Remotely Deployable Aerial Inspection using Tactile Sensors

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Abstract. For structural monitoring applications, the use of remotely deployable Non-Destructive Evaluation (NDE) inspection platforms offer many advantages, including improved accessibility, greater safety and reduced cost, when compared to traditional manual inspection techniques. The use of such platforms, previously reported by researchers at the University Strathclyde facilitates the potential for rapid scanning of large areas and volumes in hazardous locations. A common problem for both manual and remote deployment approaches lies in the intrinsic stand-off and surface coupling issues of typical NDE probes. The associated complications of these requirements are obviously significantly exacerbated when considering aerial based remote inspection and deployment, resulting in simple visual techniques being the preferred sensor payload. Researchers at Bristol Robotics Laboratory have developed biomimetic tactile sensors modelled on the facial whiskers (vibrissae) of animals such as rats and mice, with the latest sensors actively sweeping their tips across the surface in a back and forth motion. The current work reports on the design and performance of an aerial inspection platform and the suitability of tactile whisking sensors to aerial based surface monitoring applications.

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Aerial Inspection

For structural monitoring applications, the use of remotely deployable Non Destructive Evaluation (NDE) inspection platforms offer many advantages, including improved accessibility, greater safety and reduced cost, when compared to traditional manual inspection techniques. Remote inspection facilitates the potential for rapid scanning of large areas and volumes in hazardous locations where manual inspections would be costly to perform safely.

The current Remote Sensing Agents (RSA) developed within the Centre for Ultrasonic Engineering (University of Strathclyde (UoS)) feature a fleet of differential drive crawlers capable of performing inspection tasks using a variety of sensor payloads including Air-coupled Ultrasound, Eddy Current Array, 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 [1, 2].

Although successfully used for real inspections [3] these RSA's have obvious access limitations and on-going research has investigated the design and use of aerial based platforms to allow more flexibility in inspections not constrained to gravity or limited to ferromagnetic materials [4]. Such a robot will readily allow the inspection of complex structures not only constructed from ferromagnetic metal but also common composite materials, such as polymers and concrete, in true three dimensional space.

Aerial Inspection Platform Requirements

A robotic platform designed from the outset for aerial inspection actives in the field of Non Destructive Evaluation necessitates a very distinct and specific specification and set of requirements, unique to the task and application.

Key requirements for such a platform would therefore be;

1. At all times feature stable controlled movement ensuring human and structural safety. Critical to ensuring successful deployment of any NDE inspection technique is the ability to undertake the task involved with maximum safety, with procedures in place to ensure no risk of injury or damage to humans, the environment or structures.

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2. Possess a satisfactory level of hovering capability to allow accurate measurement from a variety of potential contact and non-contact sensors. Due to the finite sampling time required for the majority of current sensing techniques the inspection platform must consequently ensures disturbances are minimised during inspection, by primarily ensuring minimal or no deviation in the six degrees of freedom of the platform.
3. Have accurate knowledge of position and local environment in both indoor and outdoor situations. Fundamentally required for robot path planning, collision avoidance and when considering NDE applications, the true location of any found defects or areas of concern
4. Possess intelligent condition monitoring and control algorithms. Such control systems will ensure safe reliable operation, while safeguarding swift action in the unlikely event of a fault being developed.
5. Be relatively small in size and have excellent manoeuvrability to allow for use in confined environments. The resultant size of any aerial platform performing NDE inspection is application specific, dependent on parameters such as work volume, payload, runtime and access area.
6. Be reliable, robust and possess adequate redundancy. The platform must be capable of withstanding the requirements found in typical inspection environments, while also ensuring reasonable component failure and damage will not compromise the integrity, execution and safety of the inspection.
7. Feature advanced power efficient devices and features to ensure lengthy run times.
8. Optimisation of the energy efficiency of all electrical and mechanical components will ensure minimum energy usage, therefore maximising inspection and platform runtime.
9. Have considerable payload potential for transport of sensors and developed wheeled crawlers.

