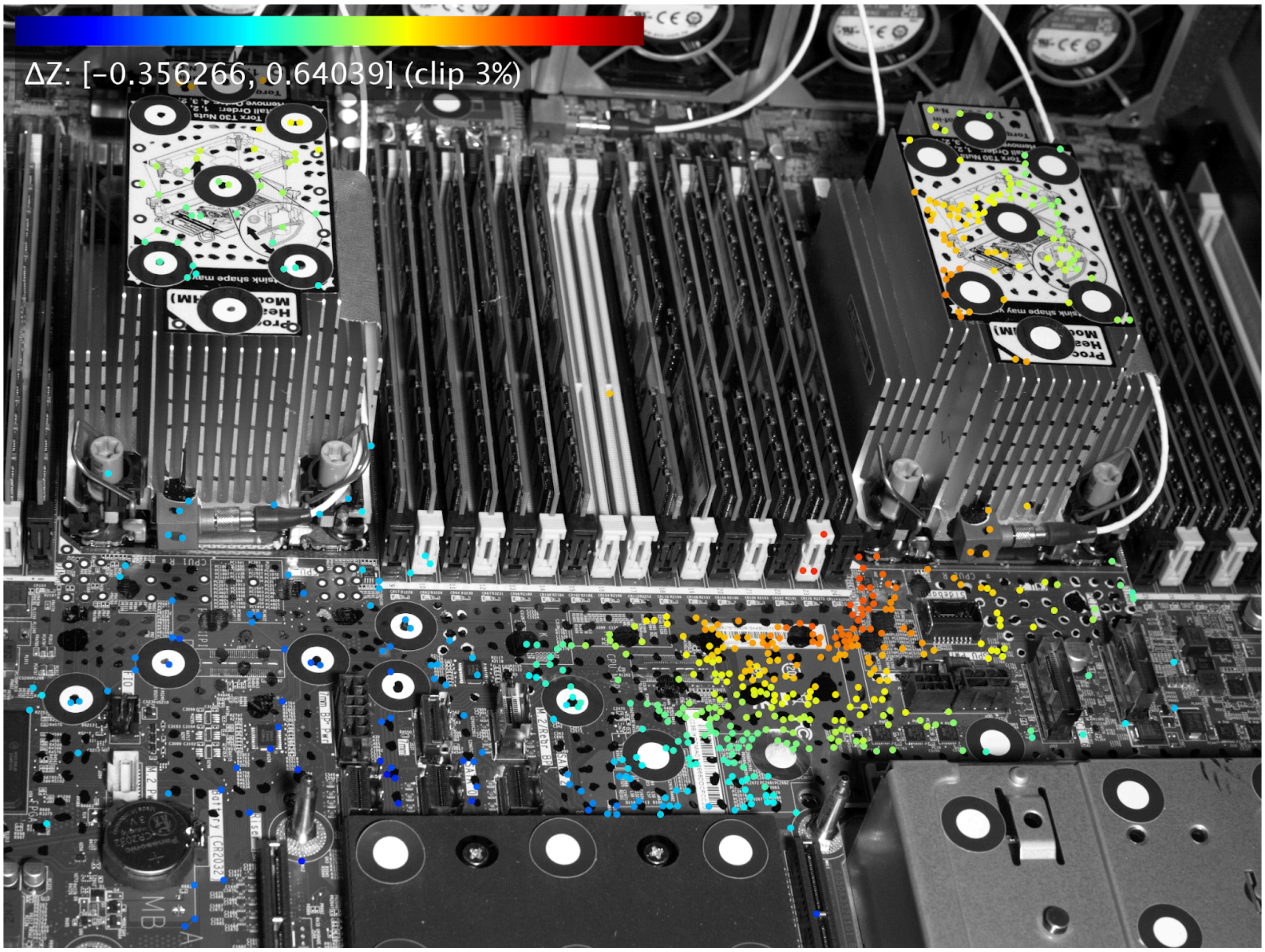


Figure 14.

