Path Planning & Measurement Registration for Robotic Structural Asset Monitoring

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PATH PLANNING & MEASUREMENT REGISTRATION FOR ROBOTIC STRUCTURAL ASSET MONITORING

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ABSTRACT

In recent years, robotic devices have been explored across a wide range of disciplines as delivery mechanisms for multiple sensing technologies applied to structural asset monitoring. Typically the drivers for moving to automated delivery relate to operation in environments that would be hazardous for human operators (working at height, on live plant, or radioactive environments). The exact measurement requirement varies dependent on application, for example specific localised measurements may be required at a known problem area, or a more general wide area survey may be undertaken. Repeated measurements may be required to quantify the evolution of structural condition/ damage in a structure. In all cases, a common requirement is for efficient path planning for the robotic vehicle, combined with accurate registration of the position on the structure that the measurement was undertaken, the latter of particular importance when considering repeated measurements. Since 2003, The University of Strathclyde has been involved with research as part of the UK Research Centre for Non Destructive Evaluation (RCNDE) to develop robotic deployment of NDE measurement probes. The use of multiple inspection vehicles (coupled with different sensing modalities), allows for a flexible, reconfigurable, and adaptive approach to remote health monitoring.

The move to increased levels of autonomy for robotic delivery of inspection for asset monitoring, demands a structured approach to path planning and measurement data presentation that greatly surpasses the more ad-hoc approach typically employed by remotely controlled, but manually driven robotic inspection vehicles. The authors describe a traditional CAD/CAM approach to motion planning (as used in machine tool operation) which has numerous benefits including the provision for detailed structural layout to be built into the path planning, and the subsequent visual overlay of measurement data back into the CAD model. Initial trials using a steel plate with varying thickness defects have been investigated. A custom robot incorporating an ultrasonic wheel probe as rear wheel has been used to perform an ultrasonic thickness scan of the sample – the results have been compared to those obtained using a high resolution wheel probe scan of the sample. The robot control was generated from an initial CAD model of the sample, and the integration of post-processor output (in this case G code), was used as the input for our custom robotic control software to generate both simulation and experimental motion control of our robotic platform.

KEYWORDS : *automation, path-planning, structural measurement, asset monitoring*

INTRODUCTION

When considering the application of automated robotic inspection to asset monitoring, anything beyond an ad-hoc (often manually driven) inspection requires a formal approach to path planning and the subsequent accurate registration of measurement data. Coverage Path Planning (CPP) is the procedure of determining a path that passes over all points of an area or volume of interest while avoiding obstacles [1]. Example robotic applications that require such a planning strategy include vacuum cleaning robots, painting robots, underwater imaging systems, demining robots, lawn mowers, agricultural robots, window cleaners and structural asset monitoring systems [2-6]. Cao et al [3] defined a set of criteria and requirements for robotic systems undertaking CPP operations in 2D environments:

1. The robot must move through all the points in the target area covering it completely.
2. The robot must fill the region without overlapping paths.
3. Continuous and sequential operation without any repetition of path is required
4. The robot must avoid all obstacles
5. Simple motion trajectories (e.g. straight lines or circles) should be used for simplicity and control.
6. An "optimal" path is desired under available conditions.

In complex scenarios it is often challenging to satisfy all the above criteria, especially number 5, and often some prioritisation is required. CPP algorithms can be classified as heuristic or complete depending on whether or not they guarantee complete coverage of the free space [1]. Additionally they can be classified as either off or or-line. Choset et al [5] assert that off-line programming requires *a priori* knowledge of the environment and relies on the environment remaining static throughout the inspection window. On-line programming algorithms differ in that they do not require such *a priori* knowledge and utilise real-time sensor measurements to profile the environment and produce path planning strategies based on the acquired information.

Specific <u>advantages</u> of off-line programming have been described by Neto and Mendes [7] and include:

1. Robot programming can occur without stopping or disturbing production. Robots can be programmed prior to installation and remain in production while being re-programmed for a new task. Therefore robot programming can be carried out in parallel with production, shortening downtime.
2. The programming efforts are relocated from a robot operator to and simulator/engineer.
3. Reduction in safety risks. The robot programmer does not have to be present in the working area during programming activities.
4. Robot programs can be first tested using simulation tools. This allows engineers to anticipate and predict the robot behaviour and optimize the process accordingly.

