Remotely Deployable Autonomous Surface Inspection and Characterisation Using Active Whisker Sensors

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ABSTRACT

For structural monitoring applications, the use of remotely deployable Non Destructive Evaluation (NDE) inspection platforms, offer many advantages when compared to traditional techniques in respect of accessibility, safety and financial outlay. The use of such platforms, previously reported by researchers at Strathclyde University, allows rapid inspection of large areas and volumes, ensuring structures are safe and operable to modern requirements.

Researchers at Bristol Robotics Laboratory have developed a biomimetic tactile sensing system modelled on the facial whiskers (vibrissae) of animals such as rats and mice. Such sensors are attempting to recreate the process in which animals detect proximity to nearby objects, along with their shape and texture. A critical feature of such a sensor is in the whisking motion, in a back and forth manner in which the end tapered tips sweep the surface.

The current work reports on our preliminary collaborative work to integrate the active whisker sensor into a robotic NDE system. A novel approach to surface roughness scanning is presented, highlighting the benefits and sensory information received from such an active sensing system. Additionally a representative test sample was characterised against conventional standard surface roughness measurement techniques.

INTRODUCTION

Areas requiring periodic inspection or detailed surveying on large scale structures such as those found in the energy and transport sectors, are often in locations not only with limited access, but also hazardous to human beings [1]. This situation along with the increasing demands for greater inspection accuracy and

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efficiency has underpinned a research and development drive to automate current NDE inspection techniques [2]. In addition to easing access issues automation of NDE procedures improves accuracy by reducing human error [3], which can often be categorised as the weakest link in the NDE supply chain [4].

This fundamental requirement for autonomous NDE systems has driven research and development in miniature Remote Sensing Agents (RSA) capable of remotely accessing challenging structures and then undertaking detailed NDE using a variety of specialised sensors and payloads[5].

The current RSA's developed within the Centre for Ultrasonic Engineering (University of Strathclyde) feature a fleet of differential drive crawlers capable of performing physical inspection tasks using a variety of sensor payloads such as Air-Coupled Ultrasound, Magnetic Flux Leakage (MFL) and visual based systems. Utilising magnetic wheels these crawlers are able to adhere to ferromagnetic surfaces and allow inspection of constrained 3D environments.

In this paper we introduce the addition of a new NDE sensor for deployment on the RSAs comprising a whisking sensor developed by researchers at The Bristol Robotics Laboratory. Actuated artificial whiskers based on the facial whiskers of rodents such as rats and mice can provide effective tactile sensory systems for autonomous robots. Such facial whiskers known as vibrissae are capable of human resolution surface texture discriminations, through an active process of sweeping the whisker tip across the surface under question [6]. The brushing of the whisker induces vibrations along the shaft that are transduced into neural signals by mechanoreceptors in the whisker follicle, providing the corresponding vibration pattern neural encodings to allow surface information to be measured [7]. This active whisking process of purposeful control and the seeking of information must therefore possess some benefit to the animal, namely the ability to control the direction of large area scans and also the velocity and duration of surface contact. It has been suggested that therefore such animals actively whisk their vibrissae to achieve greater sensory information in a similar manner to humans who adjust their fingertips movement when exploring surfaces [8].

The potential NDE applications of such sensors lie primarily in the capability for monitoring surface roughness and local profile geometry. This is particularly relevant given the continued large scale use of hot-rolled steel in industrial structures, due to its high strength to weight ratio, consistency and flexible design. This use requires extensive and substantial protection systems to reduce susceptibility to corrosion. The unstable iron-oxide mill scale, produced on the surface of steel after the hot rolling process, reacts with moisture in the environment resulting in corrosion of the steel. Throughout this process mill scale is removed from the steel leaving an irregular corroded surface behind. The rate and quantity of corrosion is dependent on many factors, however primarily being the length of time exposed to the wet environment, resulting in the chemical, electro-chemical or microbiological reactions [9].

The performance and durability of protective coatings and products applied to industrial metal surfaces are significantly affected by the state of the material immediately prior to application [10]. The primary factors influencing performance are the presence of rust, mill scale, surface containments and the surface profile. The profile of a specimen under question is the foundation to which all objective surface assessments are made, allowing all standard surface roughness parameters to be then mathematically computed from the data [11].

