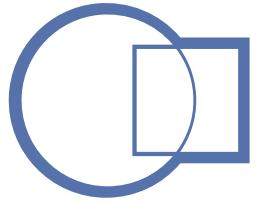


sensing, interaction & perception lab



Department of Computer Science, ETH Zürich

Semester Project

Discrete Photodetector Array Approach to High-Bandwidth Vibration Sensing

Sam Sulaimanov

1st supervisor

Prof. Dr. Christian Holz

Sensing, Interaction & Perception Lab
ETH Zürich

2nd supervisor

Paul Strelí

Sensing, Interaction & Perception Lab
ETH Zürich

January 6th, 2024

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Department of Computer Science, ETH Zürich
Universitätstrasse 6
8092 Zürich

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ssamir@ethz.ch

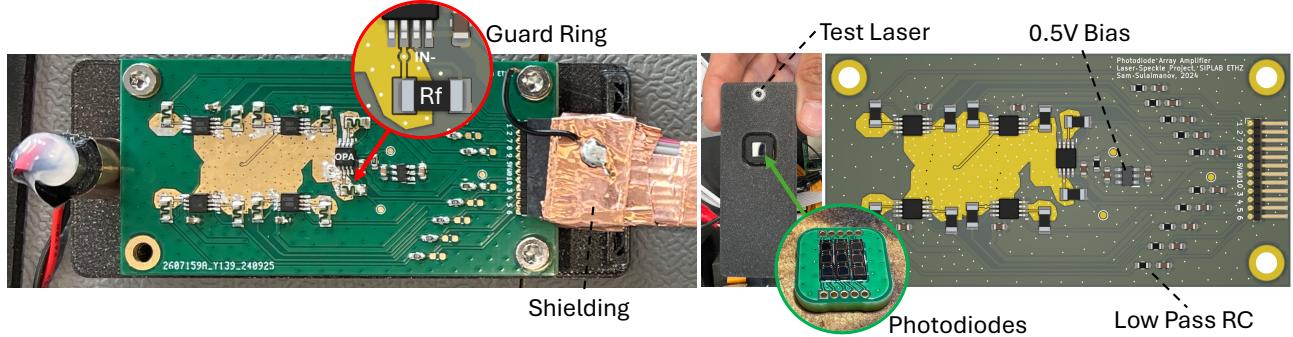


Figure 1. Left: the final assembled discrete photodetector in a test housing. Middle: Front view of the detector with IR bandpass filter. Right: Rendered PCB.

ABSTRACT

Camera imaging sensors - placed adjacent to a surface diffusing the collimated light of a laser - can be used to sense the resulting surface dependent speckle pattern. The pattern oscillates if the surface oscillates, leading to the possibility of remote vibrometry. While cameras are low cost, easy to use and highly sensitive, they have relatively low frame-rate and thus are a poor choice of sensor for high rate oscillations. The present work explores the creation of a device to increase the measurement bandwidth while maintaining the sensitivity an off the shelf imaging sensor can provide. To this end, a high gain low noise amplifier array has been designed with a bandwidth of 1 kHz. The array amplifies the currents of a grid of 3x3 photodiodes which is then low pass filtered and digitized using a high rate ADC. Tests were conducted to measure the ability of the device to detect laser speckles. Discrete IR lasers, with different beam patterns, and IR dot projectors were evaluated and a detection limit is defined. We also find that using multiple discrete laser beams illuminating a vibrating piezo disc, and the area around it, increases the signal to noise ratio measurably.

Keywords

laser speckle; remote vibrometry; speckle detection; photodiode array

INTRODUCTION

Vibration sensing enables condition monitoring and predictive maintenance of industrial equipment by detecting mechanical faults before catastrophic failure occurs. Critical applications

include monitoring of rotating machinery, bearings, and industrial robots, where unexpected downtime can result in significant production losses. Higher frequency vibrations are of particular interest [4].

Typically, a vibration sensor is physically coupled to a designated surface of a machine using adhesive or glue. However, this brings the burden of cable management onto the user. Wireless sensors need their batteries replaced once in a while and require a receiving station. These limitations motivate the need for a vibration sensor that is easier to install and maintain and capable of monitoring many instances of equipment at once.

Some monitoring approaches use microphones installed centrally in the room, using sound as a proxy for vibration. Many microphones are required to distinguish sounds coming from different sources.

Remote video cameras can be used to record vibrations [7] when aimed at a fiducial marking. Many objects can fit in the field of view of a camera and can thus be monitored.

While cameras offer a non-contact and simple method for vibration sensing, they're limited to detecting macroscopic (resolution limited) and low-frequency (frame-rate limited) vibrations. In order to measure microscopic vibrations, we can exploit the speckle patterns that an optically rough surface produces (surface height variations on the order of laser wavelength) when laser light (like from a laser pointer) hits it.

When the laser light is reflected and scattered by the optically rough surface, it produces a locally unique and stationary interference pattern. This pattern, known as a speckle pattern, results from the superposition of coherent light waves with different path lengths due to the surface's microscopic imperfections. The resulting speckle pattern can be observed on any imaging plane at a distance from the surface. To capture this pattern one can expose the bare image sensor (without lens) of any camera to the reflected and scattered light.

When the surface is mechanically deformed, the imperfections are altered, causing the pattern to change as well. If the surface is translated under the laser light, the pattern appears to shift.

In this work, we exploit this phenomenon for high speed remote vibration sensing. Our approach exceeds the bandwidth limitations of camera-based vibration sensing by capturing speckle patterns with an array of discrete high-speed photo-detectors arranged in a 3x3 grid - essentially a discrete image sensor.

The novel discrete image sensor combines the advantages of remote, non-contact sensing with the ability to capture vibrations at a higher sampling rate than conventional cameras.

To implement this concept, we designed and built the analog photo-detectors on a custom printed circuit board (PCB).

