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Automatic UAV Inspection of Tunnel Infrastructure in GPS-denied Underground Environment

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Abstract. In the Architecture, Engineering and Construction (AEC) industry, unmanned aerial vehicles (UAV) has been widely acknowledged as a promising tool to perform adaptive structural health monitoring automatically. However, there still remains some challenges for drones to collect image data of underground structures, primarily due to low light and no GPS conditions. In order to facilitate data acquisition, this article developed a mobile software development kit (MSDK) for drone using visual positioning and predefined controlling code, which enabled the drone to automatically fly along a designated sinusoidal route, whilst continuously taking videos and images of the tunnel surface. The developed MSDK was able to adjust the drone parameters (e.g., overlapping rate, inspection range, heading, flight direction between frames of the video) for different underground infrastructure conditions. Furthermore, a field test is conducted in an abandoned windless tunnel near Cork (Goggins Hill Tunnel) to test its feasibility. Results show that the 40-m difference between the designated routine and actual routine was 1.9%, and the collected data processed by Pix4Dmapper could reconstruct the complete tunnel scene and surface details. The navigation method proposed in this paper allows UAVs to perform automatic inspection without GPS, and the collected image data is used to build a tunnel panorama view.
Keywords: UAV Inspection, Tunnel inspection, Automated Flight, GPS-denied environment, Video Stitching.

1 Introduction

To facilitate infrastructure asset assessment and maintenance, it is essential to monitor the health condition of ageing infrastructures on a regular basis. Compared with manual inspection, the use of unmanned aerial vehicle (UAV) for structural surface inspection can gather more image data with lower labour cost. On top of that, due to high image quality and well controlled acquisition routes, the gathered digital data can be processed with artificial intelligence algorithms, enabling quantitative evaluation or measurements of structure defects. Furthermore, regular drone inspections could facilitate infrastructure structural health maintenance and reveal the infrastructure deterioration.

Over the years, although drones have been widely adopted for structural surface inspection, the positioning and control of drones rely on GPS+GLONASS positioning. In other words, extant investigations usually employ drones to inspect the structure with either good luminosity or GNSS availability in open air, such as road, pavement and building exterior. Zakeri[1] developed a drone inspection method to take images of asphalt pavement . In similar dark and weak GPS condition around bridge, Fujiuchi[2] proposed a method of visual positioning with the help of searchlights, which can reach an error of 0.12m and 15m. For tunnel images, various artificial intelligence navigation algorithm has been developed[3], [4].

However, the drone inspection of tunnel surface still faces many challenges. Compared with the open-air condition, the dark environment in confined underground tunnel space without GPS positioning signal is not suitable for UAV flight, owning to the decrease of drone manipulation precision and automatic flight interference from intrados. The researchers are still looking for stable navigation[5], [7] and data acquisition method in this harsh environment [8]. Others resort to railcars [8] and ground robots [9] equipped with cameras for image data acquisition, alternatively. Nevertheless, such specialized equipment and the associated installation cost is usually expensive and only enables inspection along programmed route with limited adaptability, which hardly cover a complex underground infrastructure network including inclined tunnel, cross passage, shaft and etc.

To this end, this paper proposed a UAV automatic data acquisition method with the help of visual positioning, which further developed the Mobile SDK of DJI UAV (https://developer.dji.com/mobile-sdk/) to control the UAV flight following a designated trajectory. The developed method enables a drone to automatically fly along a tunnel at a given distance, whilst taking a video of the tunnel surface. In the light of a complex tunnel network, the drone flight route can be flexibly programmed and fine-tuned to cater for different underground sections (e.g., shaft, cross passage) The recorded video can be used for 3D point cloud reconstruction of the 3D tunnel infrastructure. Based upon an advanced deep learning algorithm, the defects in the 3D point cloud tunnel model can be automatically detected and classified.