To maximise NDE leverage, the platform must be capable of deploying a reasonable number of sensor technologies to maximise information through multiple sensor data fusion, in a similar manner to the current RSA platforms. Furthermore the option of transporting and deploying the RSA platforms at convenient locations in an inspection task would be beneficial albeit application specific.

Suitable Platforms

Balloon Based Vehicles

Aerial vehicle based around an envelope airbag filled with a less dense gas than air and a number of independent actuators control the position of the vehicle by applying forces in the desired direction. Recent research programs designing and utilising such designs have done so in both indoor and outdoor environments with a variety of measurement applications [5,6]. These designs require a voluminous balloon structure to carry substantial payload as their lifting ability is directly related to the resultant air pressure surrounding them [7]. The low rate of change of the critical movement parameters in such a design has control advantages, however this is obviously at the expense of rapid manoeuvrability. Such a design features very poor external disturbance rejection from the effects of increasing wind speed when flown in an outdoor environment. Under still hover conditions they require little power to ensure the position of the vehicle is maintained within acceptable tolerances, giving run times in the order of hours as the lifting action of the gas is potentially of infinite duration.

Fixed Wing Aircraft

Traditional fixed wing aircraft by their very nature utilise one or more fixed wings to generate the necessary lift force when travelling forward through air. Further mechanical linkages such as ailerons and stabilisers control the roll, pitch and yaw of the aircraft. While possessing excellent endurance characteristics as demonstrated when operating in gliding mode, due to their fundamental design are unable to hover without secondary propulsion devices [8]. Such designs are not used traditionally in enclosed confined spaces due to their requirement for large take-off and landing areas if not modified again with specific secondary powertrain components.

Biologically Inspired

Insects and birds are classed as the most efficient flyers in the environment, with unmatched dynamics, manoeuvrability, speed and agility [9]. Furthermore their pronounced ability to handle large varying surrounding conditions such as wind turbulence ensures that much research has been undertaken in understanding their flight dynamics and methods of propulsion. The normal method of mechanical actuation in such species is that of the flapping wing design, which using a number of complex unsteady aerodynamic phenomena allows the insects to produce lift and thrust forces several times their original size [10]. Additionally such designs exhibit the greatest potential for miniaturisation over other aerial platform designs, with limited understanding of the aerodynamic effects at low Reynolds numbers. Many practical design have been developed over a number of years [9-11], however they currently are far inferior to standard developed conventional aerial flight deigns, when comparing payload, robustness and overall control.

Rotary Wing Aircraft

Rotary wing aircraft or rotorcraft feature one or more rotor blades configured in a specific arrangement whereupon rotation of the blades produces the required lift and movement forces. This design allows forward flight to be sustained at far lower velocities than possible with fixed wing aircraft, in fact being reduced to nil to allow the rotary wing aircraft to hover and feature vertical take-off and landing (VTOL). Through development and innovation many rotary wing aircraft configurations exist today each with their own merits and drawbacks, however they are all still governed by the same fundamental blade theory. The main rotary wing configurations are the conventional helicopter design, tandem, the coaxial model and evolutions of a quadrotor [12].

Conventional Helicopter

Conventional helicopter designs feature a single main rotor coupled to a smaller tail rotor. The rotation of the main rotor provides the thrust and control in the vertical plane. Furthermore adjusting and tilting the plane of action of the main rotor will allow control of the fore, aft and lateral movements while also controlling both pitch and roll. Yaw control is achieved through the horizontal force generated in the vertical plane by smaller tail rotor [12].

Tandem Configuration

The tandem configuration features two main rotors located at opposite ends of the main chassis body. Vertical thrust and control is provided by both rotors simultaneously, while tilting the plane of action of each rotor controls movement in the both roll, longitudinal and lateral directions. Differential control of both thrust and rotor tilt of each rotor controls the aircrafts pitch and yaw movements. The rear rotor blades are mounted higher than the front blades to ensure that they rotate in as undisturbed air as possible to give satisfactory lifting performance. This however can give rise to undesirable effects when undertaking manoeuvres at slow speeds and low altitudes as the aircraft can enter a nose up attitude, due to the rear motor sinking into the downwash of the front rotor blades [13].

