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Localisation of a mobile robot for bridge bearing inspection

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ABSTRACT

Bridge bearings are a critical component of a bridge and require regular visual inspection to ensure the safe operation of the bridge throughout its life. However, the bearings are often located in spaces that are difficult or hazardous to reach, which can impact how often the bearings are inspected. In addition, these spaces are small and offer significant challenges for tele-operation due to line-of-sight restrictions; hence, some level of autonomy is required to make robotic inspection possible. In this work, a robotic solution to bridge bearing inspection is presented, and localisation methods are assessed as the first, and most, important step towards automation. Robot localisation is performed in both a lab environment and a real bridge bearing environment. In this paper, Adaptive Monte-Carlo Localisation is considered for localisation in a known map and gave comparable results to Hector-SLAM, with all results less than a defined error threshold of 10 cm. A combination of both of these methods are proposed to give a more robust approach that gives errors lower than the defined threshold in the real bridge. The experiments also show the need to provide an accurate starting point for each inspection within the bearing, for which we notionally suggest the use of a docking station that could also be used for improved autonomy, such as charging. In addition, proof-of-concept approaches for visual inspection tasks, such as geometry changes and foreign object detection are presented to show some of the proposed benefits of the system presented in this work.

1. Introduction

Bridge bearings transfer the loads from the superstructure of bridges (e.g., the deck) to the abutments or intermediate supports, which then transfer these loads to the bridge foundations. Bearings are therefore an integral part of bridge structures and their failure can have considerable impact on the bridge life [1, 2], leading to the overall failure of the entire bridge [3]. It is not uncommon for bridge bearings to be replaced at high costs and disruption (e.g., [4]). Some authors (e.g., [5] and [6]) have shown, through a life-cycle cost analysis, that replacement of bearings due to poor maintenance is significant and can be partially prevented, through appropriate inspection methods. The inspection requirements for structural bridge bearings are detailed in the relevant European Standard [7] as: “close visual inspection without measurements, spaced at equal, reasonably frequent, intervals ”, with inspections occurring at least as often as the bridge structure is assessed. Specifically, the standard requires that the bearings are assessed for visible defects including: cracks, incorrect position of the bearing, unforeseen movements and deformations of the bearing and visible defects on the bearing or surrounding structure.

Most of the main problems affecting bridge bearings are reflected by changes to geometry, regardless of the source of the problem or the type of bearing [8, 9]. These problems include: out-of-position translation, rotation or deformation of the bearing. Current methods to measure changes in the bearing geometry are somewhat rudimentary and involve inaccurate and non-repeatable measurements [9] such as: metric tapes, gap gauges, air bubble levels, quadrant rulers, compasses and verniers, levelling and topographic surveys or direct visual observations. Other, more sophisticated, systems include displacement transducers [10], tell-tales [11] and other instruments that do not measure geometry but measure the actual effect of changes on the bearing or structure directly (e.g., cells and strain gauges [3, 9], fibre optics [12], radar interferometries [13], magnetorheological elastomers [14]), but these are typically outside the norm, with most bridges being inspected via operative-led visual inspection [15].

Other main anomalies in bridge bearings are related to deterioration and degradation of the material itself. Similar to other civil engineering structures, these anomalies typically manifest as cracks, corrosion [16] or crushing [8] that are also visible during visual inspections; such information also has the potential to be extracted from vision sensors [17, 18]. In addition, a visual inspection will also record additional anomalies, such as build up of debris and vegetation growth [9].

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The examples above present inspection solutions for bridge bearings using different types of sensors that reduce the human labour involved and expertise required for visual inspection of the bearings. However, the bridge bearing space is often limited in size and not accessible or hazardous for human access. To this end, robotic platforms mounted with sensors have been deployed for bridge inspection, usually with a focus on structural condition or material degradation [19-21] of the bridge. However, there has been no development of a robotic platform specifically for bridge bearing inspection, where close access to the bearings is required to obtain sufficient detail. In addition, the robotic platforms presented in these examples are manually controlled and are therefore difficult to manipulate if the robot moves out of line-of-sight of the operator. In order to achieve autonomy when performing robotic inspections, a robust localisation approach is essential, especially since errors in the limited bearing space could lead to catastrophic failures such as the robot falling from height.

In this paper, localisation is performed on a robotic platform using a 2D LiDAR as the primary sensor. This proof-of-concept platform is tested in a controlled lab environment and on the cable-stayed Millennium Bridge in Leeds, United Kingdom. This paper focuses on the problem of localisation and mapping since it is critical for any further development of autonomous technology for bridge bearing inspection. The work presented here is not platform dependent and could be incorporated into different configurations with different control systems: a suggested work-flow is given in Fig. 1. In summary, the main novel contributions of this paper are:

- The novel combination of two localisation techniques, namely ACML and Hector-SLAM, to provide a robust localisation of the robot that meets the performance requirements, i.e. less than 10 cm accuracy, see Section 5.5.
- A demonstration of an in situ robotic platform for visual inspections in bridge bearings with two applications: geometry changes of the bearing and detection of foreign objects.

