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Early sinkhole detection using a drone-based thermal camera and image processing

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HIGHLIGHTS

- Using a thermal far-infrared camera attached to a drone to detect potential sinkholes.
- Combining the light convolutional neural networks with handcrafted feature.
- Generating the sinkhole dataset using a thermal camera.
- Detection accuracy is higher than those of related algorithms.

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ABSTRACT

Accurate advance detection of the sinkholes that are occurring more frequently now is an important way of preventing human fatalities and property damage. Unlike naturally occurring sinkholes, human-induced ones in urban areas are typically due to groundwater disturbances and leaks of water and sewage caused by large-scale construction. Although many sinkhole detection methods have been developed, it is still difficult to predict sinkholes that occur in depth areas. In addition, conventional methods are inappropriate for scanning a large area because of their high cost. Therefore, this paper uses a drone combined with a thermal far-infrared (FIR) camera to detect potential sinkholes over a large area based on computer vision and pattern classification techniques.

To make a standard dataset, we dug eight holes of depths 0.5–2 m in increments of 0.5 m and with a maximum width of 1 m. We filmed these using the drone-based FIR camera at a height of 50 m. We first detect candidate regions by analysing cold spots in the thermal images based on the fact that a sinkhole typically has a lower thermal energy than its background. Then, these regions are classified into sinkhole and non-sinkhole classes using a pattern classifier. In this study, we ensemble the classification results based on a light convolutional neural network (CNN) and those based on a Boosted Random Forest (BRF) with handcrafted features. We apply the proposed ensemble method successfully to sinkhole data for various sizes and depths in different environments, and prove that the CNN ensemble and the BRF one with handcrafted features are better at detecting sinkholes than other classifiers or standalone CNN.

1. Introduction

Disasters involving sinkholes are currently attracting renewed attention. The earliest definition of a sinkhole was a sub-circular surface depression or collapsed structure formed by the collapse of small subterranean karst cavities [1]. Recently, the cause of sinkhole has been expanded to the physical and chemical dissolution, cover-collapse, and large-scale construction. Sinkhole is generated by some form of slow subsidence or sudden collapse induced by physical–chemical erosion of rocks in the shallow subsurface. Moreover, the size of sinkhole may vary from a few to hundreds of meters both in diameter and in depth [2]. Because sinkhole development not only impacts local infrastructures or facilities of human but also affects the area's hazard and risk, early monitoring of sinkhole is need to protect loss of life and severe economic damage from sinkholes [3].

With the development of underground expedition techniques, the four primary causes of sinkholes are now known to be as follows [2–6].

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- Dissolution sinkhole: this is caused mainly by the physical and chemical dissolution of karst rocks such as limestone, dolomite, and anhydrite by rain or underground water flowing through the karst aquifer.
- Cover-subsidence sinkhole: this develops over a relatively long period of time in places where sand-based covering sediments can permeate the interstices of the underlying rocks.
- Cover-collapse sinkhole: unlike a cover-subsidence sinkhole, this develops over a relatively short period of time in places where the covering sediment contains a significant amount of clay.
- Human-induced sinkhole: this is similar to a cover-collapse sinkhole, but the main reasons for this type of sinkhole to occur in an urban area are groundwater disturbances and leaks of water and sewage caused by large-scale construction, as well as excessive use of groundwater.

Of these four types of sinkhole, the frequency of human-induced ones in urban areas has been increasing of late [4,6]. According to a survey report [4], at least seven sinkholes occurred in the Seoul area of South Korea in 2014. Examples of human-induced sinkholes in urban areas are shown in Fig. 1. The biggest problem with such sinkholes is that they pose a severe risk to life and property. Hence, we consider various techniques for detecting sinkholes and discuss their relative advantages and disadvantages. We make the case for drone-based thermal-camera detection of sinkholes on the basis of necessity and efficiency.

1.1. Current approaches of sinkhole monitoring and early warning

Although sinkholes can cause loss of life and inflict severe economic damage, relatively few papers have been published about sinkhole prediction and monitoring [10–14,1,15,16]. The simplest method for detecting a sinkhole is blind drilling in areas in which sinkholes could exist. However, the chances of finding a sinkhole feature this way are minimal, and there is the risk of breaching the confining layers and exacerbating sinkhole development [10]. Another destructive method is the cone penetrometer test (CPT) [11]. An electric CPT uses strain-gage load cells to measure the tip bearing pressure. Although CPTs are relatively quick and simple to interpret, a hand CPT has a relatively limited depth and a CPT push rig (truck) could again exacerbate sinkhole development.

Of the alternatives to destructive testing, ground-penetrating radar (GPR) is currently the most common and widely used geophysical survey method for the investigation of potential sinkhole activity [10–14]. GPR sends short radar pulses into the ground from a surface antenna and detects the returned wave using a receiving antenna [14]. Although GPR allows us to map the position and size of sinkholes and to verify the correctness of monitoring data, it is not practical to monitor a wide area because the equipment is manual. In addition, the signal can be scattered in heterogeneous conditions such as rocky soil or alluvial deposits with a high clay contents.

Similarly to GPR based method, seismic waves are transmitted into the ground through a seismic source of energy such as dynamite, air gun, or seismic vibrator. The reflected waves by the boundary are recorded by geophones and processed to map the subsurface geological boundaries. In addition, the spatial variation of the Earth's magnetic field is recorded to detect and map geological features characterized by a differential in the magnetic properties [2].

Electrical resistivity tomography (ERT) and dynamic penetration measurements (DPSH) together with some borehole logs are also used to point out the apparent absence of sinkholes in local municipality areas [2].

Ground-based interferometric synthetic aperture radar (GB-InSAR) has been used for large-area sinkhole monitoring and prediction [1]. GB-InSAR is typically installed at height to cover an area with microwaves and register the backscattered signal coherently. The phase and amplitude information obtained from this are then used to assess the area for possible sinkholes. Although GB-InSAR can monitor much larger areas than can CPT and GPR, its dependency on installation location means that its application is limited.

Airborne laser technology is one way to monitor a large area. The primary objective of this technology is to identify potential sinkholes by observing temporal topographic surface changes using a laser signal. An aerial infrared camera system has also been tested [15]. Surface anomalies can be interpreted as potential sinkholes by identifying dissimilar soils via surface temperatures resulting from the relative amount of entrapped water. Cooper [16] used airborne multispectral (visible, near infrared and thermal channels) scanning instead of laser sensing. This method indicates subsidence areas by using vegetation, soil colour and temperature variations that cannot be discriminated by conventional photography. However, any airborne method requires flights over several locations to see if changes in topography are evident, which is time consuming and expensive. In addition, the monitoring results can be influenced by the weather.

Unlike other methods of detecting potential sinkholes [10–14,1,15], thermal imagery uses the fact that the surface temperature of a sinkhole area is different to that of the normal surrounding area. In addition, to overcome the high cost of non-destructive sinkhole detection using airborne [15,16], we use a drone to monitor a large area at a lower cost than that of other airborne methods. We use a thermal far-infrared (FIR) camera


(a) (b) (c)

Fig. 1. Three types of human-induced sinkholes: (a) sinkhole occurred in Incheon city, Feb. 2012 by subway construction [7], (b) sinkhole occurred in front of the national assembly of Korea, June 2014 by leaking of water and sewage [8], and (c) sinkhole occurred in Songpa District of Seoul city, Aug. 2014 by construction of large building [9].