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 Streli
Sensing, Interaction & Perception Lab
ETH Zürich

January 6th, 2024

Sam Sulaimanov
Discrete Photodetector Array Approach to High-Bandwidth Vibration Sensing
Semester Project, January 6th, 2024
Supervisors: Prof. Dr. Christian Holz and Paul Streli

ETH Zürich
Department of Computer Science, ETH Zürich
Universitätstrasse 6
8092 Zürich

Discrete Photodetector Array Approach to High-Bandwidth Vibration Sensing

Sam Sulaimanov
Sensing, Interaction & Perception Lab
Department of Computer Science, ETH Zürich
ssamir@ethz.ch

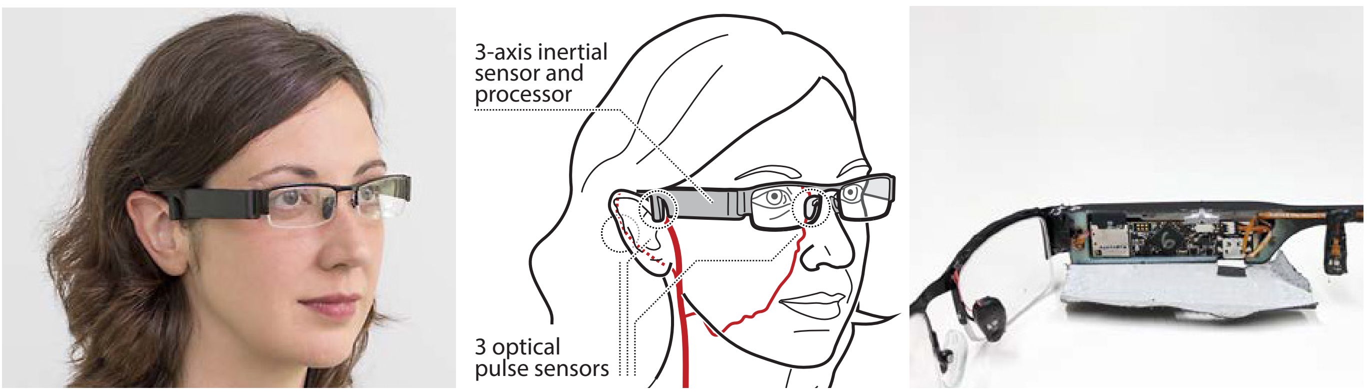

Figure 1. *Optional:* Consider including a teaser figure. Think of it as a visual abstract, illustrating the main contributions of your project. This could include photos, algorithms, results, etc. Oftentimes, this teaser contains multiple subfigures, such as (a) something, (b) something, and (c) something.

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 thus a poor choice of sensor for high rate oscillations. The present work explore 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.

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 [**?**].

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 [**?**] 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 photodetectors 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 [?] 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:

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

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. [?] 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.

figures/pattern_laser_progression.png

Speckle size can be tuned without changing d or a by defocused imaging, proposed by Heikkinen and Schajer [?]. 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. [?] 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. [?] 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 if proportional to the velocity [?]. 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 [?].

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. [?] 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. [?] 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

- add system block diagram -

Camera Sensor Proof of Concept

- how many photodiodes can we use? how small can we get them to be? area of photodiodes ==> how much photocurrent. therefore, setup an experiment with a RPI HQ camera sensor and see view the resulting speckle pattern. translate the house and watch the speckle pattern translate too. use red laser as the wavelength doesnt for easy experimentation.

video of the speckle pattern motion

Hardware Implementation

- photodiodes are typically amplified by TIA. there are other possibilities, like the current integrator (DDC118) - this application aims to capture high freq up to 1khz, so we have the following opamp requirements: -> at least 2 opamps in 1 package -> price around 5usd per chip -> JFET inputs / low input capacitance -> operable on a single supply

- thus the choice of amplifier –> OPA2380 with 90 MHZ, 2 opamps per chip, 5 usd

Signal Processing

- rpi with two types of ADC were used - first ADC was unable to sample at high enough frequencies. it used a MUX but the channel switching was controlled via SPI. therefore the switching delay was hard to control and introduced a high amount of noise. Github issues online also found this issue to be limiting. - a second ADC was tried, that has a higher sample rate and advertised synchronous sample readout capability. this ADC is a raspberry pi hat and uses the Pis 5V supply as its analog reference, which is very noisy, with peak to peak noise in the millivolt range. To mitigate this issue, a bench supply powered the ADC externally. - ADC raw data was recorded and observed in realtime or post processed. Realtime observations were done while watching the speckle camera and the IR camera simultaneously.

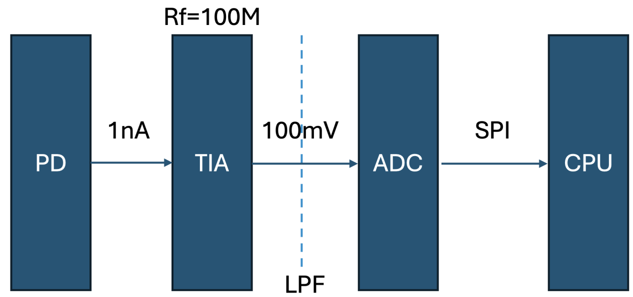

Figure 2. Block diagram).

dont forget to mention how speckle size [?]

