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Original article

Efficiently capturing large, complex cultural heritage sites with a handheld mobile 3D laser mapping system

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ABSTRACT

Accurate three-dimensional representations of cultural heritage sites are highly valuable for scientific study, conservation, and educational purposes. In addition to their use for archival purposes, 3D models enable efficient and precise measurement of relevant natural and architectural features. Many cultural heritage sites are large and complex, consisting of multiple structures spatially distributed over tens of thousands of square metres. The process of effectively digitising such geometrically complex locations requires measurements to be acquired from a variety of viewpoints. While several technologies exist for capturing the 3D structure of objects and environments, none are ideally suited to complex, large-scale sites, mainly due to their limited coverage or acquisition efficiency. We explore the use of a recently developed handheld mobile mapping system called *Zebedee* in cultural heritage applications. The *Zebedee* system is capable of efficiently mapping an environment in three dimensions by continually acquiring data as an operator holding the device traverses through the site. The system was deployed at the former Peel Island Lazaret, a culturally significant site in Queensland, Australia, consisting of dozens of buildings of various sizes spread across an area of approximately 400 × 250 m. With the *Zebedee* system, the site was scanned in half a day, and a detailed 3D point cloud model (with over 520 million points) was generated from the 3.6 hours of acquired data in 2.6 hours. We present results demonstrating that *Zebedee* was able to accurately capture both site context and building detail comparable in accuracy to manual measurement techniques, and at a greatly increased level of efficiency and scope. The scan allowed us to record derelict buildings that previously could not be measured because of the scale and complexity of the site. The resulting 3D model captures both interior and exterior features of buildings, including structure, materials, and the contents of rooms.

1. Research aims

Cultural heritage sites exhibit a wide diversity of physical complexity and configuration, ranging from sparse, open areas containing multiple structures or ruins, to compact and dense buildings, monuments, or natural areas. Given this variability, technologies for 3D digitisation of large-scale sites must be versatile, reliable, and efficient.

This study investigates the application of a recently developed handheld mobile mapping system called *Zebedee* to cultural heritage sites. *Zebedee* can generate 3D point cloud maps from laser range data collected as the operator walks around a site. A primary research aim is to explore the suitability of the system for complex, large-scale cultural heritage sites in terms of accuracy, efficiency, scalability, ease of use, and budget considerations. We also introduce an enhancement of the system in which a video camera is added to colourize the point cloud, which is expected to make the data more informative for cultural heritage applications.

2. Introduction

Technologies and methodologies for digitisation of cultural heritage sites are wide-ranging, from manual measurements to high-resolution laser scanning and computer vision techniques. Each approach has distinct characteristics appropriate for particular scales and complexities of the objects or environments captured [1,2]. A significant number of cultural heritage sites consist of multiple structures spatially distributed over large areas (thousands of square metres). The process of effectively digitising

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such geometrically complex locations in detail requires measurements to be acquired from a variety of viewpoints.

Currently, the most efficient way to cover a large site is from above, using airborne scanning and imaging (e.g., [3]) or satellite-based sensing. A 2011 report by English Heritage [1] compares a number of technologies, and suggests that these are the only methods capable of surveying large-scale complex areas. Sensing from above, however, cannot capture all of the detail that is available at ground level and generally only captures—at limited resolution—the tops of structures, treetops, and exposed ground.

Terrestrial laser scanning (TLS) can acquire millions of range measurements with high precision from ground level, and has been employed at a number of cultural heritage sites [4–7]. These systems are typically mounted on a tripod and require several minutes to generate a 3D scan from a static location. As a terrestrial scanner can only measure surfaces visible from its current position, shadows occur in the data due to occlusions. Therefore, in order to achieve reasonable coverage of a complex site, a scanner must be placed at multiple (typically carefully selected) stations. Multiple scans can be aligned using software post-acquisition; however, this step requires sufficient overlap between the scans, and often (depending on the software used), accurately surveying the tripod location or placing reflective targets in the environment.

Despite the high data-capture rates, when considering large-scale complex heritage sites, TLS is still relatively inefficient and expensive in terms of equipment cost, time in the field, and data post-processing effort. As a result, relatively few examples appear in the literature where TLS is used for digitising large sites, though such campaigns are becoming increasingly more common [5–7]. One of the most impressive recent examples is the scanning of Lalibela, Ethiopia, in which a 700 × 400 m site containing rock-hewn churches was digitised using 1,150 terrestrial scans [7]. The authors report that data acquisition required six weeks in the field, which was followed by four months of effort to register the laser scans into a common coordinate frame.

