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Automatic execution of workflows on laser-scanned data for extracting bridge surveying goals

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ABSTRACT

With the capability of capturing detailed geometry of bridges in minutes, laser scanning technology has attracted the interests of bridge inspectors and researchers in the domain of bridge management. A challenge of effectively utilizing laser scanned point clouds for bridge inspection is that inspectors need to manually extract and measure large numbers of geometric features (e.g., points) for deriving geometric information items (e.g., the minimum underclearance) of bridges, named as bridge surveying goals in this research. Tedious manual data processing impedes inspectors from quantitatively understanding how various data processing options (e.g., algorithms, parameter values) influence the data processing time and the reliabilities of the surveying goal results. This paper shows the needs of automatic workflow executions for extracting surveying goals from laser scanned point clouds, and presents a computational framework for addressing these needs. This computational framework is composed of formal representations of workflows and mechanisms for constructing and executing workflows. Using a prototype system implemented based on this framework, we constructed and quantitatively characterized three workflows for extracting three representative bridge surveying goals, using three metrics of workflow performance defined in this research: exhaustiveness of measurement sampling, reliability of surveying goal results, and time efficiency.

1. Introduction

Laser scanning is a 3D imaging technology attracting the interests of scientists and engineers working in the domain of bridge inspection [13,14,16,20]. A terrestrial laser scanner continuously sends and receives laser signals while rotating horizontally and vertically for measuring the 3D environment around it, with data collection rates of thousands to hundreds of thousands points per second [40]. Such high data collection rates make it possible to acquire dense point clouds capturing features smaller than 1 cm within 50 m from the scanner, while keeping the data collection time less than 10 min (these values may vary based on the scanner used). A case study conducted by the authors shows that an inspector can use a scanner to collect dense point clouds for a 30 m highway bridge within 1 h [38]. Using commercially available 3D reverse engineering environments [18,19], bridge inspectors can construct 3D surface models of bridges based on point clouds, and conduct measurements on these models. This process is known as "virtual surveying" [18,22,24].

During virtual surveying, bridge inspectors manually measure bridge models and derive geometric information items of bridges. Examples of such items are the geometric data items required by the National Bridge Inventory (NBI) program, such as "the minimum vertical underclearance of a bridge" and "the cross-section losses of bridge components." In this paper, these data items are referred to as "*Surveying Goals.*" Even though "virtual surveying" saves on-site surveying time [1,13,36], bridge inspectors need to manually repeat multiple data processing operations for most surveying goals [38]. In the United States, the NBI program requires bridge inspectors to report 27 surveying goals for more than 600,000 bridges biennially [43,46]. Repeating large number of measurements for the surveying goals of all these bridges leads to large amounts of labor hours and possible errors. In addition, each data processing operation in a "virtual surveying" workflow could have multiple alternative implementations based on algorithms of similar data processing functionalities. Furthermore, each algorithm may have multiple parameters influencing the surveying goal results and data processing time [38]. As inspectors desire to know which data processing options best satisfy their needs (e.g., the needed reliability of the surveying goal results), manual data processing seriously constrains inspectors' capabilities of evaluating large number of data processing options.

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For better utilizing laser scanned point clouds in bridge inspection, this research aims at:

(1) Formalizing a computational framework for constructing and executing 3D data processing workflows that can automatically extract bridge surveying goals from laser scanned point clouds;
(2) Exploring the capability of this computational framework in characterizing and comparing the performances of data processing workflows (e.g., reliability, time efficiency) so that inspectors can better explore and understand the impacts of various 3D data processing options.

In [38], we described formal (i.e., computer-interpretable) representations of workflows to capture users' data processing procedures for extracting surveying goals from point clouds. That study identified nine generic operations (detailed in Section 3.1), modeled them as generic operation classes, and created an extensible operation library. Users can select operations from this operation library, and semi-automatically connect them into workflows. Based on formal workflow representations, the research described in this paper focuses on constructing executable workflows for representative surveying goals, exploring mechanisms capable of automatically executing these workflows, and characterizing the performance of these workflows in terms of the exhaustiveness of measurement sampling, reliability of surveying goal results, and time efficiency (detailed in Section 8). Specifically, we studied three representative surveying goals: "the minimum vertical underclearance of a bridge," "the minimum horizontal clearance under a bridge," and "average cross-section losses of individual piers of a bridge." We selected these three goals because they cover two major categories of surveying goals: Space Clearance, and Area; 18 out of 27 NBI related surveying goals fall into these two categories. Detailed discussions about the representativeness of surveying goals are in [38].