2 Autonomous drone inspection in a GPS denied underground environment

2.1 Autonomous flight system

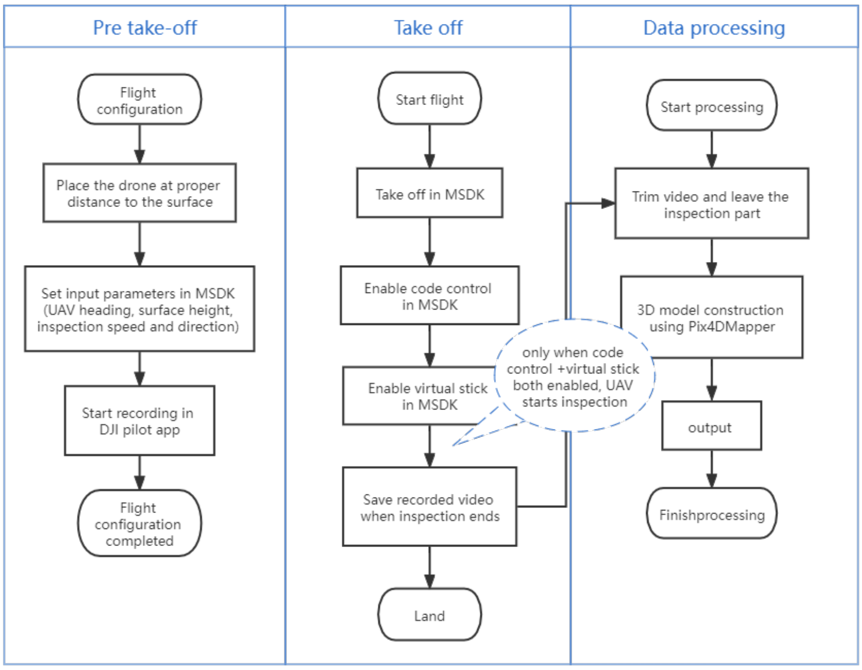

Figure 1. Autonomous drone inspection procedures

Due to the lack of GPS positioning signal, UAV rely on visual positioning for navigation in underground environment. In this case, the biggest challenge for drone inspection in dark tunnels becomes lack of luminance. Only with natural or artificial light, an UAV can perform inspection autonomously based on a MSDK. The MSDK is designed for typical straight railway tunnel and the operating procedures are described (see Fig. 1). It's an integration of in-built visual positioning and SDK programming. The in-built visual positioning stabilizes the drone's location in relative to the tunnel wall by its six pairs of visual sensors, whilst the SDK programme plan a time-dependent drone flying route. Based upon a prior tunnel map with dimension details, the drone routine can be first programmed prior to inspection. The pre-flight route design is not completed until operator's site supervision and judgments. At the site, the drone operator gives refined parameter setting.

2.2 Flight trajectory setting

Conventionally, the drone inspection of civil infrastructure usually follows a grided-shaped in a rectangle area. In a low-illuminance underground tunnel, however, such several pieces of long-distance inspection bring risks of dislocation for video stitching.

To this end, a novel flight trajectory is developed in this study (see Fig. 2): it shows a one-way sinusoidal continuous flight path. In Fig. 2 (1), the black sinusoidal curve represents the trajectory of the camera in longitudinal and vertical direction. The camera views at two peaks of movement are represented as red and blue rectangles. The UAV is programmed to make movement with constant distance to tunnel walls.

To ensure that all the inspected surfaces are covered in a single flight, there has to be enough overlap area rate α between two adjacent peaks and valleys of the curve in the recorded video. Eq. 1 defines the determination of *Dhmax*.

$$Dhmax < (2 - \alpha) * \mathrm{W} \tag{1}$$

Dhmax is the horizontal spacing of the camera in the peak positions. *W* is scene width in a single frame. α is overlapping rate (say 60% for rough inspection). A satisfactory α could be achieved by setting *Dhmax* by Eq.1.

Scene width *W* can be measured on site or calculated by Eq.2.

$$\mathrm{W} = \tan\left(\frac{\Theta}{2}\right) * 2\mathrm{D} \tag{2}$$

Θ represents the field of view (say 63° for Mavic 2). D represents the distance between the lens and the wall. In Goggins Hill Tunnel the tunnel diameter is 5.8 m. To keep a large inspection area, the *D* could be chosen roughly between 2.9 m and 5.5 m.