The performance of the hardware was assessed in experiments using laser modules and a laser dot projector at 850 nm, with surface reflectivity being a critical factor in detection quality. A key finding was that multiple aligned laser sources could be used simultaneously without degrading the signal quality, enabling easier aiming from a distance.

Hardware design parameters like pixel size and sensitivity were empirically deduced by using a reference the Raspberry Pi™ HQ camera 12.3 MP (IR filter and objective lens removed) as a reference image sensor.

Detection of genuine speckle patterns was verified through comparative testing against non-coherent LED illumination, which produced no detectable vibration signal.

Our discrete sensor has a bandwidth of 1 kHz exceeding the maximum sampling rate of conventional cameras by an order of magnitude. Our sensor has a comparable sensitivity to the reference sensor.

Contributions

The work in this semester project makes the following contributions.

- High-bandwidth discrete sensor. Developed 1 kHz single-supply bandwidth sensor, surpassing conventional cameras by order of magnitude.
- Sensitivity optimization. Achieved comparable sensitivity to reference sensor while maintaining high bandwidth.

RELATED WORK

The work in this thesis is related to Laser Speckle Imaging, Laser Doppler Vibrometry and Laser Speckle Vibrometry.

Laser Speckle Imaging

Laser speckle imaging analyses the interference patterns generated when coherent light from a laser, scatters off an optically rough surface. These "speckles" can be captured by any photosensitive surface - and most commonly - a camera image sensor. The mean speckle size is an important parameter, as the pixels of the image sensor must be smaller in order to resolve a pattern. The speckle size is a statistical property of the interference pattern and depends on the laser wavelength, sensor-to-surface distance and illuminated area. Cloud [2] defines the speckle size as "the center-to-center spacing of adjacent dark or adjacent light spots in the speckle pattern".

It can be expressed approximately:

$$\text{Mean speckle size} \approx \lambda \cdot \frac{d}{\sqrt{a}}$$

where:

- λ is the wavelength of the laser light,
- d is the distance from the scattering surface to the observation plane,
- a is the diameter or size of the illuminated area (e.g. laser spot area).

Hu et al. [6] show that the size of the speckle is not impacted by the structure of the laser beam. Using multiple lasers increases the illuminated area and reduces the speckle size. 9

Speckle size can be tuned without changing d or a by de-focused imaging, proposed by Heikkinen and Schajer [5]. They use a de-focused telephoto lens to optically change d and show that the resulting speckle pattern is comparable if d was changed physically. The method has an additional advantage of sampling a larger speckle field and capturing more light, important for weaker signals.

Laser speckle imaging is simple to implement and does not require significant hardware, which motivates this semester project. Yan et al. [11] developed "LaserShoes," a system using a USB webcam and Raspberry Pi mounted on shoes to classify ground textures based on speckle patterns. They evaluated different laser wavelengths and achieved accurate surface recognition with a compact, low-cost system. Chan et al. [1] measured liquid characteristics (e.g., milk fat content) using smartphone LIDAR to image speckles, though many frames were needed due to the low power of the LIDAR laser.

Laser Doppler Vibrometry

Laser Doppler Vibrometry (LDV) measures an objects velocity by detecting the Doppler shift in the frequency of reflected coherent light. The measurement setup required is more complex as it involves mixing the emitted and back scattered laser light to detect a beat frequency, which is proportional to the velocity [8]. LDV offers high precision and can measure large vibrations, but the complex setup makes it costly and challenging to scale. Speckle noise is a known limitation in LDV, caused by random phase shifts in scattered light due to surface roughness. Addressing this noise often requires advanced signal processing [8].

Laser Speckle Vibrometry

Laser Speckle Vibrometry detects vibrations from changes in the speckle pattern over time. Unlike LDV, it is much simpler, requiring only at least 1 photodiode or camera to capture intensity changes.

Veber et al. [10] used a single photodiode with a spatial mask and telephoto lens. Their system was able to measure vibrations at distances up to 50 m using a high power (1.5 W) laser. It detected oscillations of a sheet of paper exposed to sound pressure at 50 dB up to 5 kHz. On the other hand, Streli et al. [9] demonstrated a camera-based method using a 200 FPS camera with laser pointer modules to detect finger taps on a surface. However, the limitations of camera frame rates restrict detection to lower frequencies.

Speckle vibrometry is effective for small-amplitude vibrations (including translation and pitch) but struggles with vibrations parallel to the laser beam (where LDV excels). Its simplicity and cost-effectiveness make it an attractive alternative to LDV for lower-cost applications.

IMPLEMENTATION

System Design

Backscattered light from an object hit by a laser, like a speckle pattern, is typically very low in intensity. How low depends on the situation.

The light intensity I_b at a distance d is proportional to the laser power and decays quadratically with distance and can be calculated using a simplified model:

$$I_b = \frac{P \cdot \rho}{2\pi d^2}, \quad (1)$$

where:

- P is the power of the incident laser beam, measured in watts (W),
- ρ is the reflectivity of the surface (unitless),
- d is the distance from the scattering surface to the photodiode, measured in meters (m).

How much current?

A photodiode converts the backscattered light intensity into current:

$$I_{\text{photo}} = I_b \cdot A_{\text{PD}} \cdot R, \quad (2)$$

where:

- I_b is the incident intensity at distance d (W/mm^2),
- A_{PD} is the area of the photodiode (mm^2),
- R is the photodiode responsivity (A/W).

Using typical values like $R = 0.5\text{A/W}$, $A_{\text{PD}} = 2\text{ mm}^2$, $P = 1\text{ mW}$ and $d = 0.3\text{ m}$ we are left with tiny photocurrents in the 500 pA range!

Therefore, a low noise and high gain first stage amplifier becomes necessary to achieve a workable output signal.