These are accompanied by a series of <u>disadvantages</u>:

1. Relatively high initial investment required in software and training.
2. The calibration process requires stringent procedures and controls. A poor calibration process can lead to severe inaccuracies during operation.
3. A priori environmental and robot information is required in advance. Accurate environment and platform modelling is therefore critical in off-line robot simulators as inconsistencies and incomplete modelling hinder safe and successful deployment. Changes in the

environment from when the knowledge was acquired or changes to the platform kinematics or dynamics must be continually relayed back to the simulator [8].

1 PATH PLANNING FOR STRUCTURAL ASSET MONITORING

It is clear that automation of path planning can yield benefits in terms of process throughput, efficiency, safety, financial and environmental considerations. In contrast, traditional human operator taught paths for robotics can be inefficient in terms of workflow, throughput and material usage. CPP for industrial component inspection has recently undergone significant research in high value manufacturing applications, especially in aerospace, with a variety of NDE (Non-destructive Evaluation) sensors being deployed [8-12]. Research into CPP for robotic crawler devices covers a diverse range of applications such as material handling and logistics, vacuum cleaners, agriculture, demining and structural inspection [2-6]. Traditional path planning algorithms for such platforms has focussed on configuration space (C-Space) representations such as Voronoi diagram [13], regular & occupancy grids, generalised cones [14], quad-tree [15] and vertex graphs [16]. In Aerial platform applications (e.g. UAVs), CPP has mainly received attention for opportunities in surveillance [17] and remote sensing [18], but the principles described translate well into asset monitoring. Although sharing similarities to other industrial robotic applications employing CPP strategies, automated inspection CPP is highly challenging insofar that typical NDE applications require scanning of features that would often be classed as obstacles in traditional robotics. This distinction must be considered to allow traditional NDE sensors to be deployed with often small surface stand-off distances. Critically the stand-off distance must be consistent, along or around an object, and highly repeatable to allow standards compliant inspection strategies to be deployed at regular intervals. This latter point ensures operators are able to confidently monitor the evolution of change of inspected structures.

2 INSPECTION PATH PLANNING RELATED PARAMETERS

A number of specific sub-constraints exist for path planning for automated inspection, these include:

Delivery Platform - The chosen or desired inspection deployment platform naturally dictates the optimum path planning strategy to be investigated. Full 6 DOF platforms (aerial, fixed robot arm) can naturally manoeuvre to positions along paths that surface traction platforms (crawlers) cannot achieve.

Area/geometry to be inspected/imaged_- The area, point or object requiring inspection again naturally dictates the path planning strategy.

Measurement sensor deployment – The sensor active area or footprint is of critical importance to the path, as the interplay between the two dictates the number of imaging passes required to completely satisfy the coverage requirements.

NDE path pattern - The NDE path pattern is directly dictated by parameters such as inspection speed and desired resolution.. Measurement resolution is fundamentally limited by the maximum sensor and path resolution.

Robot/Sensor Positioning Strategies - The accuracy and repeatability of the sensor delivery platform and sensor positioning system ultimately limit the maximum inspection coverage rate as inaccuracies would yield to greater required path overlap and multiple sweeps.

3 CNC PATH PLANNING APPROACHES

The automation of traditional machine tools, such as milling machines and lathes, began with the advent of numeric control (NC) by MIT researchers in 1952 [19]. NC offered electronic control of mechanical actuators, through commands encoded on a storage medium. The advent of computer technology establishing Computer Numeric Control (CNC) allowed the advent of far more complex multi-axis machining tool paths to be generated efficiently and safely. The late 1980's saw a great rise in the volume of published research in CNC path planning and generation from a variety of specialised areas such as manufacturing, electrical, mathematics and software [20]. The industrial standard for machine tool operation through Computer Aided Manufacturing (CAM) techniques is that of G-Code, a standardised high level NC language that is accepted by a majority of CNC machine tools. Standard movements such as straight line interpolation and arc are permitted with control of plunge and feed-rate along with spindle speed. These basic functions allow a variety of operations to be undertaken and correspondingly a range of machining functions to be performed.

3.1 Post processor

A post-processor is a tool that translates output statements from a robot simulator to a target robot language, for deployment of off-line path planning programming algorithms [8]. Post processors can be categorised as system-dependant, application dependant or generic. *System dependant* post-processors translate robot simulation commands into a specific robot language, traditionally applicable to a certain manufacturer or system protocol. *Application dependant* post-processors are made for a specific application with custom sequences. *Generic* post-processors are theoretically capable of translating multiple simulator commands into languages for multiple robot controllers. The authors' present approach has been to implement a system-dependent post processor and associated tool-chain which has been developed for a specific wheeled robot platform developed by The Centre for Ultrasonic Engineering (a derivative of previously reported hardware [21-22]) and illustrated in Figure 1; the design incorporated an active back wheel containing an ultrasonic probe.