There is something special about 3D displacement data of random vibration that has to be seen in video format. The modes from sine vibration are definitely re-occurring, but a lot of other things are going on as well:

- High frequency jitter of the heatsinks during the slow frequency modes
- Various modes mixing and interacting with each other
- The slowness of the PCB movement, which looks more like breathing than anything else
- All the components' movement, whether 3D data is available or not

Lenovo SR650 V2 3D Displacement During Rack Level Test, Truck Transportation, Frame 25 Thru 376

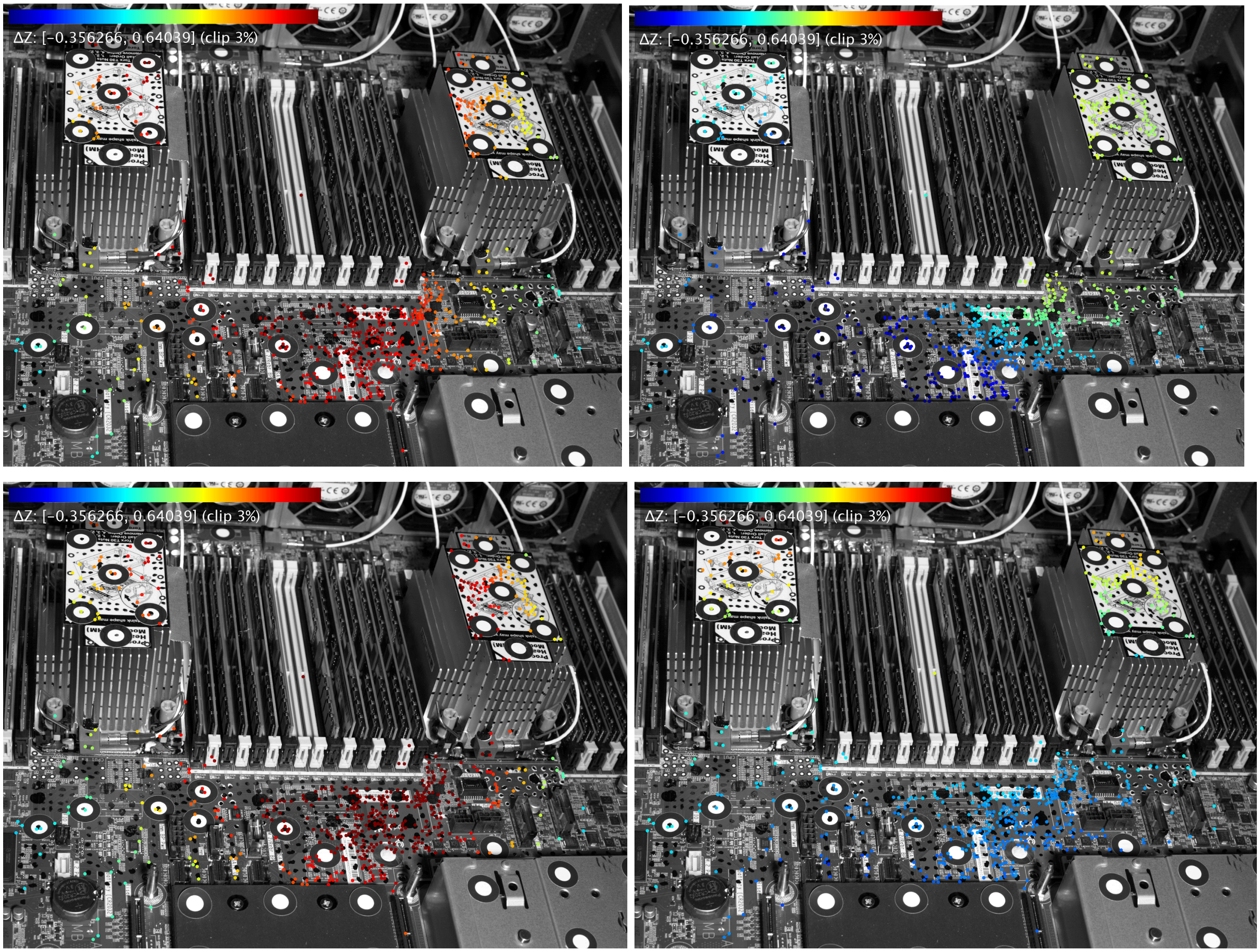


Figure 15.

Random vibration really isn't something that can be described with simple acceleration and strain plots.

<u>Tracking 3D Displacement For Prolonged Periods of time</u>

Random vibration poses a difficult challenge for 3D displacement measurement in terms of the amount of data to analyze and how much can be reasonably be achieved using typical lab desktop or laptop computers.