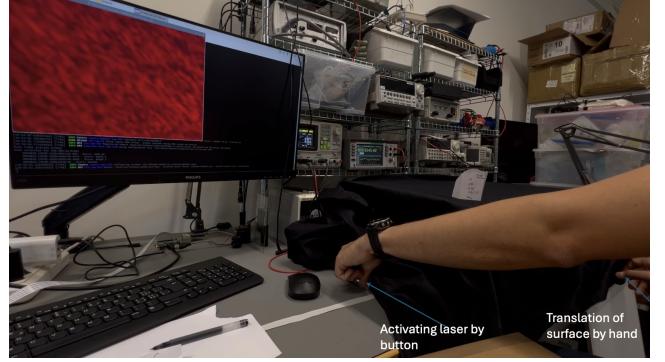


Figure 2. Speckle pattern visualised by RPI Cam HQ (from Setup in Figure 10)

To be certain, we conduct a small set of experiments (setup is shown in Figure 10) to measure the current produced by a photodiode exposed to incident laser speckle pattern.

A typical store-bought class 1 red laser pointer has an output power under 0.5mW. Using this laser pointer and the Thorlabs PDA36A2 photodector (with a photodiode area: $A_{\text{PD}} = 13\text{ mm}^2$ and same d as above), we observe 13 nA of current. This means that we need to at least be able to measure currents on this order of magnitude for class 1 lasers at 30 cm distance.

How big a photodiode?

Can we test if a photodiode of a given size can be sensitive to a speckle pattern in motion? Recall that the sensor must be smaller than the speckle size in order to resolve speckle motion. Using the formula for mean speckle size, assuming a red laser at 650 nm and 30 cm distance, we find the resulting mean size to be around 100 um. This is too small for common photodiodes, but we make the assumption - based on observations of real speckle patterns - that the variance in size is large.

To validate this assumption, we masked the detector with a 0.9mm x 0.9mm pinhole on copper tape to cover the aperture of the detector (inspired by [10]). We set the surface in motion and observed the output on a multimeter as well as on camera. As the speckle oscillated on camera, so did the multimeter output.

On Digikey, found the most sensitive, small, low cost photodiode: the VEMD2704 by Vishay with an area of 1.5 mm².

We make the following observations:

- A CMOS sensor pixel is a photodiode and has as determined size.
- We can emulate the output of a larger photodiode by integrating over all pixels over the same area as the larger photodiode.
- The sensor area of the RPI camera is large enough to accommodate 9 VEMD2704 photodiodes (see Figure 4).

Using this knowledge, we record a video of a speckle pattern in motion and cut out the pixels corresponding to a grid of

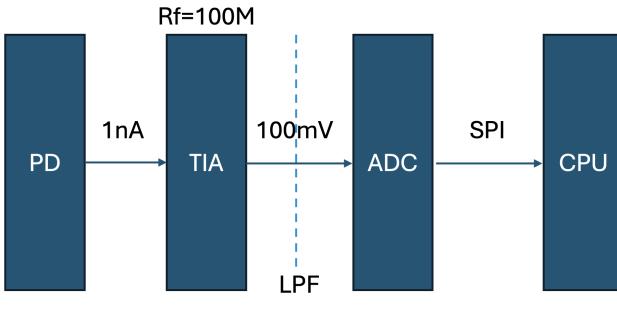


Figure 3. Block diagram

areas the same sizes as the VEMD2704. We establish that an algorithm similar to the one used by Strelci et al [9] can be used to combine the outputs of the photodiodes in order to create a 1d motion signal. Figure 4 shows the resulting 1d signal of motion. The section on Signal Processing discusses this in detail.

Hardware Implementation

The system block system block diagram is given in 3 using the order of magnitude values devised in the initial experiments.

Photodiodes are commonly amplified using a transimpedance amplifier (TIA), although alternative options exist, such as current integrators like the DDC118. This application focuses on capturing high-frequency signals of up to 1 kHz, necessitating specific requirements for the operational amplifiers used.

The essential requirements for the op-amps include:

- A minimum of two op-amps in a single package.
- A target price of approximately \$5 per chip.
- JFET input with low input bias current.
- Capability to operate on a single power supply.

The OPA2380 fulfilled these requirements and a PCB was designed and built according to the datasheet recommendations. Coupled with the VEMD2704 and a 100 MOhm feedback resistor, we can achieve Particular attention to leakage currents was taken, like the implementation of a guard ring. The guard ring is a low impedance path for any stray AC that might want to make its way into the feedback path of the amp. The PCB is shown in Figure 1 and contains a modular photodiode array with bandpass filter.

The bandpass filter is chosen to be at 850nm as that is where silicon photodiodes are most efficient. Lasers at 850nm are common and we are able to filter out a lot of environmental light.

Signal Processing

In this project, a Raspberry Pi 5 (RPI) was used with two types of Analog-to-Digital Converters (ADC).

The first ADC was unable to sample at high enough frequencies. Although it utilized a multiplexer (MUX), the channel switching was controlled via SPI, making it challenging to manage the switching delay. This limitation introduced a

significant amount of noise, which was also noted in several GitHub issues reported by users.

A second ADC was then tested, featuring a higher sample rate and advertised synchronous sample readout capability. This ADC is designed as a Raspberry Pi HAT and uses the Pi's 5V supply as its analog reference. However, this reference is very noisy, with peak-to-peak noise in the millivolt range. To mitigate this issue, a bench power supply was used to power the ADC externally.

To convert the 9-channel photodiode array readings into a single vibrometry signal, we compute the inter-channel variance, explained later on. First, we remove common-mode fluctuations by subtracting the instantaneous mean across all channels:

$$s_i(t) = r_i(t) - \frac{1}{n} \sum_{k=1}^n r_k(t) \quad (3)$$

where $r_i(t)$ is the raw intensity reading from channel i and $n = 9$ is the number of channels. We then compute the inter-channel variance:

$$V(t) = \frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^n |s_i(t) - s_j(t)| \quad (4)$$

This metric quantifies the average magnitude of pairwise intensity differences between spatial channels in the instantaneous speckle pattern. Changes in $V(t)$ over time indicate surface motion and vibration while being robust to common-mode noise.