Coaxial Configuration

The coaxial configuration features two rotor blades mounted vertically on the same axle. Vertical lift and control is again provided by the combined thrust of both rotor blades, while longitudinal, lateral, pitch and roll control is provided by tilting the plane of action of both blades. Yaw control is provided by differential rotor torques which can result in the undesirable effect of autorotation when descending. Autorotation is the effect of lift forces altering their direction of rotation and then forcing the air to rotate the rotor instead, resulting in yaw control reversal.

Fixed Pitch Rotary Wing Configuration

The quadrotor and its evolutions feature four or more fixed pitch rotor blades organised symmetrically along a parallel plane. Control of the vertical lift and movement is a result of the combined thrust of all rotors, while differential thrust between the front and rear rotors produce a pitch torque enabling longitudinal translation motion and similarly differential thrust between the left and right rotors produce a roll torque enabling lateral translation motion. Separate rotors spinning in opposite directions allow such designs to control aircraft yaw angle. While all blades rotating at the same velocity sum the reactive yaw torque to zero, changes in the speed of one of the clockwise or anticlockwise set of rotors will force the aircraft to rotate in the direction of the induced torque.

Platform Comparison

When reviewing the requirements for a suitable aerial platform for NDE application, a weighting factor was given to each of the key differing features, whereupon a complete comparison matrix was developed (Table 1). From this it became clear that only a multiple rotor - rotary wing aircraft such as the quadrotor design could satisfy all the requirements and perform to the required standard.

Table (1). Aerial Platform Comparison Matrix

Requirement	Weighting	Balloon Based	Fixed Wing Aircraft	Insect Inspired	Rotary Wing Helicopter	Rotary Wing Multiple Rotor
Stationary Hover Flight	3	4	1	2	4	5
Low Speed Flight	3	5	1	3	4	5
VTOL	3	4	3	3	5	5
Robustness and Redundancy	3	2	4	2	2	4
Indoor Usage	3	2	1	3	4	5
Safe Manoeuvrability	2	1	2	4	4	4
Endurance	2	5	4	2	2	2
Power Cost	1	5	3	3	2	2
Control Cost	1	5	3	2	2	3
Payload Capacity	1	1	5	1	3	3
Miniaturization	1	1	3	5	4	4
TOTAL		75	56	62	80	96

The Rotary Wing Multiple Rotor design features a number of advantages of conventional rotary wing aircraft, primarily negating the need for complex rotor actuation mechanical control linkages. The application of four or more thrust forces acting at a distance away from the centre of gravity can yield far more stable hovering capability , than that found in conventional helicopter deigns where one thrust force acts through the centre of gravity [14]. Furthermore the diameter of each individual rotor is considerably lower than that for an equivalent payload capacity conventional helicopter design, therefore lowering the stored kinetic energy in each propeller in-flight, mitigating the risk posed by such designs if involved in collisions [15].

Requirements such as safe stable hover can be maximised through the usage of such rotary wing based designs, while redundancy can be achieved through the introduction of multiple similar function rotors. Payload capacity is greater than that of traditional helicopter designs of a similar area footprint [14], however due to the requirement of multiple rotors, such a footprint becomes reasonable large due to the constraints of the design. Multiple rotors require large energy requirements and hence endurance and run-time capabilities are reduced accordingly.

Aerial Platform Position Control

Accurate control and position of an aerial vehicle within a measurement volume, to deploy and undertake useful NDE measurements, requires implementation of an overall control system capable of measurement and action.

An external VICON tracking system is utilised to determine and measure the six degrees of freedom (6DOF) position of the aerial platform. By uniquely arranging a number (>3) of retro-reflective markers to the object of interest, full position and orientation information can be acquired in real-time with an update rate of 100Hz [16].