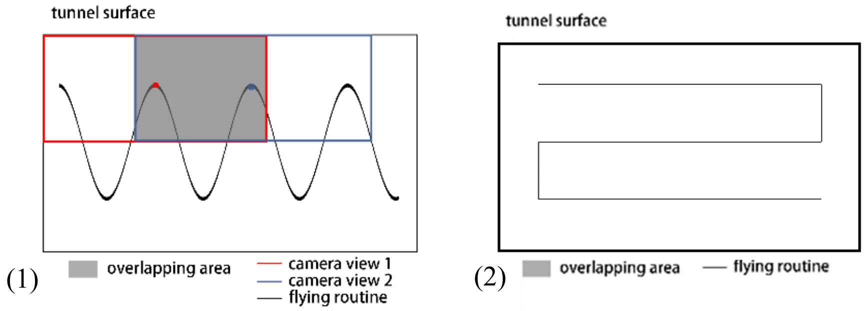

Figure.2 Drone flying route (1) by setting parameters and (2) in conventional practice

The above formulas help operators to determine all four parameters in the MSDK. Inspectors can input the four following parameters to the user interface (see Fig.3) knowing tunnel dimensions. Besides, the pair of buttons called enable and disable virtual stick is a switch of controlling mode between manual and automatic. Another pair of buttons called start and stop flight control is a switch of sinusoidal motion. During the inspection task, the drone's sinusoidal motion command signal is sent every 20 ms and stabilized by visual positioning.

The parameter called yaw is the direction of the heading of drone in the North-East-Ground (NED) coordinate system. It's limited to a range of [-180, 180] degrees. When yaw equals 0, the drone points to the North. Since this system relies on compass, it works in abandoned tunnels where there's no electromagnetic field interference.

The parameter called height is the maximum height of the flight path, which must be set lower than the height of the tunnel crown, whilst the minimum height is fixed to be 0.5 m to keep safe.

The parameter called period is the period of sin function. To meet the overlapping requirement, the period is set as 5 seconds here.

The last parameter called pitch defines horizontal velocity, which gives around 0.17 m/s horizontal velocity when set pitch as 0.3 as default. When horizontal flight speed is modified to negative, the UAV can move forward and backward longitudinally.

After setting the parameters and enabling autonomous flight system, the operators need to follow the drone and keep it in sight before the inspection task ends. After each inspection, the acquired data could be sent to Pix4Dmapper for a quick check. According to tunnel conditions and error types in the quality report, the operators make adjustments to the above parameters.

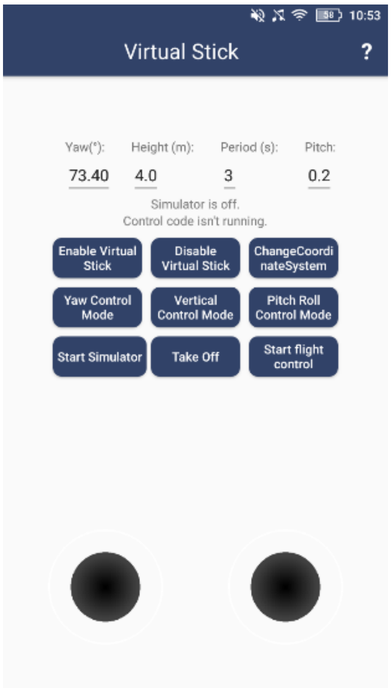

Figure. 3 UI design of MSDK

3 Field test in Goggins Hill Tunnel

To test the feasibility of the proposed method, a field test was conducted in Goggins Hill Tunnel. It's a straight-wall-arch tunnel with a maximum diameter of 5.8 m and height of 5.2 m measured by laser range finder. Two parts of the tunnel are inspected in this field test. One is a bright tunnel section close to the entrance and is 38.2 m long; the other is a dark tunnel section and is 45.5 m long. For the safety of drone inspection, the drone flies Between 1.2 m and 3.5 m height. And to cover most of the surface in one inspection, the drone flies at a distance of 5 m aways from the inspected wall.

The Mavic 2 Enterprise Dual (M2ED) needs to work in front of surface with clear pattern and adequate lighting (lux > 15). Luminance at the entrance of tunnel in this inspection comes from natural light. But in the inner dark part of tunnel, the only light source is from spotlight of M2ED on top of the drone. It's luminance is 11 lux @ 30m Straight max and has 17° field of view (FOV), which is too narrow for use at close range. To evit detail loss caused by high contrast between directly lighted area and the rest, the appropriate luminosity in dark tunnel is set at round 10% and verified.