2. Motivating case

To understand the potentials of using laser scanned data for bridge inspection, we conducted a case study on a 30 m single-span highway bridge, which was hit by oversized trucks twice partially due to inaccurate documentation of its "minimum vertical underclearance." Once the point clouds were collected using two different scanners, we constructed 3D bridge models using a commercially available 3D reverse engineering environment (Fig. 1a), and manually took measurements on these models (Fig. 1b and c).

The reverse engineering environment used in this case study provides functionalities for generating cross-sections on a user-defined plane and for measuring point-line distances on cross-sections. Using this software, one approach for obtaining the vertical underclearances underneath the bridge involves: (1) cutting the constructed 3D models using vertical planes (Fig. 1b) and (2) measuring the distances between the bottom of the superstructure and the road under the bridge on these vertical cross-sections (Fig. 1c).

Analysis of this "virtual surveying" process revealed several of its limitations. First, this manual process involved repetitions of some operations, which could lead to substantial time requirements. For instance, we spent about 2 min to finish 35 point-line measurements on five cross-sections. For over 600,000 national bridges in US, each of which need to be inspected at least biennially for getting 27 surveying goals, finishing all these NBI geometric documentation will take millions of person-hours. Second, even with large amounts of time invested into manual measurements, the reliability of the generated surveying goal results is still not clear to inspectors. For instance, as 35 measurements of the vertical underclearance vary from 4.5 m to 4.8 m, it was still unknown how close the minimum value of these measurements is to the minimum vertical underclearance captured in the collected data. In other words, inspectors are not sure to what level the sampled measurements can be trusted compared with an "*exhaustive*" measurement process on the constructed 3D bridge models (e.g., measure vertical clearances at all locations having laser scanned points). In fact, it is subjective to say that 35 measurements will be sufficient in determining the minimum underclearance of this bridge given a user-defined uncertainty level. An interview with a bridge inspector indicated that without any objective method for quantifying the "*exhaustiveness of measurement sampling*," inspectors tend to add a "buffer" value of about 2 cm to the minimum underclearance result obtained through a manual measurement sampling on the point clouds. That "2 cm buffer" again is a subjective value decided by bridge inspectors based on their experiences, and it might vary person by person, or even case by case. For instance, for a skewed and sloping bridge, inspectors tend to be more conservative and set a larger "buffer" value.

All these problems can potentially be resolved by automating the generation of the results of surveying goals from point clouds. Through such automation, it is conceivable to imagine sampling more than 35 measurements for determining the minimum vertical underclearance of a bridge in shorter periods of time. The challenge with such automation is to develop a general approach that is applicable to a variety of bridge surveying goals, and to characterize how exhaustively, reliably, and efficiently the measurements are generated for deriving these surveying goals given the collected point clouds. Based on a workflow representation and composition approach detailed in [38], this paper focuses on: (1) Formalizing and implementing data processing workflows for extracting three representative surveying goals by reusing existing geometric algorithms; (2) developing mechanisms for automatic executions of these workflows on laser scanned point clouds; (3) characterizing the exhaustiveness and reliability of the surveying goal results generated by these workflows, and analyzing the trade-off between the workflow execution time and the measurement exhaustiveness of the surveying goal results.

3. Previous research

Two research fields are related to extracting geometric information from 3D point clouds through the automation of data processing workflows: (1) Algorithms for 3D data processing and modeling; and (2) scientific workflow and process modeling.

3.1. Algorithms for 3D data processing and modeling

In Ref. [38], we have identified nine categories of 3D data processing algorithms required by bridge inspectors for extracting surveying goals:

(1) Object recognition (e.g., recognize which points belong to the bridge superstructure).
(2) Geometric primitive extraction (e.g. plane fitting).
(3) Sampling points on geometric primitives (e.g., sample random points on a plane).
(4) Grouping objects (e.g. group a number of piers into rows).
(5) Extracting relationships between geometric primitives (e.g., extract the distance between two points).
(6) Observation of geometric attributes (e.g. observing the area of a polygon).
(7) Identification of objects with attribute values falling in a user-specified range (e.g. identifying polygons smaller than a threshold).