Mobile mapping technology positions the scanning equipment on a moving platform during data acquisition. The platform's motion ensures that the sensors continuously view the environment from a variety of viewpoints, thereby significantly reducing shadowing from occlusions. Most existing systems are mounted on vehicles [8] and require reliable GPS coverage; therefore, they are not suitable for delicate, vehicle-inaccessible, restricted, indoor, underground, or confined cultural heritage spaces [1].

Members of our team have developed a handheld mobile mapping system, called *Zebedee*, that generates 3D point cloud maps of an environment—indoors, outdoors, and underground—as the operator holding the device walks through it [9]. Large-scale and complex environments are mapped relatively quickly, requiring minutes or hours to capture sites that might require days or weeks with terrestrial scanners. We demonstrate the system's capabilities and advantages, applied to modelling a historic lazaret on Peel Island, near Brisbane, Australia, consisting of dozens of small buildings spread across an area of approximately 400 × 250 m. The site, which we estimate would have taken multiple days to scan with TLS, was scanned with *Zebedee* in under half a day, producing a 3D point cloud map consisting of over 520 million points. We have also enhanced the *Zebedee* system by adding a video camera, which allows us to generate true-colour models by fusing the image data with the laser data. The raw data is processed in less time than the acquisition and automatically, with no human intervention required to produce the final point cloud model. In terms of cultural heritage practice, the point cloud models produced enable remote 3D visualisation of sites for cultural heritage interpretation and documentation that have been previously too expensive and/or time consuming to generate.

We propose that the introduction of a lightweight handheld 3D mobile mapping system, and in particular, *Zebedee*, can deliver multiple benefits to cultural heritage applications stemming from several key properties :

- efficiency: the reduction in both data acquisition and data processing time can translate into significantly lower project costs. Notably, efficient operation presents the capability to generate results in the field, thereby providing feedback that can guide further data collection while still on site;
- accessibility: *Zebedee* can be used to scan areas where it may be difficult or impossible to use other systems; for example, on rough or steep terrain. The *Zebedee* system can also be more practical for accessing sites with limited availability;
- automation: since data processing is fully automated, the complete workflow for acquiring data and generating registered point clouds can be performed by users with minimal training;
- compatibility: the maps produced by *Zebedee* are standard point clouds that can be integrated with data collected from other devices, and post-processed with existing software packages.

3. Materials and methodology

Zebedee is a handheld mapping system of a site that it is carried through by a human operator by a human operator (Fig. 1) [9]. Its primary exteroceptive sensor is a 2D laser scanner, which captures 43,200 measurements per second of ranges to visible surfaces in the environment based on the time-of-flight of an infrared laser pulse. In order to extend the laser scanner's 270° two-dimensional field of view into a three-dimensional field of view, a flexible spring connects the scanner to the device's handle. The spring allows the scanner to pivot relatively freely (sweeping up to 170° in amplitude and tuned to a desired frequency of approximately 0.5 Hz) as a result of the operator's natural walking or arm motion. An industrial-grade MEMS inertial measurement unit (IMU) is also mounted on the laser scanner side of the spring to provide rough estimates of the scanner orientation. The IMU provides three-axis rotational rate, linear acceleration, and magnetometer readings with a 100 Hz update rate. The system also includes a small laptop computer for recording the data, and a lithium-ion battery which can power the system continuously for several hours. The handheld device has a mass of approximately 650 g, and the entire system can be transported in a small pack with a total mass of 3.8 kg (including device, laptop, cables, battery, and the bag itself).

The *Zebedee* system uses a continuous data registration procedure to convert the raw range measurements into a consistent 3D point cloud. In order to do so, an accurate measurement of the scanner *trajectory* (i.e., its position and orientation at all times) must be available. The system does not rely on any external positioning systems (such as GPS)—the device is self-localising, in that specialised software computes the scanner trajectory based on the sensor measurements (laser and IMU). The solution concept is largely based on the observation that as the scanner is moved through the environment, static surfaces in the local view appear to move. By continually tracking this apparent 'motion', the scanner trajectory can be inferred. In general, estimating both a sensor platform's motion and a map based on the sensors' measurements of the environment is a well-studied problem in the field of Robotics called Simultaneous Localisation and Mapping (SLAM) [10]. The solution developed for processing *Zebedee* data is unique in that it must accurately correct for significant distortions initially present in the raw measurements that arise from the continuous, highly non-deterministic motion of the sensors during acquisition.

Over the long-term, small errors in the trajectory estimate can accumulate, resulting in inaccuracies or misalignments in the map