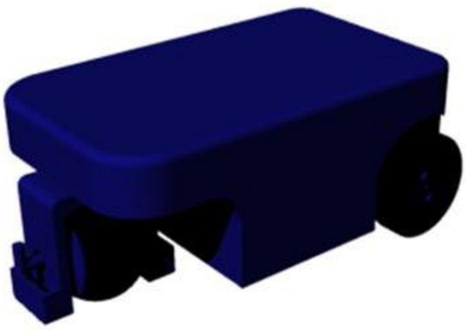


Figure 1: Inspection robot employing active back wheel ultrasound probe

A custom post processor (based on that of the Southwestern Industries Inc. ProtoTRAK SMX) was developed to interface with Mastercam X6 and export the necessary numeric code in a format suitable for driving the inspection robot. To represent the robot, it was defined as a custom machine tool - the working envelope of the robot was represented as a cylinder of diameter 460 mm. This was calculated from the turning centre origin between the drive wheels to the safe outer maximum limit of extension of any part of the platform. A MATLAB based parser was implemented to accept the post-processed numeric control output and convert this into suitable commands (in the appropriate XML structure format) for driving the robot to a desired location.

4 EXAMPLE APPLICATION – ULTRASONIC THICKNESS MAPPING OF STEEL PLATE

A 2000 x 1000 mm Carbon Steel (S275) plate of nominal 10mm thickness was selected to mimic a traditional plated floor. Two obstructions were affixed to the plate to mimic typical industrial obstacles protruding through the floor. These obstacles were a rectangular box of width 270 mm and breadth 170 mm, centred at (-865,-415) to simulate a pipe duct, and a 40mm Diameter Cylinder centred at (500,-75) to simulate a pipe riser. Additionally seven flat bottom holes, of 25mm diameter and varying depths from 1mm to 8 mm, were machined into the plate at various locations to simulate localised loss of thickness. A plan of the sample is shown below in Figure 2.

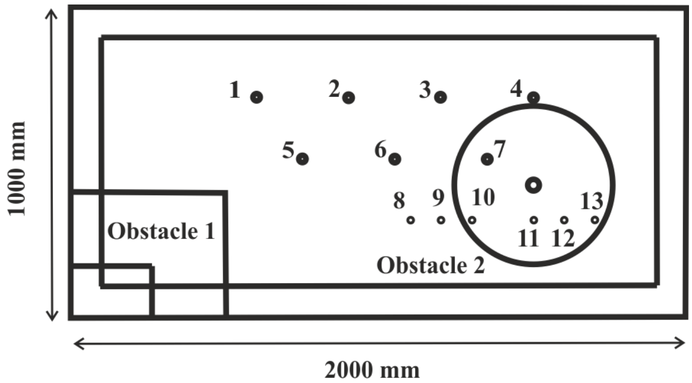


Figure 2: Test sample, 10mm thickness steel plate with simulated defects (1-13) and obstacles.

4.1 Reference NDT scan

A reference ultrasonic NDT inspection of the industrial sample was undertaken to define a benchmark. Normal incidence ultrasonic thickness mapping was undertaken using a GE Roto-Array wheel probe and Olympus Omniscan MX2 PA controller. The wheel probe featured an internal 5 MHz 64 element linear ultrasonic array enclosed in a liquid filled tyre. The Omniscan featured a 16:64 phased array module with 16 individual pulser/receiver channels and the potential to drive a maximum of 64 elements at 115 Volts. The reference thickness map of the sample is shown below in Figure 3 highlighting the nominal 10mm thickness and varying depth defects.

