High Level Framework for Bridge Inspection Using LiDAR-equipped UAV

N. Bolourian [a] , M.M. Soltani[a], A.H. Albahri[a] and A. Hammad[b]

[a]Department of Civil, Building and Environmental Engineering, Concordia University, Canada
[b]Concordia Institute for Information Systems Engineering (CIISE), Concordia University, Canada

E-mail: n_bolour@encs.concordia.ca , mo_solta@encs.concordia.ca , a_albah@encs.concordia.ca, hammad@ciise.concordia.ca

Abstract –

According to Statistics Canada, bridges in Canada have a service life of approximately 43 years. With the majority of bridges passing half of their expected service life, a large amount of investment needs to be made to inspect and maintain them in a safe condition. Manual inspection methods are both time-consuming and costly, which may discourage further inspections and follow-up of defects. Thus, there is a great need for using an automated data collection system. Surface defects (e.g. cracks) in concrete bridges can be inspected using 3D Light Detection and Ranging (LiDAR) scanner as a Non-Destructive Testing (NDT) method. However, the commonly used terrestrial LiDAR is limited to stationary data collection, which reduces the accessibility to some components of the bridges. To tackle this limitation, a LiDAR attached to an Unmanned Aerial Vehicle (UAV) provides more flexibility and accessibility for inspecting large surface areas without threatening inspectors' safety. After providing a comprehensive literature review about the usage of UAVs and LiDAR for the inspection of different types of structures, this paper proposes a high level framework for bridge inspection using LiDAR-equipped UAV. The framework includes the following steps: (1) planning a collision-free optimized path with respect to the minimum cost and maximum coverage considering a variety of constrains and requirements related to the hardware and the inspection task, and (2) data analysis for detecting the surface defects based on the collected point clouds.

Keywords –
Bridge inspection; LiDAR-equipped UAV; Path planning

1 Introduction

According to Statistics Canada, bridges built in Canada have a service life of approximately 43.3 years. With the majority of bridges built over the past few decades, more than half of their expected service life is over, and a large amount of investment is needed to rehabilitate and maintain these infrastructures [1]. In order to achieve efficient maintenance, accurate condition assessment based on regular and detailed inspection is required. However, current bridge inspection is mainly based on visual inspection and manual measurements of defects. This approach is time consuming and requires the inspectors to have access to the different components of the bridges using certain tools, which may affect the traffic on the bridge and could be unsafe for the inspectors. In many cases, the geometry of the bridges is complicated and using these tools may not be easy or feasible, such as in the case of highway bridges. Therefore, new automated inspection systems should be developed to provide safer and more efficient and accurate methods for bridge inspection [2].

Surface defects (e.g. cracks) in concrete bridges can be inspected using 3D Light Detection and Ranging (LiDAR) scanners as a Non-Destructive Testing (NDT) method. However, the commonly used terrestrial LiDAR is limited to stationary data collection, which reduces the accessibility to some components of the bridges. To tackle this limitation, a LiDAR attached to an Unmanned Aerial Vehicle (UAV) provides more flexibility and accessibility for inspecting large surface areas without threatening inspectors' safety. Using LiDAR-equipped UAV has the following advantages: (1) easier accessibility to most parts of the structure, (2) higher coverage, (3) better efficiency, and (4) higher safety by decreasing the probability of falling hazards. LiDAR-equipped UAV is mostly used in surveying and agriculture. Both the scanner and the UAV have their own limitations and specifications which should be considered to achieve an efficient result.

After providing a comprehensive literature review about the usage of UAVs and LiDAR for the inspection of structures, this paper proposes a high level framework for bridge inspection using LiDAR-equipped UAV. The framework includes the following main steps: (1) planning a collision-free optimized path with respect to the minimum cost and maximum coverage considering a variety of constraints and requirements related to the hardware and the inspection task, and (2) data analysis for detecting the surface defects based on the collected point clouds.

2 Literature Review

The literature review will cover the methods for surface defects inspection and UAV path planning.