VIBRISSAE BASED SENSING SYSTEMS

Researchers at Bristol Robotics Laboratory (BRL) investigating biomimetic sensing and technology have focussed their research on the manner in which vibrissae endowed animals acquire sensory information on their surroundings. Through the BIOmimetic Technology for vibrissal Active Touch (BIOTACT) European Union FP7 project they have undertaken a long-term collaboration with biologists and engineers, to further understand the operation of vibrissae systems and their potential use and application in automated engineering systems [12]. An outcome of this collaboration is the development of modular fully controllable artificial active whisking sensors.

ARTIFICIAL WHISKER MODULE

The whisker shafts are produced using composite material and Data Light Processing (DLP) rapid-prototyping technology to achieve fine taper tip sizes coupled with sufficient strength and toughness to withstand repeated impact against surfaces. Smaller tip sizes allow for greater surface sensing resolution along with reduced impact on sensing performances if tip breakages occur.

The whisker shaft is actively swept back and forth using an integrated three-phase brushless geared DC motor and its corresponding protraction angle (θ) with respect to the module normal measured to 14 bit resolution using a non-contact Hall-effect sensor. Real time drive signal generation and closed loop Proportional-Derivative (PD) control is provided by the integrated 16bit digital signal microcontroller, allowing for whisking frequencies comparable to that of real rat vibrissae. Furthermore the orthogonal X and Y axis deflection (X,Y) of the whisker shaft base are again measured to 14 bit resolution using a non-contact Hall-effect sensor. All three measured properties (θ,X,Y) are transferred at 2Khz sampling rate to a host PC via an external Field Programmable Gate Array (FPGA). Each whisker module shown in Fig. 1, weighs approximately 8g while being 20mm by 15mm by 15mm in size.

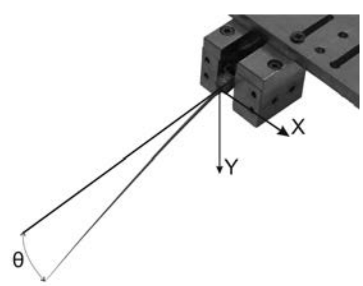

Figure 1. Whisker Module.

Current research has focussed on the particulars and importance of motor control in the whisking motion [12]. In this work the drive signal for motor control is a fixed-amplitude, fixed-frequency sinusoidal signal with no control performed on sensory information from whisker-environment contact.

SURFACE ROUGHNESS MEASUREMENTS

The conventional method of determining the surface profile of a sample is through the use of styli contact based system [11], whereby measuring the deviations of an infinitely small stylus following the peak and troughs of the sample a two-dimensional outline of the surface can be obtained. A simpler method makes use of a depth gauge to average a series of deviations of the valleys of the surface, measured respectively to the peaks on which the device rests. Numerous optical methods exist based on techniques such as interferometry, Schmaltz optical sectioning and confocal microscopy. The traditional referenced British standard [13] on determining sample surface texture utilises a comparator panel with four sections of defined standard roughness characteristics [9]. A manual operator makes visual and tactile comparison and classifies the sample surface as Fine, Medium or Coarse, dependant on its similarity to the referenced segments.

Modern surface profilometers, are limited in practicality and flexibility when considering automated large scale industrial scanning. Firstly many of the devices based on contact and non-contact methods are fixed installation products which are naturally unsuitable for such tasks. Secondly the presence of highly irregular surface profiles, produced by large scale corrosion or the presence of surface artefacts such as weld beads, lap joints and rivets, results in large scale peak to trough deviations often in the tens of millimetres. Many modern styli based surface profile and roughness measurement devices sacrifice vertical axis travel for greater sensing resolution [14], coupled with vertical travel ranges in the hundreds of micrometre range are therefore then completely unsuitable for practical full scale industrial surface mapping. Furthermore loose or flaking surface particles inhibit the operation and reliability of such precision mechanisms, rendering the device unusable. Optical methods possess inherent drawbacks and practical limitations such as surface condition/reflectivity and colour along with automated processing of data being convoluted [11].

Therefore a surface profilometer and roughness measurement system for rapid large scale automated scanning must feature wide vertical axis travel coupled with sufficient axis resolution and repeatability, along with the ability to handle the presence of practical surface artefacts.

VIBRISSAE INSPIRED NDE APPLICATIONS

To characterise and evaluate the performance of such an active sensing system for NDE applications, the whisker module was mounted on a fixed x-y scanner arm, allowing controlled and repeatable raster scans of test surfaces to be performed. Using a calibrated three dimensional Laser Tracker (LT) system [15] the scanning arm and ground truth reference measurement surface were both levelled to gravity. A Vicon Six Degree of Freedom (6 DOF) tracking system [16] was utilised to acquire real time 100Hz positional information of the whisker module. The scanner, Vicon and whisker module control were integrated together in the MATLAB programming environment, allowing for a complete closed loop scanning system to be implemented and operated.