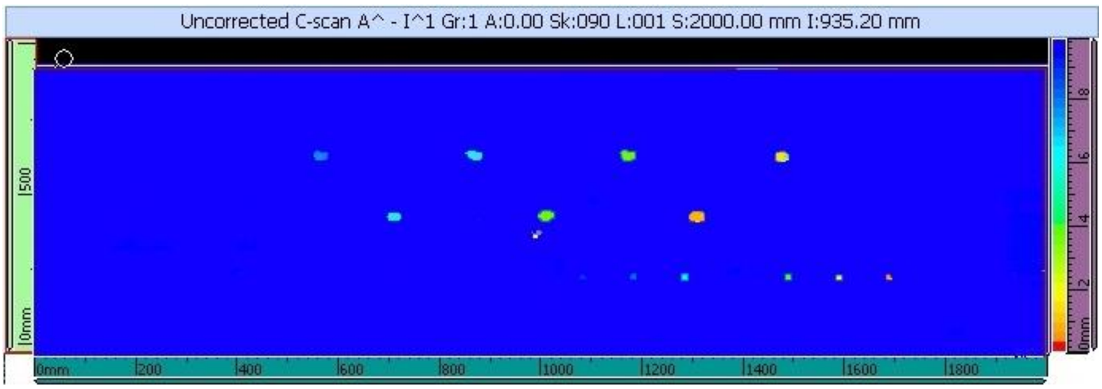


Figure 3: Reference Thickness Map

4.2 Inspection robot scanning strategy

To demonstrate the concept of robotic path planning and simultaneously implement an NDT thickness mapping, a suitable measurement strategy had to be devised. A raster scan, with consistent spacing, across the sample and avoiding the riser obstructions was adopted. An open pocket motion strategy with multiple island operations was adopted for the path generation as the sample was a plate with no sides, each riser represented an island obstruction not requiring inspection. A standard path was then generated in Mastercam using a custom "tool" definition of the inspection robot. The initial CAD model with overlaid generated path is shown in Figure 4.

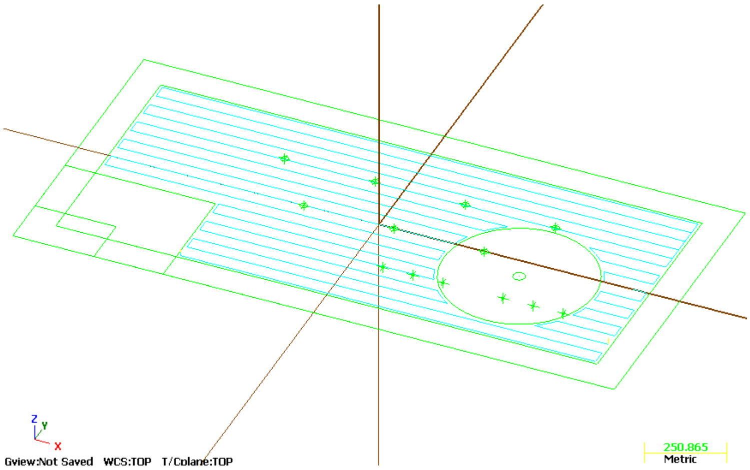
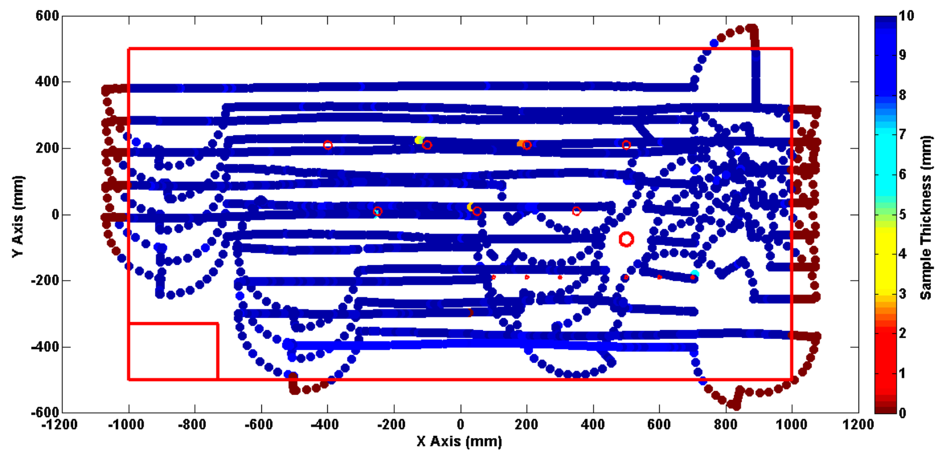


Figure 4: Mastercam CAD model and generated toolpath

The output was then exported through the custom CUE RSA post-processor to give the NC output file which was then parsed by MATLAB to generate the desired waypoints were then computed and output to the robot simulator (for path verification) and the robot hardware (for actual scanning).
For the NDE thickness measurement, all captured ultrasonic A-Scan datasets were loaded within MATLAB and the corresponding thickness of the material calculated using successive back-wall echo timings. The thickness map produced from the numeric control driven robot scan is illustrated in Figure 5 showing the local thickness (colour mapped) and the successful avoidance of both obstacles. For clarity the thresholded thickness are shown in plot (b).