Normally, during sine vibration, only a few cycles of the vibration are needed to visualize the mode shape. At 24Hz, only 1/24 Hz = 0.0416 seconds are needed to observe the motion of 1 cycle. At 4000 frames per second, that's (1/24 second per cycle) / (1/4000 second per frame) = 166.66 frames to show a full cycle. **I typically analyze 200 to 500 frames to ensure the motion is repeatable**.

There is no such certainty with random vibration. How often a specific frequency is repeated depends on how the shaker table controller operates and what parameters are used. Modes may be overlapping with each other, interfering constructively or destructively with each other. That's why we want to capture as much data as possible. When we do that, we hit real limits in terms of:

1. Storage capacity at high speed cameras (up to 256GB RAM and up to 1TB for on-camera storage).
2. Computation capacity of typical laptops and desktops, which limit how many points can be analyzed using algorithms/models such as digital image correlation, segmentation-anything, and stereo matching in parallel.
3. Amount of time available for data analysis.

With a single server with 128GB RAM on Google Cloud, 800 points for sine vibration can be analyzed over 500 frames in 8 to 12 hours. When the **number of frames increases to 64,000 (16 seconds)**, near the maximum RAM capacity of the v2640 cameras at 2048x1952 resolution and 4000 frames per second, that amount of time **increases to 1,024 to 1,536 hours, which is 43 to 64 days(!)**.

One way around that to **reduce the number of tracked points**. After major modes were identified during sine vibration, 8 points were chosen to show 1) which mode was excited, and 2) at what amplitude. Even then, it still took several days and some trial and error for the pieces to come together:

1. 8 key points at the edge of PCB and top of heatsinks were chosen so that a) rigid body motion can be removed, and b) relative displacement can be calculated to demonstrate mode shape and amplitude.
2. These points were tracked though the 64,000 frames high speed videos using open source digital image correlation algorithms.
3. The points were calibrated and triangulated to calculate real world 3D coordinates.
4. Rigid body motion was removed to achieve 3D relative displacement data.
5. Points at the top of the heatsink were plotted and analyzed to calculate the amplitude and number of cycles of relative displacement.

Example Lenovo SR650 V2 2D Displacement Tracking During Rack Level Test, Left Camera, 20,000 Frames

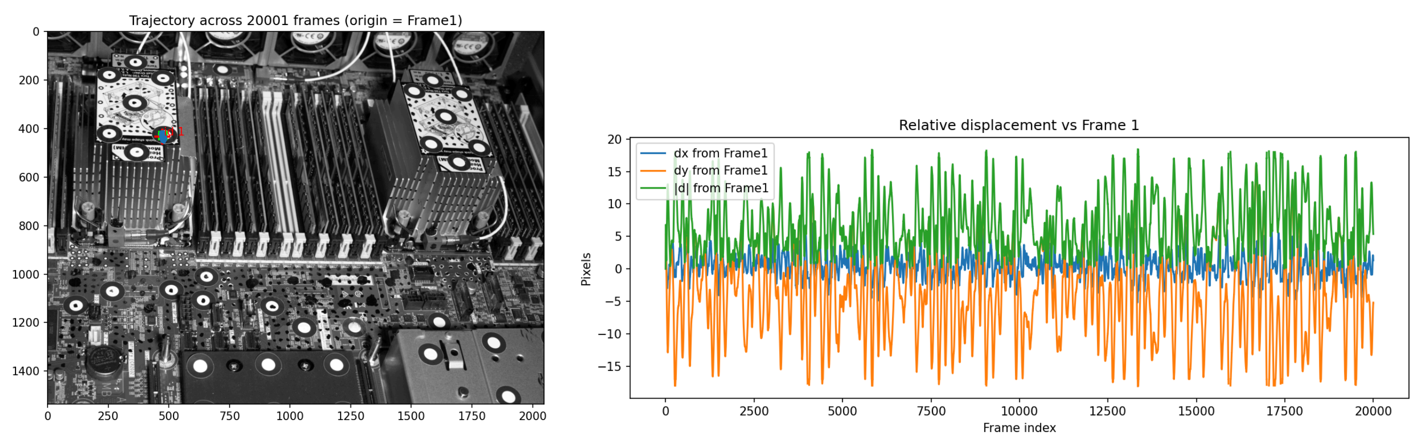


Figure 14.