The whisking frequency (f_w) was selected as 1.8Hz.This is slower than the traditional whisking frequency of rats (Dominant frequency 8Hz), however the 112mm long whisker used throughout this work is greater than that of a typical rodent. This frequency was selected arbitrarily and limited testing has shown that this is not critical in achieving successful texture classification [12].

In this work each whisking process is defined as five seconds of eight complete cycle whisks. The surface contact point of each whisk cycle corresponds to a trough in the measured theta angle, with the corresponding mean of the complete eight troughs computed to derive the average theta angle per process. Both relative orthogonal whisk X and Y axis displacement components are obtained through subtraction of the relative reference unperturbed free space whisk displacement. The Power Spectral Density (PSD) of the data is computed and the resultant mean total energy per whisk process, given by the average integral of the PSD whisk cycle curves. Therefore for each complete whisk process, a relative mean angle value along with the mean energy for both orthogonal X and Y axis components is computed.

VIBRISSAE BASED SURFACE ROUGHNESS CHARACTERISATION

Five samples of similar area, namely 20mm by 60mm, commercial grade abrasive paper were selected ranging from P240 to P80 ISO grit designation. A test piece was configured with the samples arranged in order of decreasing grit size as shown in Figure 2, with P240 furthest left, and 20mm wide aluminium spacing between each subsequent sample, giving a total length of 220mm. Using the LT the mean maximum deviation of the peaks in the vertical axis from a referenced plane, defined as the underside base of the backing paper, of each sample was measured over a length of 60mm. Each sample was then indented by its corresponding height value into an aluminium block of 15mm depth through milling removal, resulting in the mean vertical height of all six samples and the aluminium block to be 15mm. Such a technique permits discrimination of surface roughness and surface vertical offset.

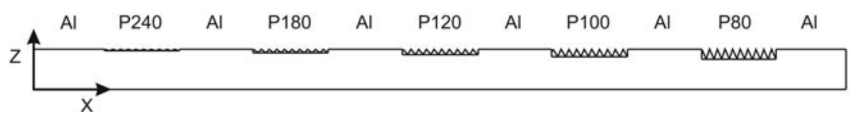

Figure 2. Indented Test Piece.

A standard method of quantifying one feature of surface texture is Roughness Average (R_a). R_a is the arithmetic mean value of the departure of the profile (y) from the centre line throughout the sampling length [11].

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|y_i| \qquad (1)$$

Using a calibrated surface roughness meter the R_a value of each sample was measured five times across the range of area, with the results shown in Table 1.

ISO Grade	P240	P180	P120	P100	P80
Mean R_a (µm)	13.70	16.71	22.91	30.84	52.91

Table 1. Sample Roughness Average Values.

A line scan of 220mm length and 1mm step size was undertaken across all five samples and six aluminium segments, with a single whisking process at each point. A moving average filter, with span of five whisking processes was utilised to smooth the raw X and Y axis energy data, which was then normalised (Fig. 3 & 4). The R_a data is normalised from the mean values shown in Table 1.

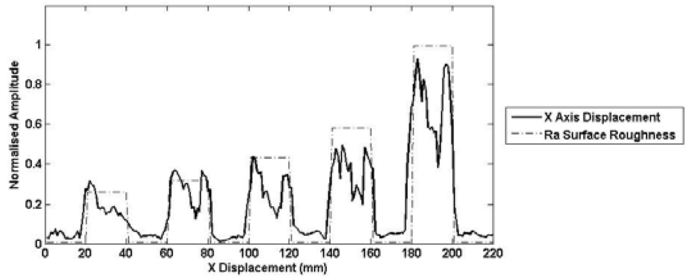

Figure 3. Indented Sample Whisker X Axis Deflection Energy.

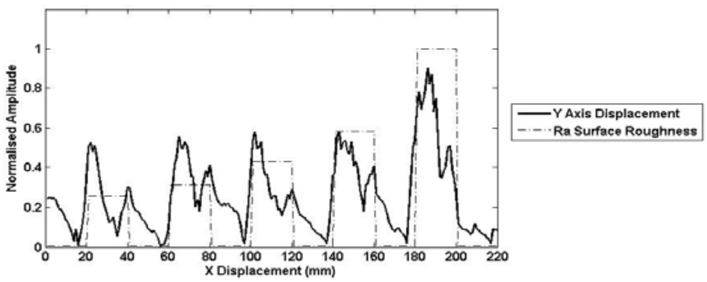

Figure 4. Indented Sample Whisker Y Axis Deflection Energy.