Due to their robust performance and functional simplicity PID controllers were chosen and implemented within the overall control strategy [17]. The control system implemented is that of a cascaded multi-loop type where the first controller base output is the reference set-point for the attitude difference calculation. The error in attitude is the second PID controller input which controls the attitude of the platform. Through attitude motion, the platform translational motion varies, which when measured provides the necessary negative feedback. Desired coordinate position and pose values are the reference inputs to the negative feedback control system.

Through such a control strategy the 6-dof position of the platform can be controlled and specified, through the indirect updating of individual overall thrust, roll, pitch and yaw values. Altitude and therefore position in the z-axis is controlled through a parallel single control loop. An incremental PID controller is selected as the effect of vertical thrust does not accumulate. All controllers were manually tuned to ensure a satisfactory response speed and minimum overshoot. A scan path can then be defined using a number of consecutive discrete waypoints.

System Architecture

The current UoS RSA platform utilises a core electronic structure to implement all the necessary functions required to deploy an autonomous wireless NDE inspection platform. The hardware consists of a Linux embedded general purpose processor (GPP) (OMAP 3530) to perform the high level and computationally heavy functions, while a microcontroller performs low level functions such as drive and motor control. The platform communicates to a host controller machine through a standard IEEE 802.11g wireless communication channel. Lithium polymer batteries provide the required power to supply the demands of the system [18].

A custom quadrotor platform was developed to provide suitable performance and to meet the requirements of aerial based inspection and NDE. This quad-rotor specification features four 10x45 composite propellers each driven by a brushless motor (Robbe-Roxxy 2827-34) with corresponding high update rate 40A Electronic Speed Controllers (ESC). Power is provided by a 4S 2200mA/h 14.8V battery, allowing an approximate payload capacity of 650g and 20 minutes runtime. The quad-rotor computational processing, control and stabilization is undertaken by an Openpilot Copter Control 3D (CC3D) platform running an STM32 32-bit microcontroller running at 90MIPs with 128KB Flash and 20KB RAM. Control and operational information is passed through Serial Peripheral Interfaces (SPI) from the UoS RSA system to the on-board flight control system (CC3D) of the aerial platform. .

Additionally a C# external Graphical User Interface (GUI) has been implemented to allow the operator to enter desired flight and inspection parameters, while also allowing graphical visualisation of the information

Flight Performance

As previously stated an Aerial NDE platform must possess a satisfactory level of hovering capability to account for the finite sampling time required for accurate NDE sensor measurement. Therefore a hover stability test was undertaken to analyse the platform performance and stability, coupled to its ability to reject unwanted external disturbances. The root mean square errors of each position parameter are shown below, for a hover test (15 seconds) at desired coordinates points throughout the tracking volume at vertical heights of 500 and 1500mm.

Table (2). Positional Performance in Vertical Plane of 500mm.

Desired Position (x,y,z) (mm) (Ψ & θ & $\Phi = 0$)	RMS Error (mm)			RMS Error (°)			Mean XYZ Error (mm)
	X	Y	Z	Ψ	θ	Φ	
0,0,500	2.49	5.81	3.80	0.18	0.38	0.50	6.90
1000,0,500	3.02	5.43	3.27	0.18	0.35	0.99	6.58
1000,-1000,500	2.74	2.27	2.94	0.19	0.16	1.17	4.33
0,-1000,500	2.38	1.93	3.18	0.17	0.18	0.63	4.05
-1000,-1000,500	3.37	5.21	3.84	0.22	0.33	0.95	6.87
-1000,0,500	3.29	5.45	4.21	0.21	0.33	1.13	6.96

Table (3). Positional Performance in Vertical Plane of 1500mm.

