Mobile laser Doppler vibrometry motion tracking and vibration compensation for in-field vehicular deployments

by Abdel Darwish

Thesis submitted in fulfillment of the requirements for the degree of

Doctor of Philosophy

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Certificate of Original Authorship

I, Abdel Darwish, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Signed: Production Note: Signature removed prior to publication.

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Abstract

The laser Doppler vibrometer (LDV) has become an indispensable tool in vibration engineering, boasting high bandwidths and spatial resolutions unrivalled by traditional contacting accelerometers - all whilst doing so via non-contact means. Since their widespread adoption, their application envelope as vibration transducers has been steadily expanding, encompassing increasingly impactful and interesting areas. This work focuses specifically on the significant potential of deploying LDV from mobile platforms, for example, terrestrial or airborne vehicles, since it has the potential to substantially increase land coverage rates whilst simultaneously enabling access to hazardous or remote areas. This field has already received some interest, with research taking place into mobile buried landmine detection, intelligence gathering from drones and structural health monitoring from drones. However, these represent only a small fraction of potential applications. The first portion of this work explores and mitigates the effects of any instrument motion on mobile LDV deployment, while the second portion explores a novel mobile application for a robust LDV: non-contact vibro-acoustic object recognition and enhanced point cloud perception for autonomous systems.

In the reference frame of the sensor head, the motion can be divided into two broad categories: translational motion along the beam axis *or* translational motion in the two orthogonal axes, plus the three rotational degrees of freedom. Since the underlying physics of the LDV dictate that the sensor head is as sensitive to self-vibration in the beam axis as it is to the target vibration in the beam axis, sensor head vibration could compromise the measurement. Whereas motion in the five non-beam axes would cause the measurement beam to stray from the intended measurement location. Two separate approaches can mitigate the effects of these two distinct phenomena, referred to herein as *measurement correction* and *arbitrary tracking*.

Since the sensor head is as sensitive to self-vibration as it is to target vibration, measurement correction is required when self-vibration is present. Despite the success of the existing, single accelerometer-based measurement correction technique, there were two main improvements to be made. Firstly, the technique was fundamentally limited to stationary signals due to the frequency domain-based signal processing employed, requiring a time domain alternative for mobile deployments. Secondly, the technique lacked proper accelerometer signal handling, leading to sub-optimal performance, therefore requiring a revised technique. As such, the first portion of this thesis focuses on the development of a new time domain and revised frequency domain-based processing techniques that display up to eight-fold improvements in performance over the previous technique. This is accompanied by a rigorous analytical model describing the effects of synchronisation quality on both techniques, delving into the nuances of time domain-based signal synchronisation. Finally, the thesis covers the extension of these signal processing techniques to be compatible with existing theoretical *scanning* LDV measurement correction work, with the first experimental validation of the technique on the Multi-Axis Simulation Table taking place.

While arbitrary path-tracking LDV solutions exist, current techniques cannot meet the strict weight requirements of a drone-mounted LDV system. As such, the development of a novel tracking system specifically tailored for the hovering drone is described; specifically focused on correcting small pitch and roll adjustments that drones make while holding their position in a hover. The proposed system employs a standard galvanometer steering mirror setup found in scanning LDV systems to counter-rotate the beam rather than the entire instrument. This technique's performance is then assessed on the Multi-Axis Simulation Table, configured to simulate a hovering drone in extreme conditions. Results show that the beam motion was reduced by 68%.

With a comprehensive framework established for mitigating the effects of both beam axis and non-beam axis motion, the focus shifts onto applications for such a system, specifically, the possibility of LDV integration into autonomous systems. Initially, this portion of the work describes a novel vibro-acoustic object recognition technique utilising convolutional neural networks to classify the LDV measurements. A rigorous five-fold cross-validation showed it is possible to recognise acoustically excited objects with up to 99.8% accuracy. Finally, the thesis explores the possibilities of merging point clouds with LDV scans for enhanced perception applications for autonomous systems in a first-of-its-kind proof-of-concept system, allowing autonomous systems to "see" the surrounding acoustic world.

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