Raw data from the ADC was recorded and observed in real-time or processed post-capture. Real-time observations were conducted while simultaneously monitoring the speckle camera and the infrared (IR) camera.

Lasers

Several laser sources were built in different configurations as seen in Figure 12. The laser module used for the square array, circular array and single laser measurements is an 850 nm laser (VLM-850-03 by Quarton Inc.). The Realsense D415 Depth Camera (by Intel) has a laser dot projector that can be turned on using the Realsense Viewer Software. To control the amount of laser dots that are output by the Realsense dot projector, an iris diaphragm (Edmund Optics 53906) is used.

Additionally, we reverse engineered the Realsense through visual inspection and found it to look very similar, if not identical, to the BELICE projector module by ams. To confirm this theory, we measured the laser output power with an integrating sphere on optical power meter (the Artifex OPM150) and found a similar nominal output power of 250 mW per module. As a proof of concept for potential future experiments, a small driver circuit was built based on the example in the LT1800 opamp datasheet [3].

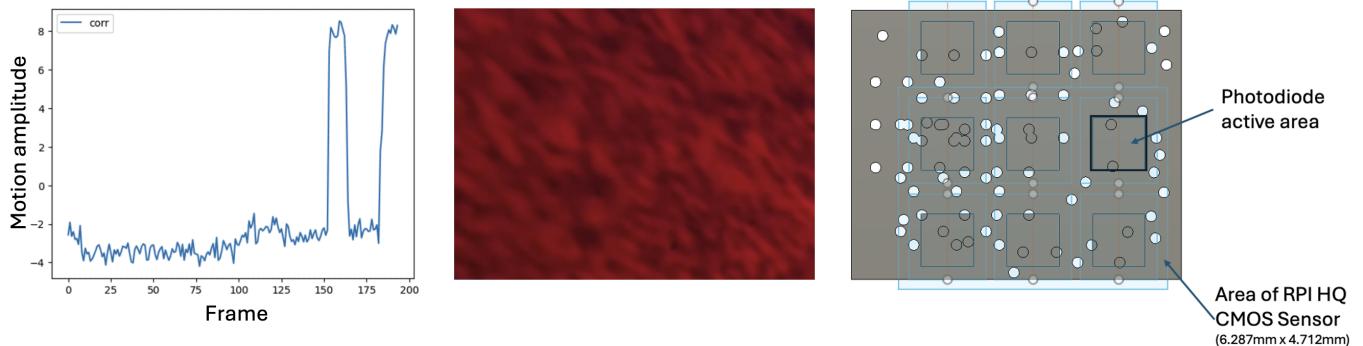


Figure 4. Left to right: Peaks show translation of speckle pattern, signifying a change of the inter-channel variance. The speckle pattern on the camera sensor. The camera sensor with an overlayed photodiode grid.

EVALUATION

Hypotheses

The primary hypothesis is that the motion of speckle patterns can be effectively visualized using a photodiode array. Additionally, it is hypothesized that the use of multiple lasers will influence the signal-to-noise ratio (SNR) of the measurements.

Apparatus

The custom-designed PCB transmitted its analog signals to an 8-channel Digilent ADC MCC 128 DAQ Hat, which was powered by a 5V low-noise bench power supply. A piezo disc, positioned at a distance of approximately 30 cm, was excited using a signal generator set to produce a sine wave at 133 Hz with a peak-to-peak amplitude of 3 V.

For visual alignment of the lasers, one camera was employed, while another camera was used to monitor the presence of speckles. Both the cameras and the photodiode array were equipped with $8 \times 8 \times 1$ mm bandpass filters at 850 nm with a 40 nm FWHM and a 90% transmission rate (manufacturer: Haian Subei Optical Glass Factory). Data acquisition was handled by a Raspberry Pi, which recorded the ADC data. Data processing was performed in real time during qualitative experiments or recorded for later post-processing.

Procedure

The initial steps of the evaluation involved SPICE simulations to analyze the Bode plot and transient response of the amplifier, as illustrated in Figures 6 and 5. These simulations provided the SNR to be 81.6 dB for an output value of approximately 80 mV (corresponding to a 1 nA photocurrent at 1000 kHz). This demonstrates that the amplifier displayed stable behavior with high gain and SNR. Based on these results, the PCB was layouted, ordered and assembled.

Following the PCB assembly, it was cleaned using isopropyl alcohol (IPA) and compressed air, particularly under the pads of the amplifier section. Removing all flux residue from the PCB was deemed critical to ensure stable operation. All measurements were conducted in a light-controlled environment to minimize interference from external light sources.

To assess the influence of multiple laser sources, a controlled surface vibration of a piezo disc (at 133 Hz) was measured,

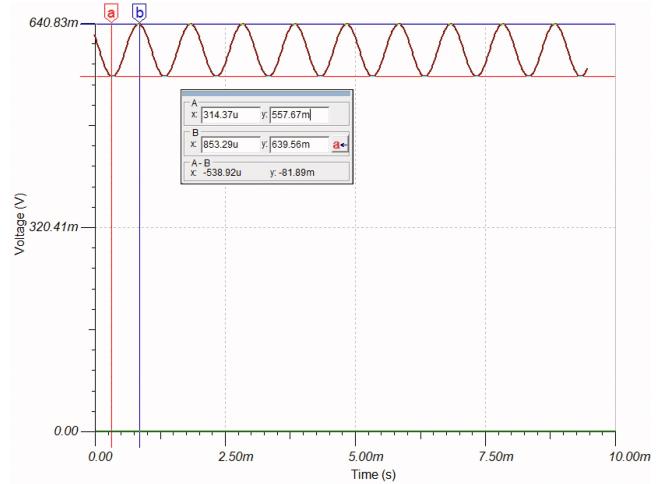


Figure 5. Transient response captured during SPICE simulation, highlighting amplifier dynamics and stability.

while lasers in the square array were activated incrementally (Figure 12).