Example Lenovo SR650 V2 Z Relative Displacement During Rack Level Test, Top of Heatsink, 20,000 Frame

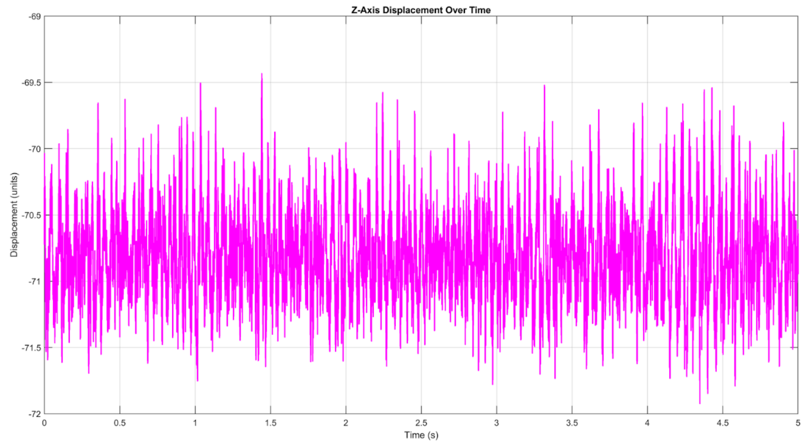


Figure 15.

Peak Detection of Z Axis Relative Displacement During Rack Level Test, Top of Heatsink

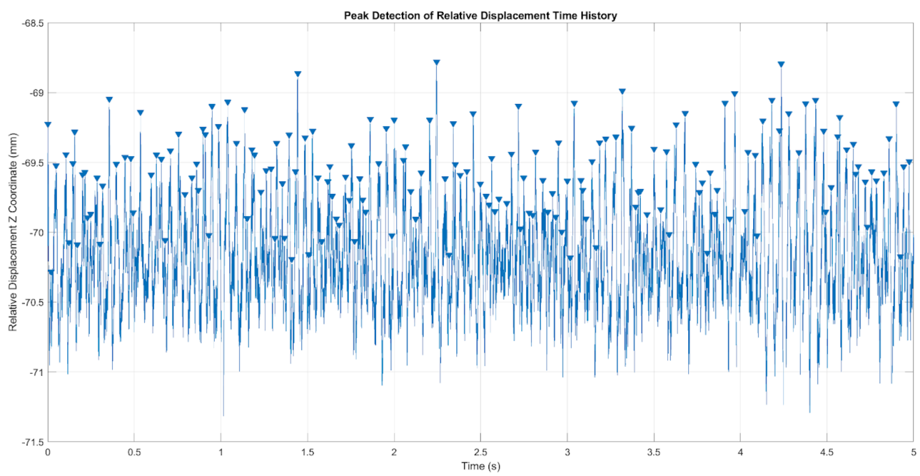


Figure 16.

Histogram of Detected Z Axis Relative Displacement Peaks, Top of Heatsink

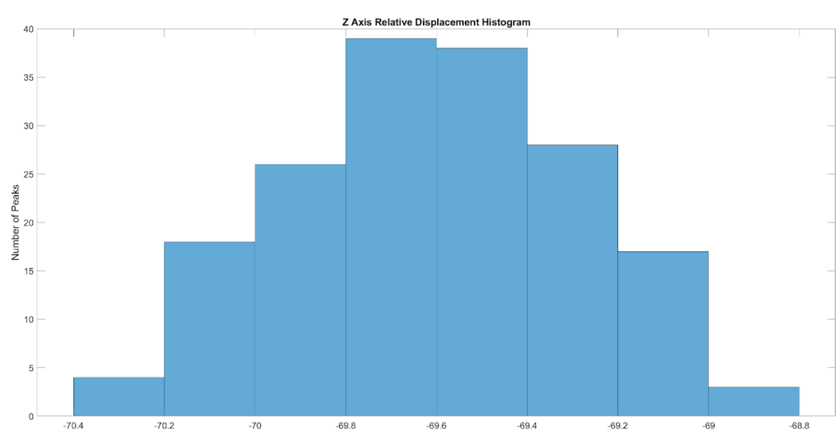


Figure 17.

The results translate to a range of 0.5 to 2.1mm relative displacement. Even with only 5 seconds of data, we already see a normal distribution of the results, which is what we expected from a shaker table random vibration test, generating peaks between +/- 3 standard deviation.