Desired Position (x,y,z) (mm) (Ψ & θ & $\Phi = 0$)	RMS Error (mm)			RMS Error (°)			Mean XYZ Error (mm)
	X	Y	Z	Ψ	θ	Φ	
0,0,1500	6.37	4.53	4.94	0.28	0.29	0.76	8.36
1000,0,1500	3.87	4.89	5.83	0.21	0.33	0.79	7.42
1000,-1000,1500	5.98	3.86	4.29	0.27	0.27	0.61	7.66
0,-1000,1500	3.91	2.65	3.51	0.18	0.19	0.78	5.40
-1000,-1000,1500	7.90	2.86	3.37	0.37	0.19	1.08	8.30
-1000,0,1500	5.87	4.60	4.16	0.29	0.32	1.15	7.94

Visual Aerial Inspection

A mock aerial inspection was undertaken of a vertically planned surface. A raster scan waypoint trajectory was developed of 2 metre length and 1 metre width, with 250mm spacing between subsequent traces.

The UoS RSA electronic and software system was further developed to include a machine grade vision camera. The device (Point Grey Chameleon) features a global shutter to ensure each pixel receives light for the same amount of time, reducing the effect of motion blur, while operating on a highly position variable platform[19]. The electronic and software system was accordingly optimised with the enabling of the OMAP on-board Digital Signal Processor to maximise streaming, storage and image processing performance. The measured and desired trajectory paths are shown below along with a superimposed photo of the operating volume and surface under inspection.

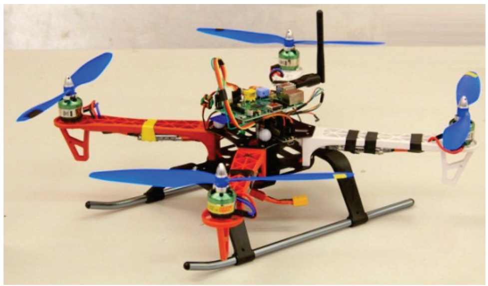

FIGURE 1 – UOS RSA Aerial Platform.

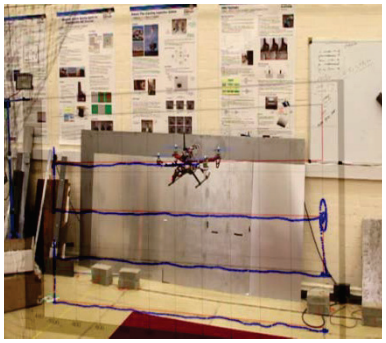

FIGURE 2 – UOS RSA Aerial Inspection.

A 640 by 480 pixel photograph was repeatedly triggered at a frequency of 2Hz with the aerial platform speed controlled at 0.25m/s. A selection of individual images are shown below (Figure 3), showing minimal motion blur and tearing. The resultant images (>200) were then stitched together using a commercially available solution (Adobe Photoshop) to create an overall panoramic image of the surface (Figure 4).

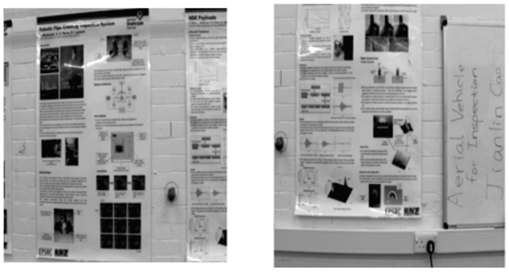

FIGURE 3 – Individual Inspection Images.

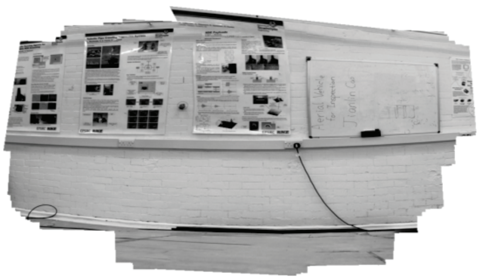

FIGURE 4 –Inspection Image Mosaic.

Biologically Inspired Tactile Sensing

The positional uncertainty of aerial platforms highlighted above, further complicates remote inspection in two distinct manners. Firstly the apparent location of identified defects can significantly alter future potential outcomes and scenarios for asset operators and owners. Secondly and more importantly is that traditional NDE sensing modalities require carefully control of sensor surface stand-off or lift-off distance, for accurate defect detection and sizing [20]. The practical complications of curved surfaces, areas of significant corrosion and the presence of surface artefacts such as weld beads, lap joints and rivets, surface containments such as dust, liquids or loose and flaking paint further limit the inspection potential, operation and performance of automated inspections.