For each configuration, the power spectral density of the inter-channel variance signal was calculated, and the SNR was analyzed. The spectral analysis, shown in Figure 8, established a positive correlation ($R^2 = 0.60$) between the number of active lasers and the detection SNR. A control measurement with all lasers switched off confirmed that the recorded signals originated from laser speckle patterns.

Additionally, time-domain signals captured by multiple photodiodes were compared to verify that each photodiode detected phase-shifted signals, which indicated the presence of a moving speckle pattern. An infrared (IR) LED was integrated into the setup to validate that the observed vibrations were dependent on coherent light.

RESULTS

Speckle Motion Detection

The results confirmed that the motion of speckle patterns was successfully detected using the discrete photodiode array. Phase-shifted signals were observed across multiple photodiodes, indicating the presence of a moving speckle pattern.

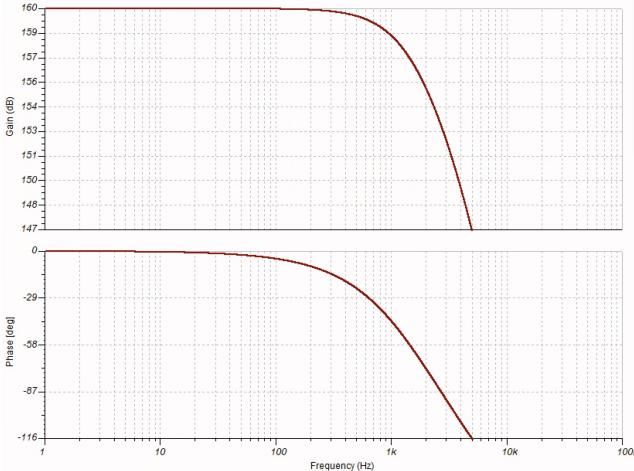


Figure 6. Amplifier frequency and phase response.



Figure 7. The Raspberry Pi No-IR (top left) was used to align invisible IR lasers, the Raspberry Pi HQ camera for showing speckle patterns and the (masked) Thorlabs detector for establishing a photocurrent baseline for our amplifier.

This phase information confirmed that the photodiode array could effectively visualize the dynamic speckle motion. The use of an IR LED further validated that the detected signals originated from laser speckle patterns and not from external light interference.

Signal-to-Noise Ratio (SNR) Analysis

The SNR analysis demonstrated a positive correlation between the number of active lasers in the square array and the measurement quality. Incremental activation of the lasers resulted in an improvement in SNR, as shown in Figure 8. The power spectral density analysis highlighted the 133 Hz vibration component of the piezo disc, with an R^2 value of 0.60 indicating a moderately strong relationship between the number of lasers and SNR enhancement.

Control experiments with all lasers turned off verified that the observed signals originated from the laser speckle patterns and not from other sources. These results support the hypothesis

that the use of multiple lasers enhances the SNR, improving the sensitivity of the system.

Circuit Performance

The custom-designed PCB and amplifier circuit were validated using SPICE simulations and experimental measurements. The Bode plot in Figure 6 demonstrated a flat frequency response with high gain, while the transient response shown in Figure 5 confirmed system stability.

Impact of Experimental Parameters

The experiments revealed several critical factors impacting the measurement results. The PCB required thorough cleaning with IPA and compressed air to eliminate flux residue, as any remaining contaminants introduced noise. Additionally, conducting experiments in a light-controlled environment was essential to prevent saturation of the opamp and ensure reliable data capture. The PCB had to be enclosed in a metal shield to limit the amount of incoming noise. Dot projector alignment, facilitated by cameras, is critical for ensuring consistent speckle patterns and uniform distribution across the photodiode array.

Limitations

The opamp saturated in sunlight, rendering the signal irrecoverable in such conditions. Dot projectors cannot be effectively used as the reflected light intensity is too low. Furthermore, the bandwidth of the system is limited to 1kHz.

Future Work

To address the identified limitations and improve the system, several avenues for future work are proposed:

- **Higher Bandwidth:** Replace the current opamp with one that has a higher gain-bandwidth product (GBW) to increase the system bandwidth and enable detection of faster speckle movements.
- **Current to Digital Amp:** Integrate a current-to-digital amplifier chip, such as the DDC118, to enhance system integration and make the PCB smaller.
- **Sensor Vibration Compensation:** Mitigate the influence of vibrations from the sensor itself by incorporating an accelerometer to subtract self-induced motion artifacts from the measurements.
- **Synchronous Detection:** Modulate the laser light with a known reference signal to perform synchronous detection (aka lock-in amplifier) for more robustness against daylight.
- **Use Less Photodiodes:** Quadrature photodiodes like the OPR5925 that pack 4 photodiodes into 1 SMD package could be used to make the sensor smaller.