Should damages occur, we can record the precise number of stress cycles and amplitude for failure analysis afterward. Such data can also help us compare different profiles - different ASTM standards, between ASTM and ISTA, or industry standards vs. real world data. The 3D distribution, concentration, and amplitude of stress will help determine whether a test sample is sufficiently stressed compared to real world conditions.

The results were obtained using the simple *findpeaks* function in matlab, but it is possible to look deeper into the time history to estimate the pulse width and the source resonance frequency behind each stress cycle. Accelerometer data can also be analyzed with the 3D displacement side by side to further understand how various modes impact relative displacement in real time. The raw relative displacement data suggests the relationship is not as simple as previously thought.

Zoomed View of Z Axis Relative Displacement

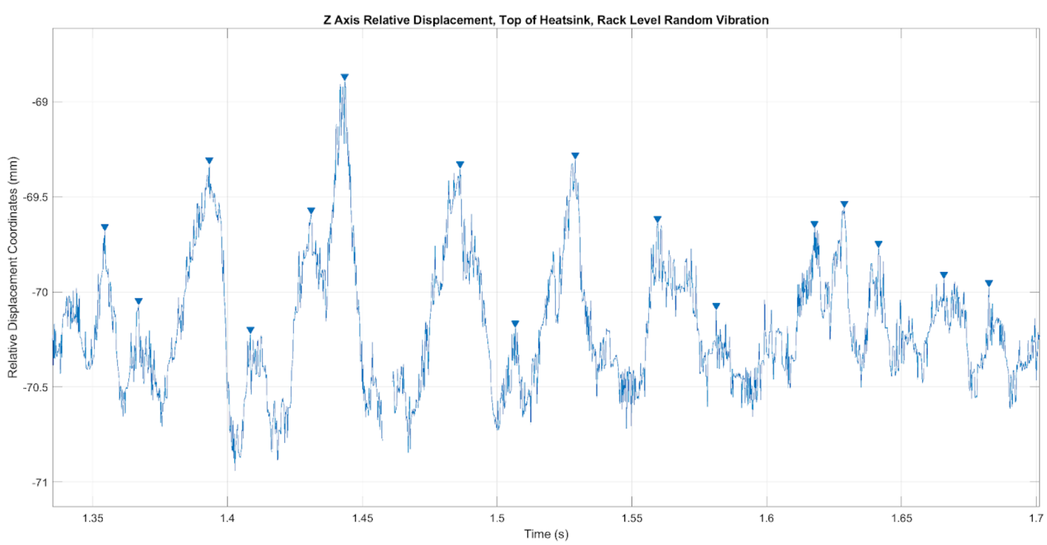


Figure 19.

ASTM d4169-14 Forklift Truck Handling Drop, 6 inches Bottom Surface, 4000 Frames Per Second
Video link: https://youtu.be/0C2t9vNmBXU

Handling drop shock impact represents a whole different discipline in shock and vibration testing. Products are expected to experience a significantly higher level of stress - so much so that companies like Intel and Cisco historically dedicated tremendous resources toward the shock testing of chips and BGA solder joints, and published extensive papers and test standards on this subject.

We want to focus on the 3D measurement of test samples during drop testing, and see what we can learn from it. The structure of a fully populated rack is much more complicated than a single machine, so it's safe to assume things won't always follow between the two.

Lenovo SR650 V2 2D Rack Level Drop Test High Speed Cameras Setup

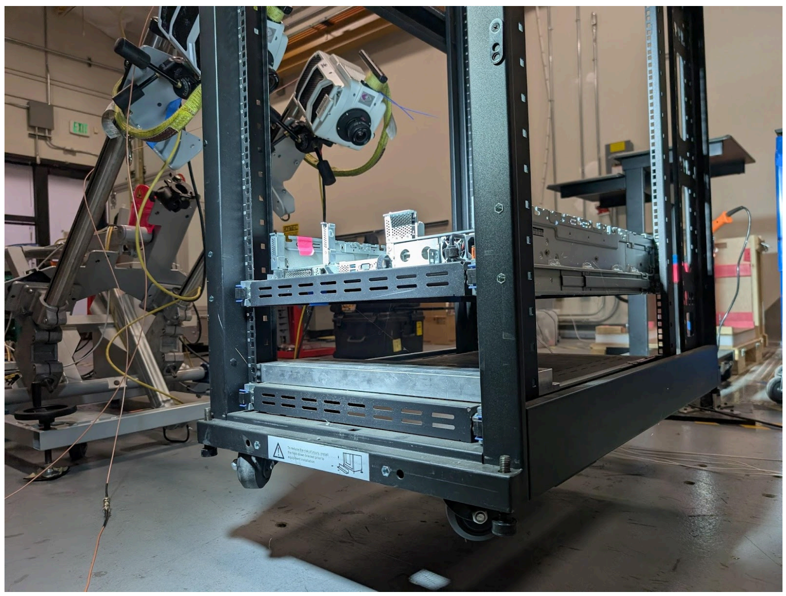


Figure 20.