With this in mind traditionally visual inspection has been the favoured technique for such remotely deployable platforms. However visual inspection methods possess drawbacks and practical limitations due to variation of lighting and conditions, spurious reflections and intensive data processing [21, 22].

To maximise inspection performance under such conditions a new NDE biomimetic actuated whisker module sensor for deployment on remote inspection platforms is presented, which was developed by co-authors at the Bristol Robotics Laboratory [23-25]. Their research focusses on the design and use of actuated artificial whiskers based on the facial whiskers of rodents such as rats and mice to provide tactile sensory systems for autonomous robots. In typical rodents the 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. 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. This active whisking process of purposeful control and the seeking of information must therefore possess some benefit to the animal, with it being suggested that such animals actively whisk their vibrissae to achieve greater sensory information in a similar manner to us humans who adjust our fingertip movement when exploring surfaces. [26-28].

The potential applications of such sensors lie primarily in the capability for monitoring surface roughness and local profile geometry. With the presence of rust, mill scale, surface containments and the surface profile of a material all affecting the performance and durability of protective coatings, and hence the structure itself a novel sensor capable of measuring these parameters is presented. This is relevant as the profile of a specimen is the foundation to which all objective surface assessments and standard surface roughness measurements are made [29, 30].

Some of key motivations behind whisker based monitoring are:

1. Firstly Positional Insensitivity – where the standoff distance between the sensor and the surface is uncritical compared to other traditional sensors. A feature which can be carefully controlled in a laboratory, but not easily in practical monitoring applications especially those featuring automated systems.
2. Simple, inexpensive and robust – All expensive sensing electronics are located far away from point of surface contact reducing wear tear and damage– the whisker shafts themselves are relatively very cheap to produce.
3. Rapid Scanning of surfaces. Currently capable of a linear single line scan range of 1m at 1mm resolution in 2 minutes per single whisker shaft. Highly dense array of whisker shafts would allow the area coverage per unit time to scale linearly.
4. Very accommodating to large scale profile changes such as curved surfaces, areas of significant corrosion or the presence of surface artefacts such as weld beads, lap joints and rivets. – Typical stylus based surface roughness systems do not have this flexibility.
5. Robust against surface containments such as dust, liquids or loose and flaking paint, again stylus based systems perform poor in this regard.

The authors have previously reported that such sensors can measure and discriminate surface roughness in the range of 14-53 µm with strong correlation (> 0.97) to standard techniques [31]. Furthermore it must be highlighted that such sensors can accommodate large changes in sensor surface lift-off with minimal effect on surface roughness measurement performance (TABLE 4).

Table (4). Module Lift-Off X & Y Axis Surface Roughness Correlation

Nominal Sensor–Surface Lift-Off (mm)	X Axis Correlation Coefficient & (Percentage error from zero lift-off)	Y Axis Correlation Coefficient & (Percentage error from zero lift-off)
0	0.988	0.973
1.5	0.986 (0.20%)	0.971 (0.21%)
3	0.976 (1.22%)	0.966 (0.72%)

The sensors have also been shown to discriminate surface profile, through measurement of artificial flat bottomed holes, down to a downward vertical resolution of 0.24mm.

Conclusion

A thorough review of remotely deployable aerial inspection platform design was presented with future requirements and configurations presented. A critical review and selection highlight the merits of different designs, with fixed pitch rotary wing configurations being most suited when ranked across all significant segments. It must be noted that other configurations will be more suitable in application specific scenarios, such as those requiring long endurance run times. A practical mock visual inspection was undertaken with a custom designed platform and its performance in terms of positional accuracy in full six degrees of freedom measured. From this it is clear that the use and deployment of traditional NDE sensors on such platforms is not trivial, due to their requirement to minimize sensor surface lift-off. The benefit of a tactile NDE sensing developed by the authors was presented and its potential suitability for remote deployment on such aerial platforms highlighted.

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