The mean amplitude of each abrasive paper sample in a 20mm window, corresponding to the width of each separate example, was taken and plotted against the mean R_a value of each sample. A third order polynomial fit was then applied to each data set (Fig. 5 & Fig. 6).

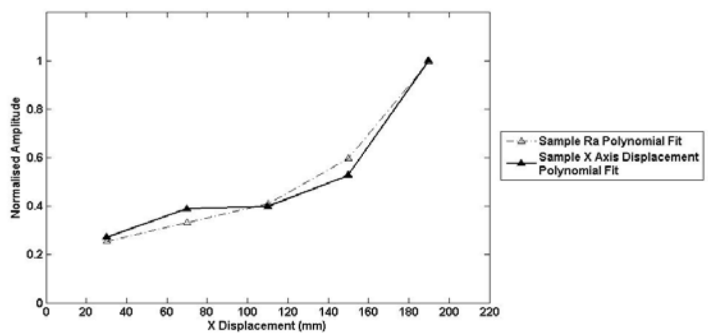

Figure 5. Mean Indented Sample X Axis Amplitude.

The correlation coefficient (r) between the mean indented X axis amplitude (X) and the mean R_a data (R_a) was computed using (2) and found to be 0.988.

$$r = \frac{\sum_N (X_N - \bar{X})(R_{a_N} - \overline{R_a})}{\sqrt{\left(\sum_N (X_N - \bar{X})^2\right)\left(\sum_N (R_{a_N} - \overline{R_a})^2\right)}} \qquad (2)$$

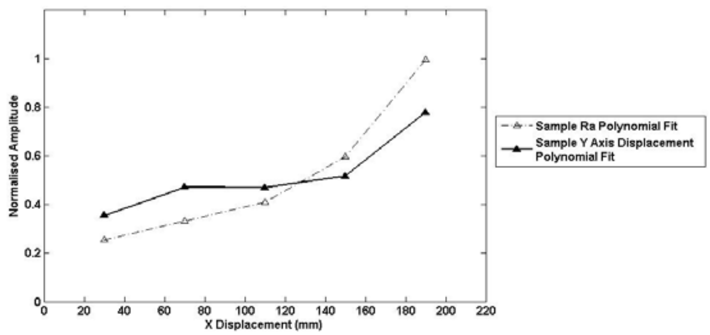

Figure 6. Mean Indented Sample Y Axis Amplitude.

Similarly the correlation coefficient (*r*) between the mean indented Y axis amplitude and the mean R_a data was found to be 0.973.

A further test was conducted using a second test piece with five similar ISO abrasive paper samples un-indented into a 15mm deep aluminium block. The mean theta angle of each sample in a 20mm window, corresponding to the width of each sample, was taken and plotted against the mean vertical height of each sample measured previously. Again a third order polynomial fit was applied to each data set, whereupon the correlation coefficient was found to be -0.942. The negative sign confirms that with increasing sample vertical height, the whisker theta angle is in fact reduced. This is due to the shortened arc length travel required to sample surface contact.

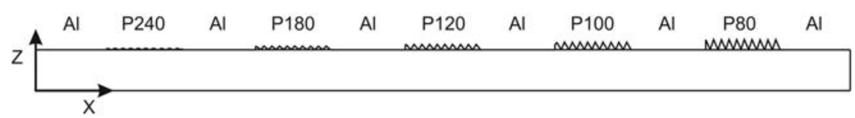

Figure 7. Un-Indented Test Piece.

CONCLUSION

This paper has introduced a novel surface roughness and NDE sensor, based on the biological vibrissae of rodents. It has been shown that the active whisking sensor can accurately categorise various sample surfaces of increasing roughness average (R_a) in the range 14-53 microns, with correlation to standard measurement techniques in the range of 0.97-0.99. This sensitivity to small changes in surface roughness will enable the sensor to be employed in a variety of NDE inspection scenarios including local profile mapping, surface texture characterisation, sharp boundary change detection (associated with surface breaking cracks), and surface roughness characterisation associated with corrosion mechanisms. The future integration and deployment of the sensor on the current RSA platform will allow such measurements to be performed remotely, with all the access benefits associated with robotic inspection of remote and hazardous areas.

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