Example Lenovo SR650 V2 2D Displacement Tracking During Rack Level Drop Test, Right Camera, 160 Frames

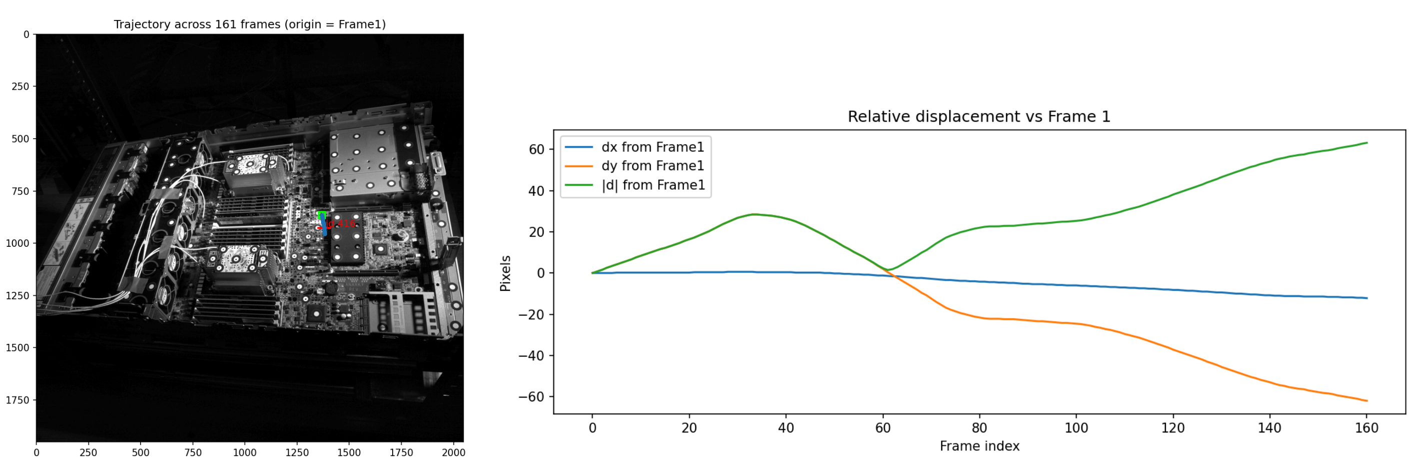


Figure 21.

Lenovo SR650 V2 3D Displacement Data During 6” Rack Level Drop Test, Right Camera, Frame 1 Thru 161