2.1 Methods for Surface Defects Inspection

Visual inspection of surface defects (e.g., cracks, spalling, corrosion, etc.) based on the non-equipped eye is the most commonly used method of bridge inspection. However, this method is subjective, costly, time-consuming, and may cause safety risks, such as falling or trying to reach far components [3]. Other NDT methods include image processing and LiDAR. Image processing methods using cameras are popular, speedy and inexpensive. Several image processing studies have been done in order to detect defects automatically [4, 5, 6, 7, 8]. However, the images are affected by the light conditions and their analysis requires supplementary information [9]. On the other hand, LiDAR is used for collecting point clouds. LiDAR-based methods are highly accurate and able to detect the depth of the defects [3, 10, 11] and mass losses [12, 13, 14]. Although the initial cost of the LiDAR is high, it is a time and cost effective method in the long term [3]. Image processing methods may be more efficient than LiDAR in detecting the boundaries of defects [15]. Integrating the texture-mapped images and laser scans is another method to detect the surface damages [16]. However, all the above methods are based on using terrestrial scanners.

2.2 UAV Path Planning

Scanning platforms are categorized into three groups: Terrestrial Laser Scanning (TLS), Mobile Laser Scanning (MLS), and Airborne Laser Scanning (ALS) [17]. TLS is a ground-based method using tripods. If a laser scanner is mounted on moving objects such as cars, vans or boats, it is called MLS [18]. MLS is mostly applied to pavement inspection in order to extract cracks or road markings [19]. ALS using airplanes or UAV has been used for military applications, surveying, etc. The above three types are all affected by the small vibrations of the scanner that may be caused by the non-stability of the LiDAR itself, the movement of the supporting vehicle (e.g. car or UAV), or the wind effect on the UAV [20]. ALS is the most sensitive system to vibration [21].

Controlling the flight path of the UAV can be done using remote control. However, applying automated path planning will lead to optimal flight path. Path planning of UAVs should consider obstacle avoidance, maximum coverage, sensor limitations, and vehicle motions, as well as time and cost efficiency. Some methods such as wavefront algorithm [22], spanning tree algorithm [23], and Neural Network [24] are used to compute the path in a simplified grid space. Other methods, such as Traveling Salesman Problem (TSP), focus on finding the shortest path passing through pre-defined viewpoints [25, 26]. Minimizing the number of viewpoints using Art Gallery Problem (AGP) is another approach to compute the optimal path [27, 28, 29]. Coverage path planning has been mostly applied on 3D-mapping [30, 31], surveying of urban environments [32, 33, 34], ship hull inspection [28, 35, 36], and structural inspection [37]. The model of Bircher et al. [37] which is based on Lin-Kernighan Heuristic (LKH) as a TSP solver, convex optimization, and Rapidly-exploring Random Tree star (RRT*) algorithm to define the optimized viewpoints and path, can be applied for other types of structures. Also, Guerrero et al. [38] worked on path planning of UAV for bridge inspection in windy environments. It should be noticed that cameras, not LiDAR, were mounted on the UAV in the last two studies.

3 Proposed High Level Framework

Figure 1 shows the flowchart of the proposed framework of bridge inspection using LiDAR-equipped UAV. The method consists of the following three main steps.

(1) Path Planning

In bridge inspection using LiDAR-equipped UAV, the following constraints should be considered.

- UAV constraints includes six Degrees of Freedom (DoFs) which are three coordinates (x, y, z) and three rotations (yaw, pitch and roll), vibration, battery capacity (time of flight), payload and take-off weight, and the size of the UAV. The minimum distance (d_{min}) between the UAV and the structure or other obstacles depends on the size of the UAV.
- LiDAR metrology method can be based on Time-of-Flight (ToF) or Phase Shift (PS). In the first method, a laser pulse is sent and the distance between the device and the object can be calculated by measuring the arrival time of the reflected pulse. PS emits a continuous sinusoidal laser beam, and the difference between the phase of emitted and reflected laser

beams is measured to compute the distance. ToF is practical for long measurement range with the accuracy of 4-10 mm at 100 m. On the other hand, PS is used for short range cases with the accuracy of 2-4 mm at 20 m [3]. PS should be used for inspection applications. Furthermore, the maximum distance (d_{max}) should be less than 10 m [3]. In addition, the Fields of view (FoVs) are possible scanning angle range in the horizontal and vertical directions. Furthermore, the beam diameter, incidence angle (θ), and angular resolution ($\Delta\theta$) should be considered.