EVALUATION

Hypotheses

speckle pattern motion can be visualised via a photodiode array multiple lasers an effect on SNR

Apparatus

short: parameters picked technology used dependent variables ? table vibration

Procedure

simulation SPICE independent variables how long an experiment lasts room is dark time domain comparison of signals between multiple photodiodes IR LED used to prove vibration is not just light

RESULTS

By aiming the laser beam at the oscillating surface sequentially, multiple vibrations sources could be sampled and distinguished from each other within the same environment. *In this section, you report the results of your evaluation and your work in a structured manner. In addition to raw values, charts, graphs, tables, use aggregates and statistical methods to evaluate the statistical significance of your results.*

Note: Even though you report your results in this section, refrain from judging them at this point. Although this section should be independent of your judgment, it should not be a mere dump of values. Define subsections when appropriate and try to tell a story using these numbers.

DISCUSSION

What was surprising? unexpected? intriguing?

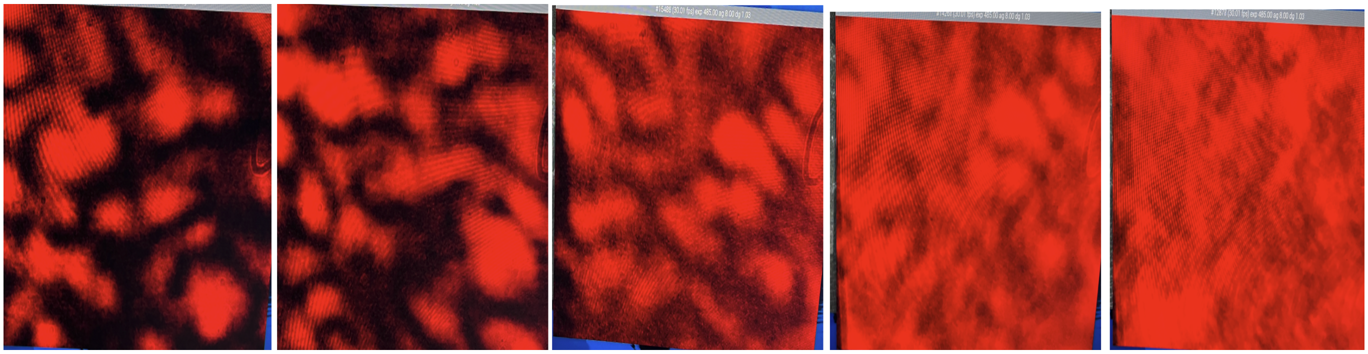

Figure 3. maxwidth cap

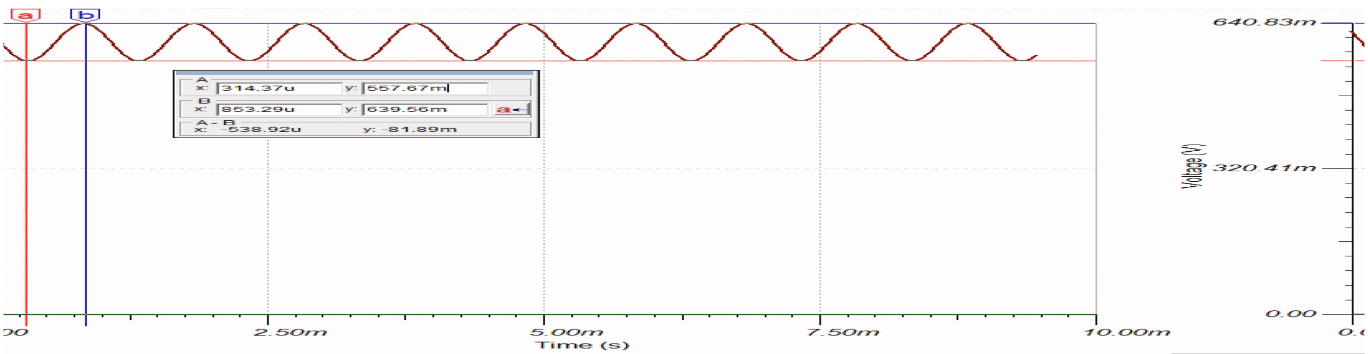

Figure 4. maxwidth cap

Were any hypotheses confirmed or rejected?

Were the predictions of any theory upheld or refuted?

What is important and worthy of again being called to the reader's attention?

What are the implications of your results?

What do they mean for this topic and your field?

Did you fulfill the promises you set out in the Introduction via the claims you made about your work?

What worked and what did not work?

CONCLUSION

research question answer: it is possible to detect a speckle pattern in motion using a discrete photodiode array

limitations: - in sunlight, the opamp saturates and the signal is unrecoverable - Bandwidth should be increased for

Future work

- use an opamp with higher GBW for higher Bandwidth - use a current to digital amplifier chip like the DDC118 for higher integration - subtrace the vibrations of the sensor itself using an accelerometer

ACKNOWLEDGMENTS

Optional space to thank people. If you include this section, make sure to mention people you collaborated with.

REFERENCES

[1] Justin Chan, Anandita 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] Ietezaz Ul Hassan, Krishna Panduru, and Joseph Walsh. 2024. An In-Depth Study of Vibration Sensors for Condition Monitoring. *Sensors* 24, 3 (2024).

[4] 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

[5] 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

[6] Rinaldo Paar, Ante Marendić, Ivan Jakopec, 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

[7] 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

[8] 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

[9] 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

[10] 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