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Practical constraints on real time Bayesian filtering for NDE applications

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ABSTRACT

An experimental evaluation of Bayesian positional filtering algorithms applied to mobile robots for Non-Destructive Evaluation is presented using multiple positional sensing data – a real time, on-robot implementation of an Extended Kalman and Particle filter was used to control a robot performing representative raster scanning of a sample. Both absolute and relative positioning were employed – the absolute being an indoor acoustic GPS system that required careful calibration. The performance of the tracking algorithms are compared in terms of computational cost and the accuracy of trajectory estimates. It is demonstrated that for real time NDE scanning, the Extended Kalman Filter is a more sensible choice given the high computational overhead for the Particle filter.

1. Introduction

Non-Destructive Evaluation (NDE) of engineering structures is an important and challenging task which can help to locate the presence and extent of structural defects before failure occurs. Regular NDE inspection of critical components can thus reduce costly outages, negative environmental impact as well as potential loss of life. A range of non-invasive NDE techniques are available including ultrasonic, visual, electromagnetic and radiography which are used to detect and characterise flaws in terms of their nature, size and position [1]. Through identification of anomalies, NDE can be used to replace only those components quantified to be defective and can thus contribute to the extension of the operational life of the component/structure even perhaps beyond its designed lifetime.

Industrial sectors for which NDE is of major importance include aerospace, nuclear and petrochemical extraction and processing. Such industries are a source of particular challenges, often presenting inspection sites located in inaccessible locations or where environmental conditions are hazardous for human operators working at height, exposed to radioactivity, proximity to high temperature and/or pressure process plant. The financial impact of NDE inspections is also significant, arising from both the intrinsic inspection costs and the associated cost of taking plant offline to conduct inspections [2]. Consequently in-situ automated inspection where feasible, is highly attractive, and potentially allows inspection of operational plant. The safety, environmental and financial benefits for automating NDE measurements are clear, and applicable across a broad range of NDE technology.

Automation is currently being addressed through deployment of sensor laden remotely controlled robotic devices, well established examples being pipeline inspection gauge (PIGS) systems [3] for internal pipe inspections or unmanned aerial

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vehicles (UAV) [4] for visual inspection. The use of such technology is very attractive in terms of safety, cost and the potential for minimal disruption to the inspection site especially if they allow plant operations to remain online.

Robotic NDE inspection platforms are an active area of research, there are numerous examples in the literature proposing devices for a broad spread of application domains. A recent paper by Schempf et al. [5] describes a robotic device to conduct inspections of natural gas distribution mains. The system is untethered and composed of interlocking modules allowing negotiation of pipe bends and utilizes a camera as the primary inspection sensor. Positioning is achieved through the use of encoders attached to the wheels of the modules and also through the counting of welds connecting pipe sections of known length. Shang et al. [6] present a robotic system for inspecting non-ferrous aircraft wings and fuselages. The described robot is a large vehicle making use of suctions cups to adhere to the inspection surface. It has the capability of carrying a significant payload mass in the form of eddy current and thermographic sensors as well as a phased array probe and a solid coupled wheel probe. Fischer et al. [7] developed a prototype system for surface inspection of gas tanks in ships making use of permanent magnets to adhere to the tank wall. The NDE sensor detected the leakage of injected helium from holes in the tank. White et al. [8] developed a suction cup based system for inspection applications in the aerospace industry; a Kalman filter was used to fuse measurements from a Leica laser tracker and encoder data to determine the 6 d.o.f position of the robot.

The current work builds upon previous work by Fredrich and Dobie [9–12] in the development of a reconfigurable mechanical scanning system for NDE composed of multiple miniature robotic vehicles termed *Remote Sensing Agents* (RSA). The goal for this system is to provide an autonomous and rapid structural scanning solution that is adaptable to the structure's surface geometry and capable of reconfiguration to optimise for specific measurement goals. The RSA approach developed at the University of Strathclyde is characterised such that the system is completely wireless, the robots are of a smaller size and in the use of using multiple robots rather than a large single purpose type device. Central to accomplishing the required degree of cooperating behaviour between multiple robots is the accurate positioning of individual the RSA units.

Our requirement for integrating NDE measurements onto the robotic platforms presents a significant challenge to the positioning problem. For useful NDE images to be assembled from the RSA scanning, there are a number of physical influences on the measurement process that can considerably degrade the quality of the NDE images and thus their usefulness. For example in air-coupled ultrasonic imaging applications, the separation and orientation of the transducers to the sample is critical [13]. This is in addition to the basic degradation of image quality from the gross RSA positional uncertainty. For example it is not possible to assert defect presence or absence based upon comparison of expected time-of-flight (ToF) and measured ToF due to delays caused by error in location. As well as affecting the fundamental measurement principles used to identify defects, positioning is of importance to register NDE measurements from different sensors acquired from multiple scans conducted at different times. It is important that the robot is able to return to the same structural location repeatedly in order to monitor the time evolution of particular defects.

Probabilistic state estimation of robot position through fusion of multiple sensor outputs is a strongly researched area in robotics. It is a long-standing problem in the field and is considered a fundamental requisite of autonomous systems [14]. A typical component of a wheeled robotic system is odometry in the form of rotary encoders attached to the drive mechanism of the robot. These devices return pulses resulting from discrete increments of rotation thus providing a low-level source of positional information. Such sensors although providing excellent short-term accuracy are subject to long term accumulation of errors introduced by wheel slippage (driving on uneven terrain or slippery surfaces) and interaction with a priori unknown objects in the environment that may perturb the course of the robot [15]. These accumulated errors eventually lead to gross error between the true location and the encoder reported location. The effect is illustrated by simulation in Fig. 2 showing the increase in error between the odometry reported path and actual path with trajectory length.

In order to reduce error in position the odometry must be supplemented with some other form of sensing. There are two main ways in which this sensory information may be provided, firstly through *a priori* environmental information in the form of fixed known location beacons placed in the environment aiding the localisation of the robot. The second way is one in which no such external information is available and the robot must utilise purely its own onboard sensors to localise – the latter is known as Simultaneous Localisation and Mapping (SLAM) [14]. Both approaches although applicable in different

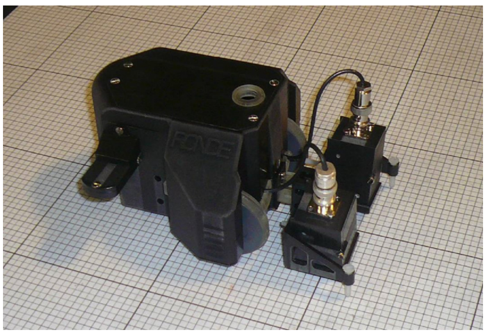

Fig. 1. RSA with air-coupled ultrasonic transducers attached. For a detailed description of the system architecture see [12]. Ultrasonic, magnetic flux leakage and eddy current sensors may be attached to the chassis in order to test the structure under investigation. Magnetic wheels are used to allow the robot to adhere to and negotiate 3D ferromagnetic structures.