- LiDAR-equipped UAV may have the LiDAR mounted on top of or under the UAV.
- Other constraints related to regulations, wind effects, etc., should be considered.

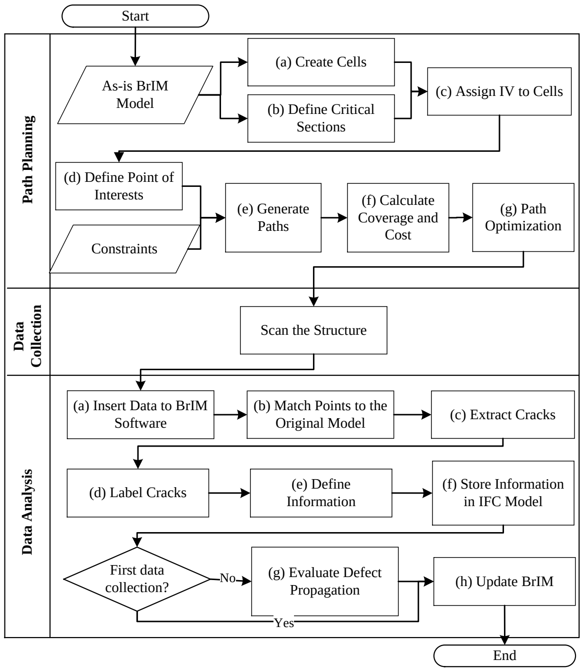


Figure 1. Proposed framework

Only the main constraints (d_{max} and d_{min}) are considered in this paper using the profiling method for scanning the structure. Figure 2(a) shows the UAV location from the side view at *g*, which is between d_{max} and d_{min}.

The proposed method is based on the assumption that an accurate as-is Bridge Information Modeling (BrIM) model is available. This model (see for example Figure 3(a)) can be created using LiDAR scanning. The BrIM model is used for the visibility analysis and path planning as explained below. The path planning has the following steps:

(a) *Creating cells:* The bridge surface should be meshed and divided into cells. The size of the cells should be proportional of the resolution of the scanner and small enough to achieve high accuracy.

(b) *Defining critical sections:* The critical sections can be determined based on the potential location of cracks or other surface defects, which could be estimated using structural analysis or based on experience. These sections can be assigned with Importance Values (IV) corresponding to the level of criticality. Figure 3(b) shows the bottom view of a bridge deck with several critical sections. These sections have low, medium, or high levels of criticality (i.e., IV=1, 2, or 3, respectively).

(c) *Assigning IV to cells:* The cells in each critical section will inherit the IV of the critical section that it belongs to.

(d) *Defining points of interest (PoI):* In profiling method, PoI are specific points which the path should pass through to increase the accuracy of the results. PoI should be added at close distance from the inspected surfaces where defects are expected.

(e) *Generating paths:* A large number of collision-free paths of the LiDAR-equipped UAV should be generated passing through the PoI and respecting other constraints.

(f) *Calculating coverage and cost of each path:* Albahri and Hammad [39] developed a method for calculating the coverage of surveillance cameras in buildings. This method has been adjusted in this research to calculate the coverage of the LiDAR-equipped UAV. Ray tracing can be used to calculate the visibility from each PoI. Furthermore, the IV of cells can be used to calculate the total coverage of the LiDAR-equipped UAV using the following equation.

$$W_{a_i} = IV_i \sum_{j=1}^{n} C_{ij} \tag{1}$$

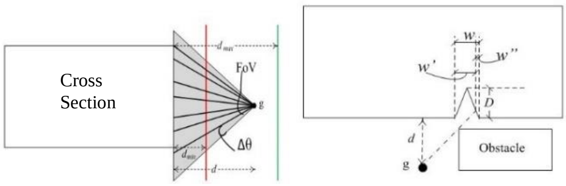
$$CC_{a_i} = IV_i \sum_{v=1}^{n'} C_{iv} \tag{2}$$

$$Total\ Coverage = \frac{\sum_{i=1}^{m} CC_{a_i}}{\sum_{i=1}^{m} W_{a_i}} \tag{3}$$

Where W_{a_i} is the weight of important area a_i, $C_{ij} = 1$ represents the cell *j* in important area *i*, and *j* = 1:*n*, IV_i is the importance value assigned to all cells in area *i*, and *i* = 1:*m*, $C_{iv} = 1$ is the covered cell v in area a_i and v = 1: n', and CC_{a_i} is the weighted covered cells in area a_i.