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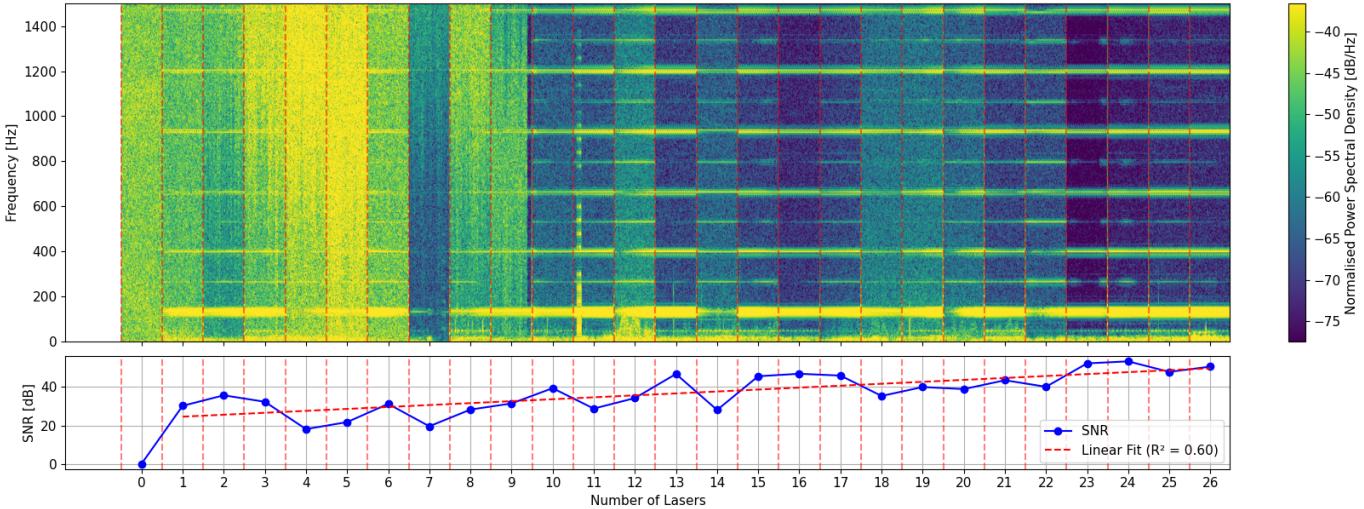


Figure 8. Spectral analysis of a 133 Hz surface vibration under different laser configurations. Top: Power spectral density showing the target frequency component. Bottom: SNR improvement with increasing number of active lasers.

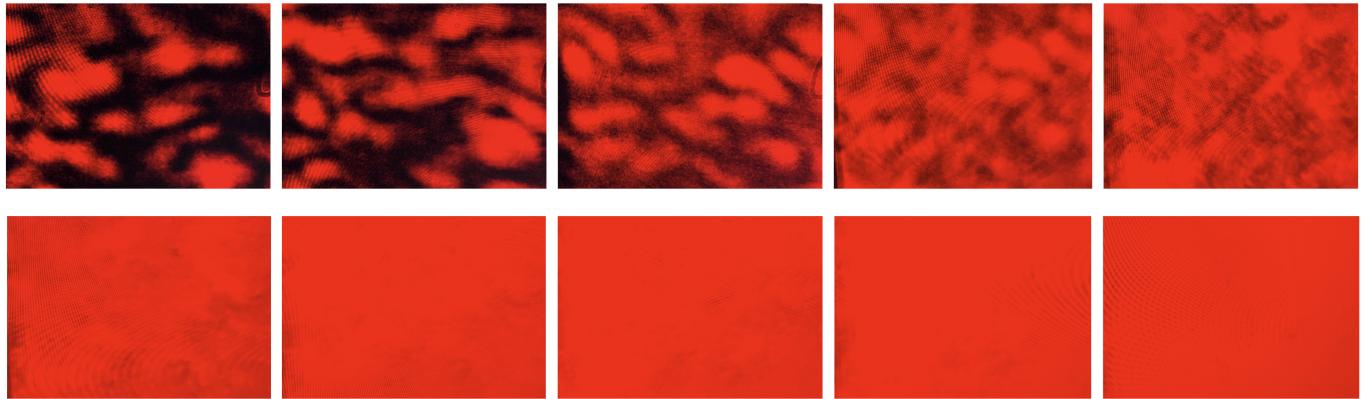


Figure 9. Visualization of speckle patterns under different 1 mW IR laser configurations using the square laser array from Figure 12. Top left: 1 laser. Bottom right: 10 lasers.

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REFERENCES

- [1] Justin Chan, Ananditha Raghunath, Kelly E. Michaelsen, and Shyamnath Gollakota. 2022. Testing a Drop of Liquid Using Smartphone LiDAR. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 6, 1, Article 3 (March 2022), 27 pages. DOI: <http://dx.doi.org/10.1145/3517256>
- [2] Gary Cloud. 2007. Optical Methods in Experimental Mechanics.: Part 27: Speckle Size Estimates. *Experimental Techniques* 31, 3 (May 2007), 19–22. DOI: <http://dx.doi.org/10.1111/j.1747-1567.2007.00201.x>
- [3] Analog Devices. 2009. LT1800 Datasheet. (2009). <https://www.analog.com/media/en/technical-documentation/data-sheets/1800fa.pdf> Accessed October 2024.
- [4] Ietezaz Ul Hassan, Krishna Panduru, and Joseph Walsh. 2024. An In-Depth Study of Vibration Sensors for Condition Monitoring. *Sensors* 24, 3 (2024).
- [5] Juuso Heikkinen and Gary S Schajer. 2020. Remote Surface Motion Measurements Using Defocused Speckle Imaging. *Optics and Lasers in Engineering* 130 (July 2020), 106091. DOI: <http://dx.doi.org/10.1016/j.optlaseng.2020.106091>
- [6] Xiao-Bei Hu, Ming-Xuan Dong, Zi-Hao Zhu, Wen-Kai Gao, and Carmelo Rosales-Guzmán. 2020. Does the structure of light influence the speckle size? *Scientific Reports* 10 (2020), 199. DOI: <http://dx.doi.org/10.1038/s41598-019-56964-0>
- [7] Rinaldo Paar, Ante Marendić, Ivan Jakopac, and Igor Grgac. 2021. Vibration Monitoring of Civil Engineering Structures Using Contactless Vision-Based Low-Cost IATS Prototype. *Sensors* 21, 23 (2021), 7952. DOI: <http://dx.doi.org/10.3390/s21237952>
- [8] S. J. Rothberg, M. S. Allen, P. Castellini, D. Di Maio, J. J. J. Dirckx, D. J. Ewins, B. J. Halkon, and others.