(a)

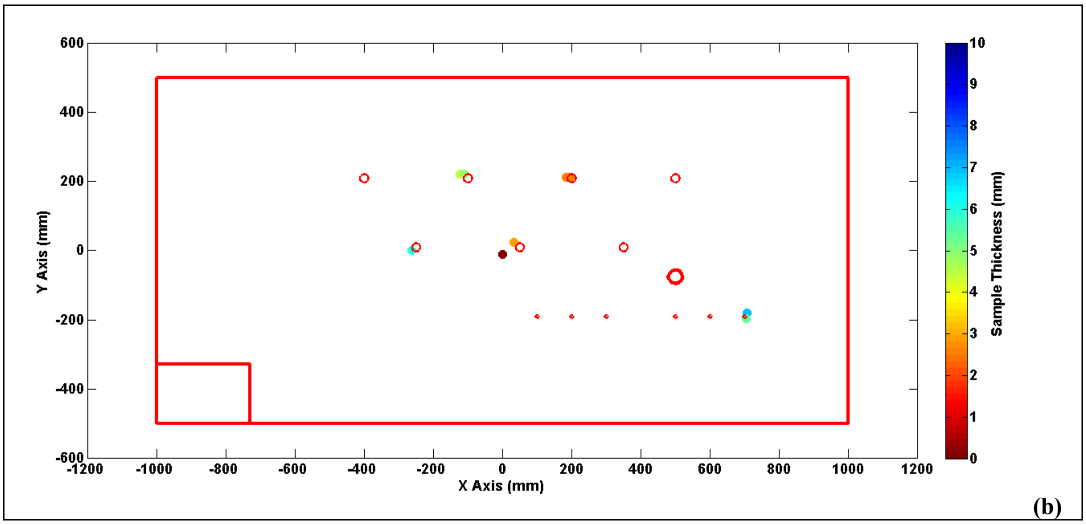


Figure 5: (a) Path trajectory and locally measured plate thickness, and (b) thickness thresholding for clarity

Defects 2, 3 and 13 were all detected successfully. Defect 13 was the only one of the six 10mm diameter holes located. Defects 8, 9 and 10 were not scanned (obstacle), while defect 1 was not fully scanned as both path trajectories did not pass through close to the defect centreline. Defects 4 and 7 were not detected due to the low nominal remaining plate thickness and the (poor) damping characteristics of the ultrasonic transducer. Similarly defects 11 and 12 were not detected due to the thin plate thickness.

CONCLUSION

The move to increased levels of autonomy for robotic delivery of inspection for asset monitoring, demands a structured approach to path planning and measurement data presentation that greatly surpasses the more ad-hoc approach typically employed by remotely controlled, but manually driven robotic inspection vehicles. The authors have presented a traditional CAD/CAM approach to motion planning (as used in machine tool operation) which has numerous benefits including the provision for detailed structural layout to be built into the path planning, and the subsequent visual overlay of measurement data back into the CAD model. Initial trials using a steel plate with varying thickness defects have been investigated. A custom robot incorporating an ultrasonic wheel probe as rear wheel has been used to perform an ultrasonic thickness scan of the sample – the results have been compared to those obtained using a high resolution wheel probe scan of the sample. The robot control was generated from an initial CAD model of the sample, and the integration of post-processor output (in this case G code), was used as the input for our custom robotic control software to generate both simulation and experimental motion control of our robotic platform.

In the future, for structures where detailed CAD models are non-existent, then the provision exists for model building using the established procedures of SLAM (simultaneous localisation and mapping) as developed through the existing mobile robotics community. The authors herein present a novel approach to robotic path planning derived from CAD/CAM, where such techniques are commonplace in generating complex toolpath trajectories on structural engineering components. The integration of post-processor output (in this case G code), is used as the input for our custom robotic control software to generate both simulation and experimental motion control of our robotic platforms.

REFERENCES

[1] Galceran E, Carreras M, "*A survey on coverage path planning for robotics*," Robotics and Autonomous Systems, Volume 61, Issue 12, December 2013, Pages 1258-1276.