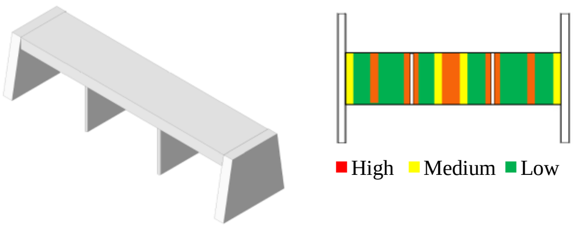
There are some cells that cannot be covered during scanning because of obstacles. As shown in Figure 2(b), if an obstacle exists too close to the bridge, the laser beams cannot reach all parts of the surface during scanning. This figure illustrates the depth (*D*) and width (*w*) of the crack while *w'* depicts the scanned width. Due to the existence of obstacles or other previously mentioned limitations, it is not always possible to achieve full coverage. The cost of each path can be calculated based on the flight time.

(g) *Selecting optimal path:* the optimal collision-free path is selected based on maximum coverage and minimum time of flight.



(a) Side view (b) Top view

Figure 2. Some limitations of LiDAR-equipped UAV in 2D view



(a) 3D model

(b) Bottom view of the deck with importance levels

Figure 3. Example of a 3-span bridge

(2) Data Collection

After planning the path, the LiDAR-equipped UAV should fly and scan the structure.

(3) Data analysis

Analyzing collected data and detecting the defects is done using the following steps.

(a) *Inserting point cloud data to BrIM software.*
(b) *Matching points to the original model*
(c) *Extracting cracks*
(d) *Labeling cracks*
(e) *Defining defect information* such as width, length, and depth of cracks.
(f) *Storing defect information in IFC model*
(g) *Evaluating defects propagation:* If there is previous bridge inspection model, the new data can be compared and the propagation of the defects can be determined.
(h) *Updating the BrIM model:* This model will be used in the next inspection process to evaluate the propagation the defects.

4 Implementation and Case Study

The implementation is limited at this stage to the coverage calculation step of the proposed framework. A three-span bridge was modelled in Revit 2017. In order to create cells, the bridge model was imported into Unity3D game engine. Due to the difficulty of accessing the area under the bridge, the focus of the case study is on the inspection of the bottom surface of the deck. The edge of the cell was set to 0.7 m resulting in a total number of 400 cells covering the lower surface of the deck (7 m × 28 m). The critical sections of the deck were defined and the IV were assigned to the cells following the rules explained in Section 3.

A path was created to test the visibility calculation method assuming that the LiDAR is installed on top of the UAV, which has four degrees of freedom (x, y, z and yaw). Fifty random points were defined for one path around the bridge including 20 PoI. d_{min} and d_{max} were set to 2 m and 10 m, respectively. The main obstacles in this model were the piers of the bridge.

The coverage of the path was calculated automatically in Unity assuming a large FoV of 120° in the horizontal and vertical directions. Figure 4 shows visible cells (red cells) where the LiDAR-equipped UAV is passing according to the defined path (pink line). The total coverage of this path is about 88%.

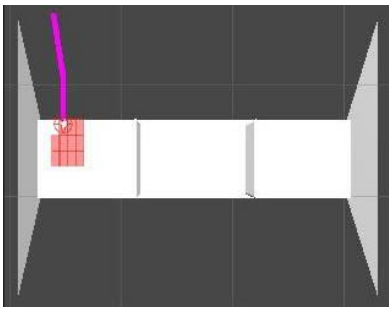


Figure 4. Part of the planned path (in pink) and visible cells (in red) under the bridge deck

5 Summary and Future Work

This paper proposed a high-level framework for bridge inspection using LiDAR-equipped UAV, which is expected to provide more accurate results than using cameras on UAV. The initial case study showed the feasibility of the proposed method for coverage calculation. Future work will aim to further investigate the optimization of path planning and automate the process of detecting surface defects based on the collected point clouds.

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