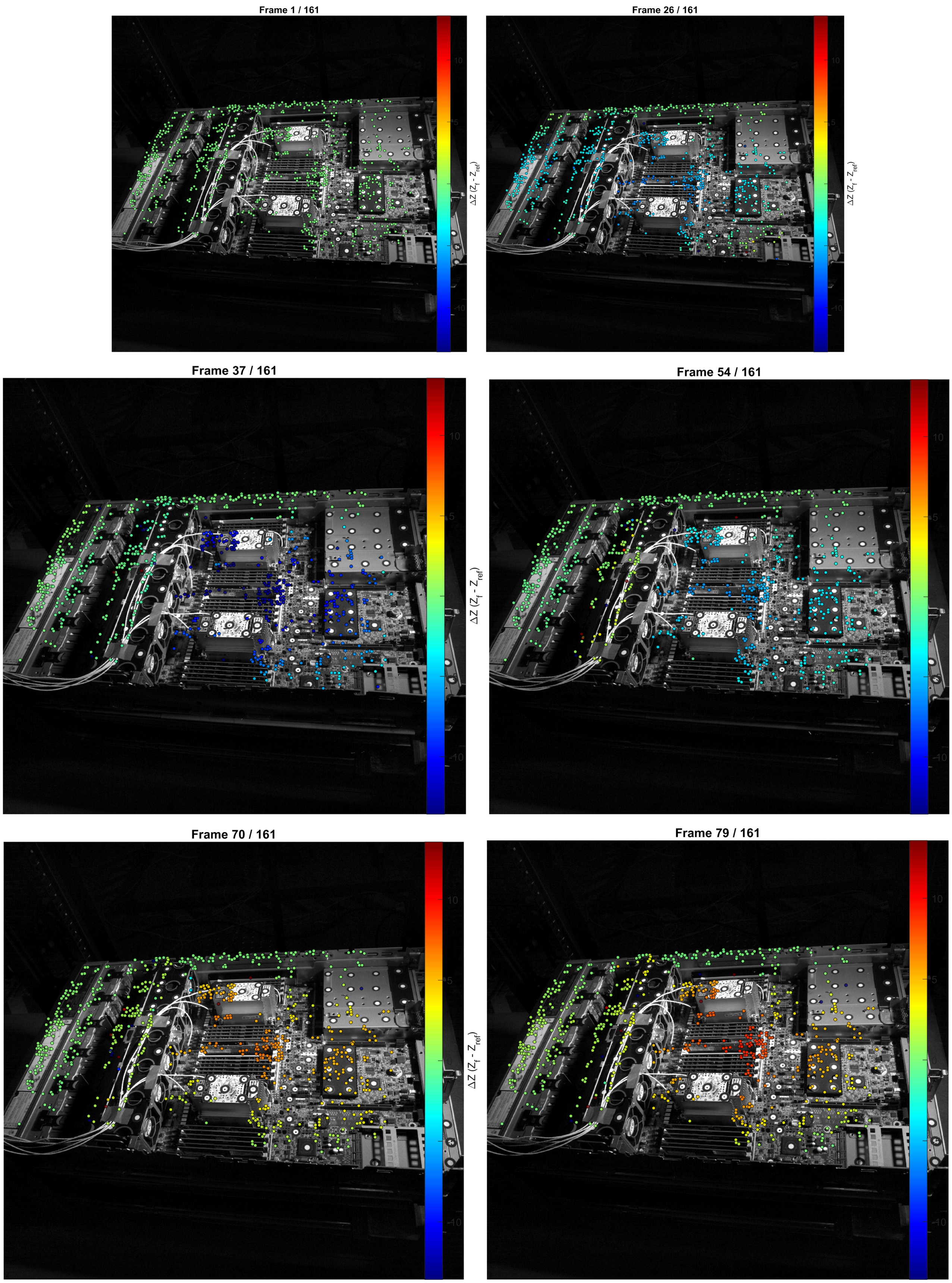
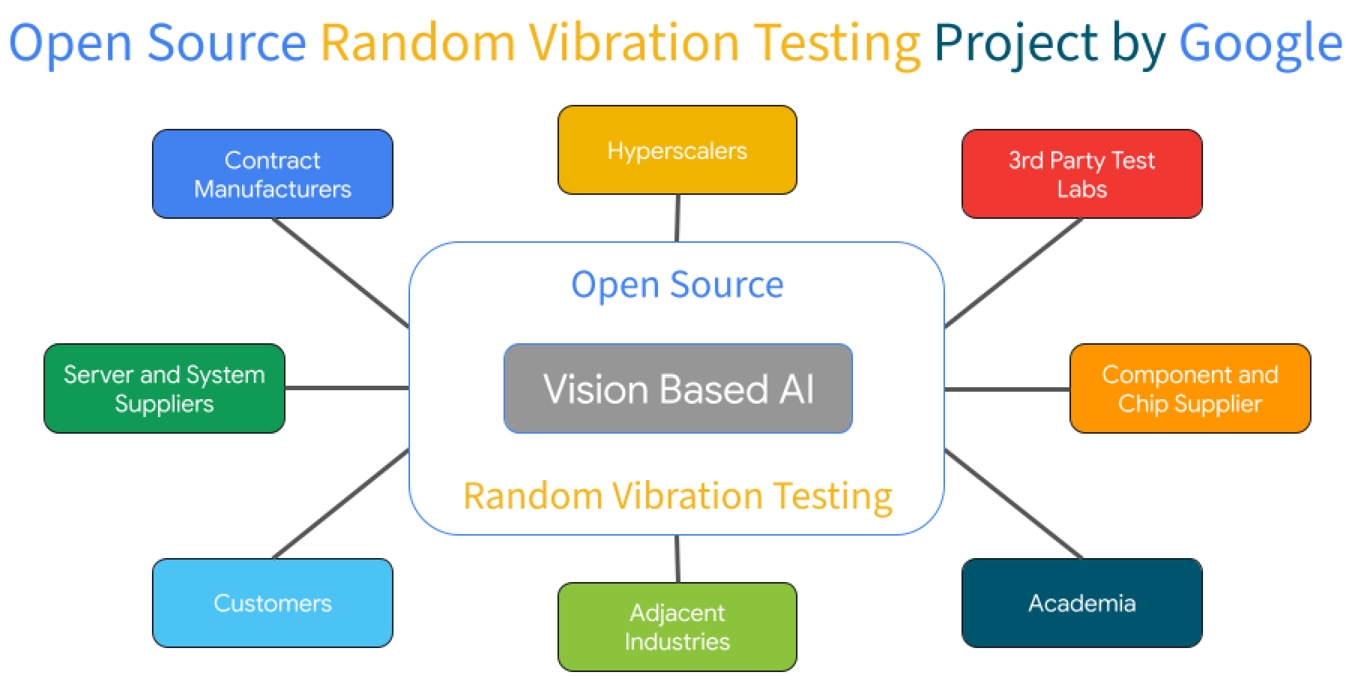


