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Christoph M. Monsberger

Distributed Fiber Optic Shape Sensing in Structural and Geotechnical Engineering: Principles and Applications

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Abstract

Civil structural health monitoring (CSHM) has become significantly more important within the last decades due to rapidly growing demand on new constructions world-wide with respect to limited space and increased sustainability, as well as longer service lifetimes of existing structures. Knowledge about the structural performance and health condition is essential to plan and design condition-based maintenance works. State-of-the-art monitoring techniques, including displacement readings at the surface (total stations, GNSS, laser scanning, etc.), internal deformation sensors (strain gauges, tilt sensors, etc.) as well as manual or image-based visual inspections, often have limitations, either in the spatial or the temporal resolution. As a consequence, local structural deficiencies might be identified belatedly or even overlooked completely.

This thesis introduces enhanced monitoring concepts for structural and geotechnical applications based on distributed fiber optic sensing (DFOS). The distributed strain sensing feature is combined with geodetic techniques and one-dimensional displacement sensors to analyze fully-distributed curvature and bending profiles along civil structures, where the optical fibers are directly embedded inside or attached along the structure. Corresponding sensing and evaluation algorithms as well as basic characteristics of different fiber optic sensing technologies are addressed. General DFOS capabilities are demonstrated through sensor calibration results and laboratory tests on the spatial resolution.

Various applications are presented, in which individually developed approaches have been integrated into real-scale structures using different DFOS sensors and installation techniques. These include linear objects with different material composition like grouted steel anchors or concrete beams and curved structures such as tunnel linings. The installations were interrogated using fully-distributed sensing units based on Rayleigh and Brillouin scattering as well as quasi-distributed fiber Bragg grating (FBG) interrogators.

The suitability of different designs is validated within laboratory experiments, where the results are proven using pointwise displacement transducers, geodetic measurements and image-based sensing techniques. It is shown that relative errors between the independent technologies can be achieved in the sub-millimeter range, depending on the DFOS system design and sensing principle. Practical realizations and autonomous monitoring campaigns on-site also demonstrate the capabilities in field environment.

Zusammenfassung

Die zuverlässige Überwachung strukturrelevanter Parameter gewinnt in den letzten Jahrzehnten ständig an Bedeutung, nicht zuletzt infolge des weltweit steigenden Bedarfs an neuer Infrastruktur mit eingeschränkten Umsetzungsräumen und zusätzlichen Anforderungen hinsichtlich Nachhaltigkeit sowie der Erhöhung der Nutzungsdauer bestehender Bauwerke. Informationen über die strukturelle Beschaffenheit und den Zustand sind zur Planung vorausschauender Erhaltungsmaßnahmen essentiell. Konventionelle Überwachungssysteme wie z.B. Verschiebungsmessungen an der Oberfläche (Totalstation, GNSS, Laserscanning, etc.), interne Deformationsmessungen (Dehnungsaufnehmer, Neigungssensoren, etc.) oder manuelle und bildbasierte Inspektionen zeigen häufig Limitationen in der räumlichen Auflösung bzw. der Messfrequenz, weshalb lokale strukturelle Defizite erst spät oder gar nicht erkannt werden können.

In dieser Dissertation werden erweiterte Anwendungskonzepte zum strukturellen und geotechnischen Monitoring basierend auf verteilten faseroptischen Sensoren behandelt. Die Eigenschaft der verteilten Dehnungsmessung wird mit geodätischen Messmethoden sowie eindimensionalen Verschiebungssensoren kombiniert, um eine kontinuierliche Beurteilung von Krümmungs- und Biegeprofilen entlang von Strukturen abzuleiten. Die optische Glasfaser ist hierbei direkt im Bauwerk integriert oder an der Oberfläche appliziert. Entsprechende Auswertealgorithmen und grundsätzliche Eigenschaften faseroptischer Sensorsysteme werden im Rahmen der Arbeit diskutiert. Zugehörige Sensorkalibrierungen und Laboruntersuchungen im Bezug auf die räumliche Diskretisierung zeigen allgemeine Fähigkeiten verteilter faseroptischen Systeme.

Die Anwendungsbeispiele präsentieren individuell entwickelte Konzepte mit unterschiedlichen Sensortypen und Installationstechniken, welche in Infrastrukturbauwerke im Realmaßstab integriert wurden. Diese inkludieren lineare Objekte mit unterschiedlichen Materialen (mantelverpresste Stahlstabanker oder Betonbalken) sowie Strukturen mit initial gekrümmter Form (Tunnelschalen). Die Instrumentierungen wurden sowohl mit verteilten faseroptischen Messsystemen basierend auf der Rayleigh und Brillouin-Streuung als auch mit quasi-verteilten Faser-Bragg-Gittern umgesetzt.

Die Eignung der entwickelten Designs wird anhand verschiedener Laborexperimente untersucht, in welchen die faseroptischen Ergebnisse mit punktweisen Wegaufnehmern, geodätischen Messungen und bildbasierten Methoden verifiziert werden. Dabei können, je nach faseroptischem Systemdesign und Messprinzip, relative Fehler zwischen den unabhängigen Messmethoden im Sub-Millimeter erreicht werden. Die praktischen Realisierungen sowie die Durchführung autonomer Messkampagnen beweisen die Einsatzfähigkeiten unter Baustellenbedingungen.

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