2017. An International Review of Laser Doppler Vibrometry: Making Light Work of Vibration Measurement. *Optics and Lasers in Engineering* 99 (December 2017), 11–22. DOI: <http://dx.doi.org/10.1016/j.optlaseng.2016.10.023>
- [9] Paul Streli, Jiaxi Jiang, Juliete Rossie, and Christian Holz. 2023. Structured Light Speckle: Joint Ego-Centric Depth Estimation and Low-Latency Contact Detection via Remote Vibrometry. , Article 26 (2023), 12 pages. DOI:<http://dx.doi.org/10.1145/3586183.3606749>
- [10] A. A. Veber, A. Lyashedko, E. Sholokhov, A. Trikshev, A. Kurkov, Y. Pyrkov, A. E. Veber, V. Seregin, and V. Tsvetkov. 2011. Laser Vibrometry Based on Analysis of the Speckle Pattern from a Remote Object. *Applied Physics B* 105, 3 (November 2011), 613–617. DOI: <http://dx.doi.org/10.1007/s00340-011-4585-1>
- [11] Zihan Yan, Yuxiaotong Lin, Guanyun Wang, Yu Cai, Peng Cao, Haipeng Mi, and Yang Zhang. 2023. LaserShoes: Low-Cost Ground Surface Detection Using Laser Speckle Imaging. (2023), 1–20. DOI: <http://dx.doi.org/10.1145/3544548.3581344>

EXPERIMENTAL SETUPS

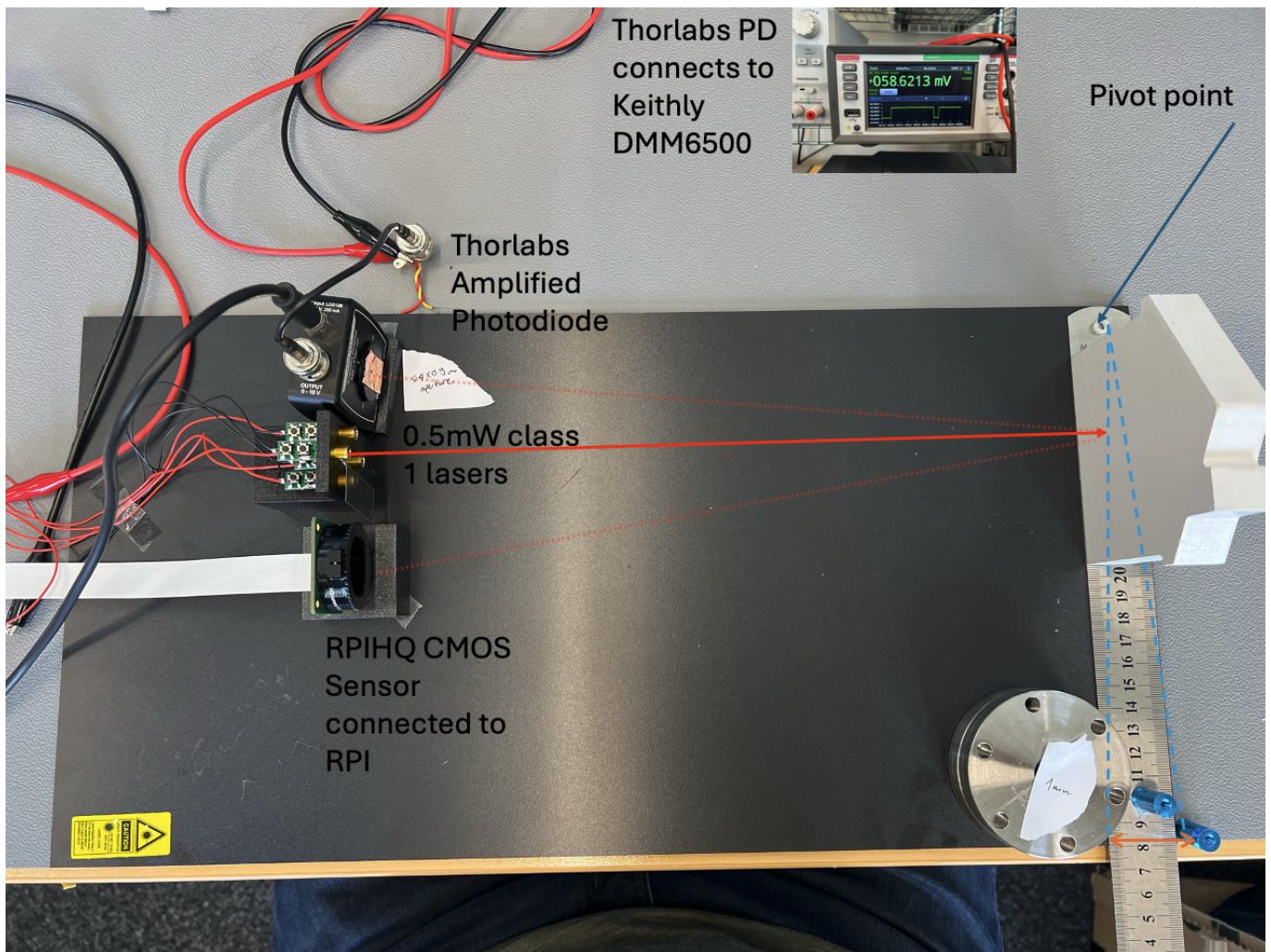


Figure 10. A laser is pointed at a painted wooden surface. A multimeter measured the current from a masked photodiode. A RPI HQ camera is used as a reference to visualise the speckle pattern.