After a drone inspection, the video data records several videos along the tunnel structure. A video enables satisfactory overlapping rate in adjacent frames and makes registration more accurately than using discrete images. One key frame is extracted from every three (in bright tunnel) or five (in dark tunnel) frame images in the videos according to need. A primary examination of flying route and video quality is done in software Pix4Dmapper. The quality report gives the position of calibrated camera (see Fig. 4). Then the extracted frames are stitched together for a three-dimensional model reconstruction of the inspected tunnel surface (see Fig. 5 and Fig.6).

(1)

(2)

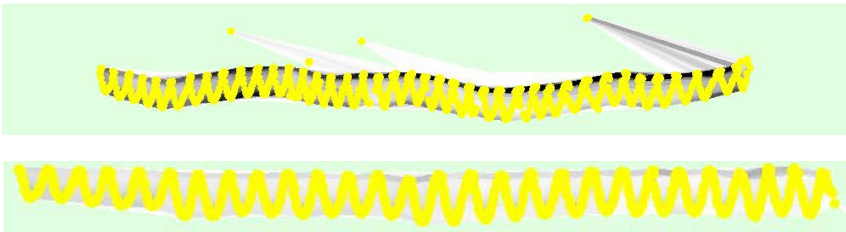

Figure. 4 Computed image positions with links between matched images in (1) bright tunnel and (2) dark tunnel (black means more point matches for registration)

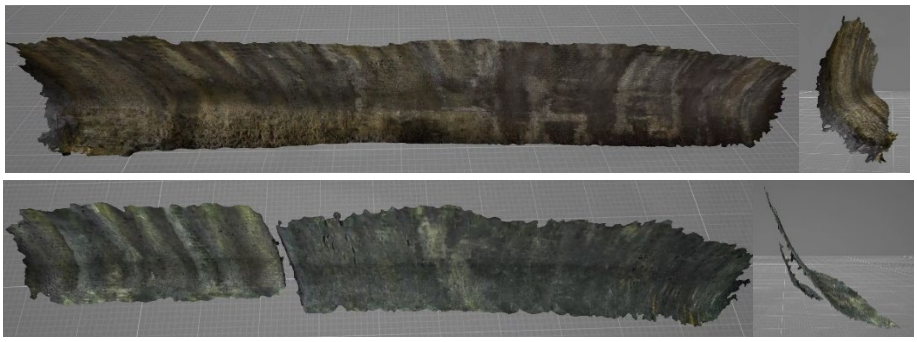

Figure. 5 3D output models in (1) bright tunnel and (2) dark tunnel

Figure. 6 Texture of a segment of reconstructed tunnel in bright tunnel

There's some loss of information during video stitching. In bright tunnels 989 out of 1000 of the frames are calibrated, and in dark tunnels the number becomes 1287 out of 1969. Those uncalibrated frames are at the start and end of inspection and are missing data. This is inevitable data loss due to limited overlapping at the ends of the flying routes. The solution is to perform inspection with 5 m margin at the start and the end of the route.

From Fig.4, the error of flight route could be calculated. For bright tunnel, the vertical flying error equals to around 1.7%, and this value for dark tunnel equals to 1.9 %. From Fig.5, the front view and side view of two cases are shown. Basically, the models keep the configuration of the tunnel. And from side view, the information of arc and curvature on tunnel wall is restored.

In the two models, there's more details of bricks in the bright tunnel compared to the dark tunnel. That's due to a better natural light condition in the former inspection. In a dark tunnel, the only light resource is from the spotlight, which leads to a high contrast between the camera center and edges and also detail loss.

In general the geometry of dark tunnel conforms to the reality. In Fig.5 (b) a separation of two tunnel segements appears in the output. That's due to the difference on two tunnel sections. The left part is reinforced section, which has smaller diameter than the right part of normal brick structure. During the flight the camera was facing the wall, and didn't get enough detail of the joint part, leading to such disconnection. This phenomenon indicates the necessity of future work on increasing the FOV of spotlight for inspection in dark tunnel.

4 Conclusion

An autonomous drone inspection MSDK was developed and field test was performed to verify the method. From the quality report, the flying route has an acceptable vertical error of 1.7% and 1.9%. From the output of the reconstructed model, the geometry and texture on a total of 3 m height and 30 m length of inspected tunnel surface is restored.

In the next step, the tunnel defects (e.g., crack and leakage) in the 3D point cloud model can be automatically detected and classified using an advanced deep learning algorithm. The automatic classification and analysis of defects in a large-scale tunnel infrastructure will deepen the understanding of tunnel deterioration condition and mechanism.

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