[2] Acar, EU, Choset H, Zhang Y, Schervish, M, "*Path planning for robotic demining: robust sensor-based coverage of unstructured environments and probabilistic methods*," International Journal of Robotics Research 22 (7–8) (2003) 441–466.

[3] Cao Z.L, Huang Y, Hall E.L, "*Region filling operations with random obstacle avoidance for mobile robotics*," Journal of Robotic Systems 5 (2) (1988) pp 87–102.

[4] Bosse M, Nourani-Vatani N, Roberts J, "*Coverage algorithms for an underactuated car-like vehicle in an uncertain environment,"* in: Proc. IEEE Int. Robotics and Automation Conf., 2007, pp. 698–703.

[5] Choset H, "*Coverage for robotics—a survey of recent results*," Annals of Mathematics and Artificial Intelligence 31 (2001) pp 113–126.

[6] Pierce SG, Dobie G, Summan R, MacLeod CN, "*Reconfigurable robotic platforms for structural non-destructive evaluation*", TESConf 2012, 5-6th November 2012, Cranfield University.

[7] Neto P, Mendes N, "*Direct off-line robot programming via a common CAD package*," Robotics and Autonomous Systems, Volume 61, Issue 8, August 2013, Pages 896-910

[8] Chan S.F, Kwan R, "*Post-processing methodologies for off-line robot programming within computer integrated manufacture*," Journal of Materials Processing Technology, Vol 139, 20 August 2003

[9] Olivieri P, Birglen L, Maldague X, Mantegh I, "*Coverage path planning for eddy current inspection on complex aeronautical parts,"* Robotics and Computer-Integrated Manufacturing, Volume 30, Issue 3, June 2014, Pages 305-314

[10] Sattar T.P, Brenner A.A, "*Robotic system for inspection of test objects with unknown geometry using NDT methods*" Ind Rob, 36 (4) (2009), pp. 340–343

[11] Mineo C, Pierce S.G, Morozov M, Nicholson P.I, Cooper I, "*Computer-Aided Tool Path Generation for Robotic Non-Destructive Inspection"* In proc of: 52nd Annual Conf BiNDT, Telford, UK, 09/2013.

[12] Englot, Brendan Hover, Franz S. TI "*Three-dimensional coverage planning for an underwater inspection robot*" International Journal Of Robotics Research Volume: 32 Issue: 9-10 pp 1048-1073.

[13] Donald B.R, "*Motion Planning With Six Degrees of Freedom*," Massachusetts Institute Technology Artificial Intelligence Laboratory, Technical report AIM-791, 1984.

[14] Brooks R.A, "*Solving the find path problem by representing free space as generalized cones*" A.I Memo No 674, Massachusetts Institute Technology, May 1982.

[15] Kambhampati S and Davis L.S, "*Multiresolution path planning for mobile robots,"* in International Journal of Robotics Research, 5(10):90-98, 1986.

[16] Sariff, N.; Buniyamin, N., "*An Overview of Autonomous Mobile Robot Path Planning Algorithms*," Research and Development, 2006. SCOReD 2006. 4th Student Conf., pp.183,188, 27-28 June 2006

[17] Babel L, "*Flight path planning for unmanned aerial vehicles with landmark-based visual navigation,"* Robotics and Autonomous Systems, Volume 62, Issue 2, February 2014, pp 142-150.

[18] Barrientos, A., Colorado, J., Cerro, J. d., Martinez, A., Rossi, C., Sanz, D. and Valente, J. (2011), "*Aerial remote sensing in agriculture: A practical approach to area coverage and path planning for fleets of mini aerial robots."* J. Field Robotics, 28: 667–689. doi: 10.1002/rob.20403

[19] Pease W, (1952) "*An automatic machine tool*" Scientific American, Sep issue, pp 101-115, 1952.

[20] Dragomatz D, Mann S, "*A classified bibliography of literature on NC milling path generation,"* Computer-Aided Design, Volume 29, Issue 3, March 1997, pp 239-247.

[21] Dobie, G, Summan, R, MacLeod, CN, Pierce, S & Galbraith, W, "An Automated Miniature Robotic Vehicle Inspection System", Review of QNDE, Baltimore, United States, 21-26 July, 2013.

[22] Friedrich M, Dobie G, Chan CC, Pierce SG, Galbraith W, Marshall S, Hayward G, "Miniature Mobile Sensor Platforms for Condition Monitoring of Structures," IEEE Sensors Journal, Volume 9, 2009 pp 1439 – 1448.