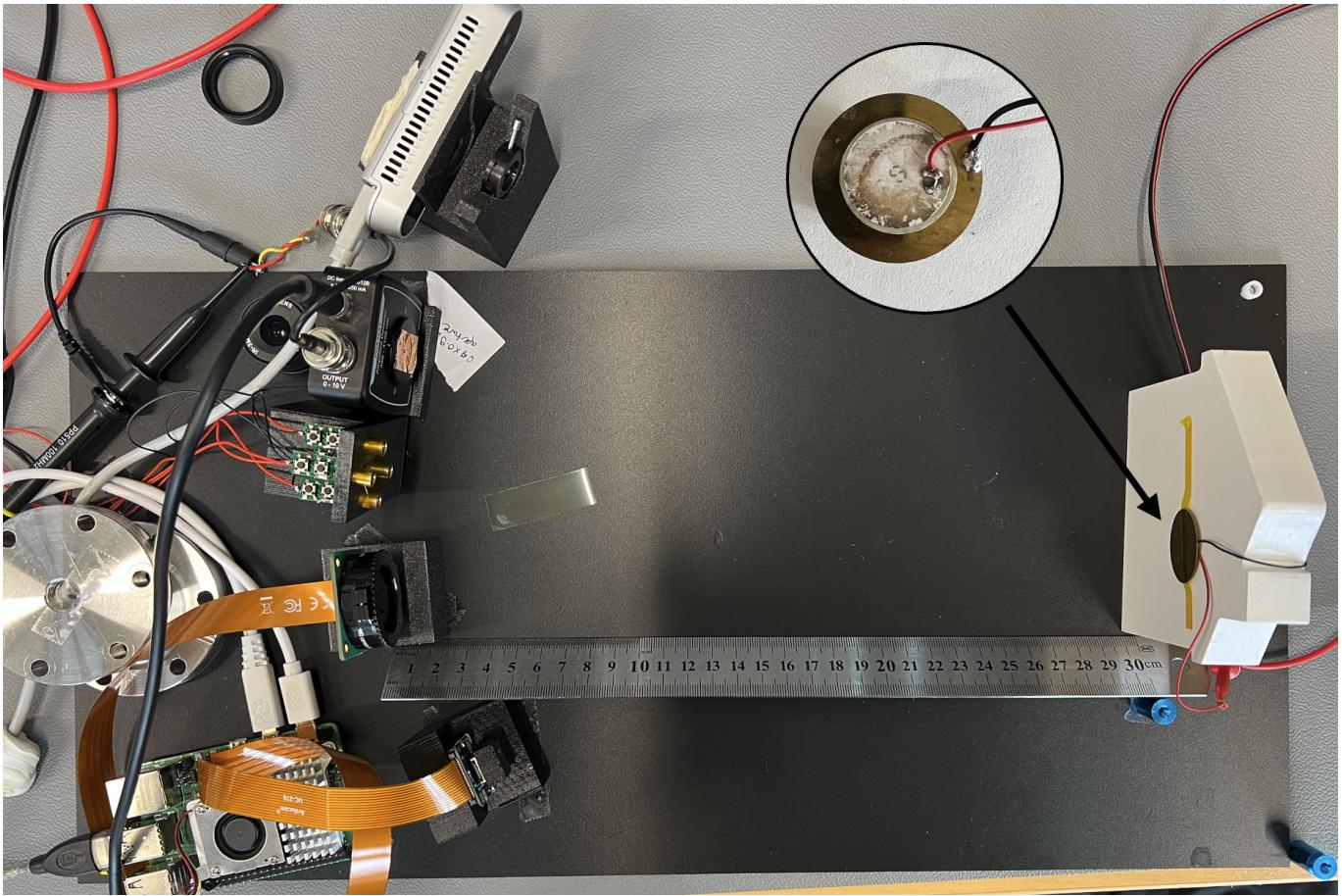


Figure 11. Photo of the experimental configuration with the piezo disc.

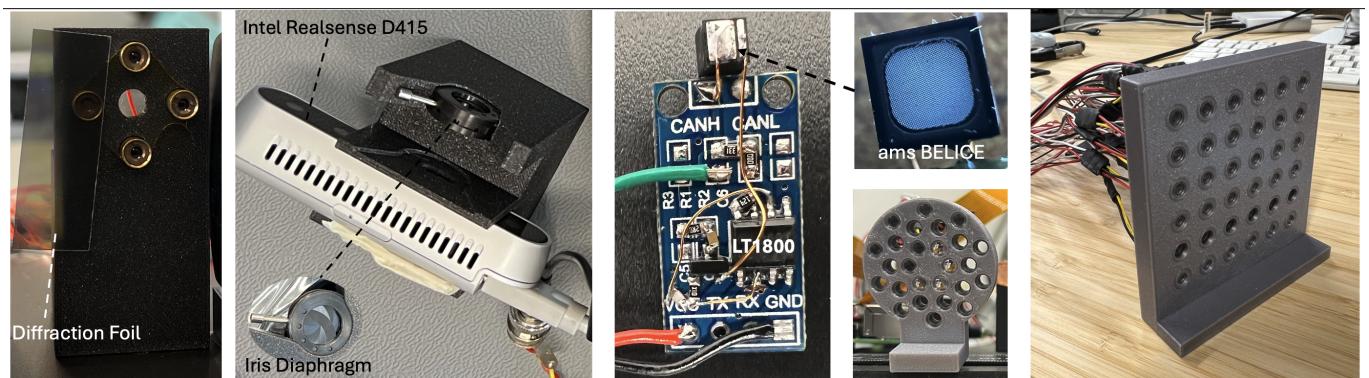


Figure 12. The different laser setups used from left to right: Red laser for initial emulation experiments, Realsense 415 dot projector with iris, reverse engineered Realsense dot projector and driver circuit, discrete circular and square IR laser arrays.