Methods to assess material degradation of bridge structures are not considered in this paper, but visual methods for the detection of cracks (e.g., [22]) and corrosion (e.g., [23, 24]) exist for a range of applications.

This paper is structured as follows: first, the related works on bridge bearing using mobile robots and robot localisation are reviewed and a

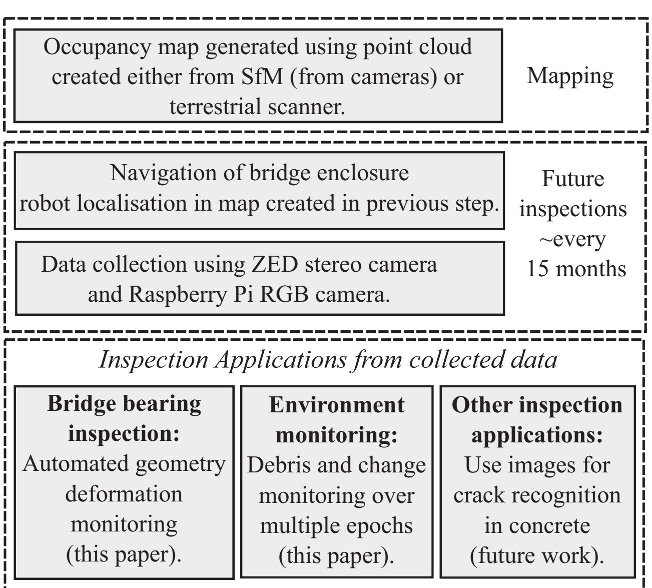

Fig. 1. Overview of how the methods proposed in this paper can contribute to the inspection procedures for a bridge bearing.

solution for localising the robot in the bridge bearing environment is proposed (Section 2 and continued in Section 3). A description of the robotic platform and on-board sensors is provided in Section 4, followed by an introduction to the experimental set-up and testing environment. The comparison of the different maps used for localisation is then provided, with validation taking the form of a comparison against a ground-truth in Sections 5.1 and 5.5, for the lab environment and Section 6 for the real bridge site. The experimental results are discussed in Section 6.4, and preliminary inspection results and conclusions are given in Sections 7 and 8.

2. Literature review

2.1. Robotic inspection of bridges

It is common to use photographs for monitoring the corrosion and structural properties of a bridge [17, 18, 25]. Small cameras can be mounted on robotic platforms, allowing inspection of hard to reach and risky environments. For example, Jahanshahi and Masri [26] obtain depth information from Structure from Motion (SfM) to assist crack detection from photographs of concrete pillars. Torok et al. [27] perform crack detection directly from SfM 3D reconstructions of concrete structures by comparing the normal values of meshes created from SfM point clouds of damaged and undamaged surfaces, with the aim of performing robotic or remote structural assessment in disaster scenarios. The authors of [28] use both SfM and image mosaicing as a method for photo-realistic structural inspection of bridge elements, performed by robotic means. Such vision sensors have been mounted on wheeled robots [20] and legged walking robots [29]. However, the presented systems are bulky and would not fit into a bridge bearing enclosure. In contrast, the authors of [19] present a solution that is small enough to enable passage through narrow spaces. The platform can move on both concrete and steel surface types (including surfaces that had peeled due to corrosion) using six air pads, with air provided by an air supply connected to an air pump and compressor on the ground. The authors also perform testing in a real bridge environment using a CCD camera to inspect the surface of truss members on the bridge as the robot moves along.

Most recently, unmanned aerial vehicles (UAVs) equipped with sensors, such as GPS, gyroscopes and cameras, have allowed large scale inspection of bridges with relative ease. For example, the authors of [21] use a UAV with a top-mounted camera to take images of the under-side of a bridge to be later reviewed by an expert. Similarly, a small UAV for photographic data collection is presented by the authors of [30] in order to perform crack detection of steel bridge members. In both cases, the UAV is unable to get very close to the underside of the bridge, which makes the UAV unsuitable for the inspection of the bearings. In addition, the authors highlight current restrictions surrounding requirements for pilot certification for UAV use and the problems of using GPS for navigation under bridge structures [30].

Overall, technology is developing to allow inspection of structures to be performed remotely, mainly using visual sensors. In addition, the use of robotic platforms and UAVs is allowing the development of inspection methods of structures that are otherwise difficult or dangerous to reach for human inspectors. However, the current development of such platforms for bridge inspection focusses primarily on the platform development. Furthermore, in the reviewed literature, these platforms must be controlled by a human operator. In constrained bridge bearing spaces autonomous inspection is required and therefore, methods for localisation and navigation in these inspection environments should be considered; this topic is the focus of this paper.

2.2. Overview of SLAM and localisation methods

Simultaneous Localisation and Mapping (SLAM) is one particular area of research in robotics where a map is built whilst the robot finds