Figure 22.

The results are rather simple. +/- 15mm of relative displacement, concentrated near the center of the board and the heatsink toward the top. But when we look at the video, it's striking how much deformation occurs and how flimsy everything looks.

During product development, we want to compare this with tray level handling drop (3" free fall on bench top or the ground without packaging) and packaging level handling drop (up to 9" free fall on the ground with single corrugated cardboard box and foam packaging) and see how they compare. This is something we do daily during Google Cloud product testing to assess the risk of fully populated rack deployment.

<u>The Bigger Picture</u>



With the advancement of computer vision and vision based AI, it is easier than ever to perform scientific measurements and complex motion analysis of day to day phenomena. The field of shock and vibration testing is ripe for the kind of revolutionary changes that are sweeping through the rest of the world, having relied on traditional acceleration and strain data for decades.

Traditional sensors and methods are used for a reason. There are many things that only accelerometers and strain gauges can do, many of which are described in Part 1.1 through 1.5. For example:

1. Accelerometers can produce highly accurate measurement of ultra high frequency movements and behaviors at minimal hardware and equipment cost.
2. Strain gauges can detect stretches and compressions of materials down to a fraction of a micrometer at locations deep inside a rack or a workstation.

These things are difficult for high speed cameras and 3D displacement measurements without jumping through a lot of hoops. But there are also things HS cameras and 3D displacement measurements can do that traditional sensors can't, such as capturing the macro dynamic behaviors of complex structures with a lot of parts and sub-assemblies in random vibration and shock scenarios that are historically challenging.

Vision based AI itself is also exploding in the era of AI, revolutionizing itself every 6 to 12 months, delivering solutions never thought possible before:

1. Meta's Segment Anything Model 3 (SAM 3) is now able to perform detection, segmentation, and tracking of objects in images and video using text, exemplar, and visual prompts.
2. State-of-the-art models from companies like NVIDIA, Apple can reconstruct detailed 3D geometry from a single 2D image or video sequence.
3. Foundation AI and LLM models can now easily analyze images and videos, understand context across multiple formats, and perform tasks like visual question answering or captioning.
4. Computer vision has grown far beyond algorithms that powered 3D DIC software. All the necessary functions that enabled 3D DIC are now available in open source libraries for free, including:
    a. Automated points matching of stereo images
    b. Automated calibration of stereo or multi camera setups
    c. Open scripts for Digital Image Correlation and sub-pixel points tracking
    d. Automated 3D depth estimation and dense mesh reconstruction

High speed videos themselves are informative even without any processing. Anyone can look at them and understand exactly what is being tested and what happened during testing, something difficult with traditional sensors, without tremendous engineering experience and resources for capital equipment (both of which struggle to scale with modern advancement of compute and AI hardware, and wide spread of AI chips in robotics, automation, autonomous vehicle, and edge computing).

Moving forward, particularly in Part 3, we will be releasing as much 3D data as possible to make everything simple to understand and easy to follow.