Portable 7 DOF Scanning Arm For Non-destructive Inspection Of Objects With Unknown Geometry

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Abstract: **The aim of this work is to develop a dextrous and adaptive robotic scanning system that can be carried by mobile climbing and walking robots to perform non-destructive testing (NDT) of remotely located infrastructure. To achieve this aim, a seven-axis lightweight robot arm has been especially developed for NDT [1]. The redundant degree of freedom is of advantage in cases such as avoiding obstacles in the workspace and joint limit avoidance. [2] The design is for portability, dexterity and ruggedness in an industrial environment. It weighs 23 kg and assures a repeatability of one millimetre. For ultrasonic NDT, the arm scans imprecisely known contoured surfaces by keeping the sensor probe normal to the test surface while maintaining constant contact forces with it, thereby ensuring good data acquisition. This is difficult to achieve when the surface is not known accurately as would be the case in test surfaces located remotely and in hazardous environments. An ability to adaptively modify a planned scan trajectory to deal with surface uncertainty would ensure better data acquisition. Further progress and new results on the subject of surface adaptation and NDT ultrasonic data acquisition are presented here. The focus is on the quality of data gathered from the NDT inspection system when combined with the robot's trajectory motion.**

Keywords: **l7-Axis Robot Arm, Robotics NDT, Force Control, Trajectory Adaptation**

I. Design of Automated NDT Inspection System

The Automate NDT procedures need to emulate human behaviour and therefore be able to direct forces in a controlled way and react to contact information. The robot needs to demonstrate force-sensing capability and compliancy. Reported systems have been developed to control a redundant manipulator in real time so that a prescribed geometric path can be followed. [2] The previous work established the development of a sound robotic system. The robot provides an easy and reliable movement inside its working envelope. In areas of automated NDT surfaces can be of a complex structure, such as aircraft turbine blade, or placed remotely where the need for an automated real time inspection system would decrease inspection times and therefore costs as well as enables human operators to control the inspection located in a hazardous environment from a safe environment.

The focus of this paper is to establish accurate adaptation for NDT purposes on unknown objects. For that reason passive compliance and force sensing have been researched to be the most suitable as e.g. both techniques provide persistent contact with the test piece. In the latter case the system has to rely on reliable information from sensors to deal with uncertainty in the environment. [3]

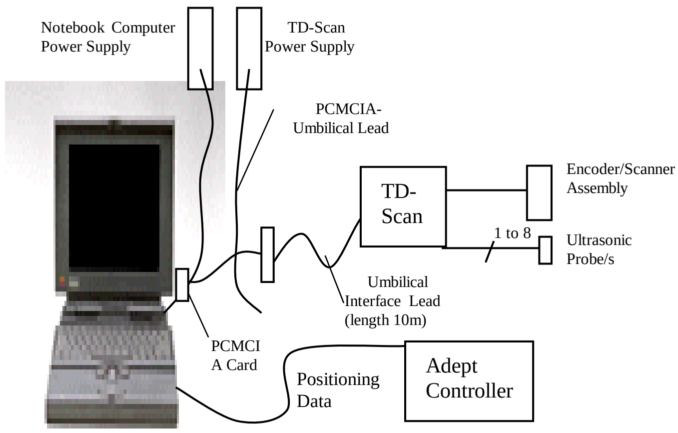

Fig. 1. Block diagram of NDT System arrangement

Regardless the type of adaptation technique, discussed in chapter 2 where results on the quality of data gathered from the automated NDT inspection system are presented in the following chapter, the development of a sound automated NDT inspection system requires the tight coupling of planning, sensing and execution. [5] Accordingly it is necessary to establish a sound interaction of the NDT and robotic systems which results into a reliable real time operating unit. For that reason a NDT data acquisition system, Technology Design's pocket Scan, has been added to the control system for the 7-axis arm, which is presented in figure 1. This chapter is concentrating on the alliance of both engineering areas, where the significant part is the capability to examine the object using ultrasonic inspection with the knowledge of the real time positioning data. A particular program has been developed which transforms the positioning data known by the robotic system and sends it to the TD pocket scan during the execution cycles. This enables the user to either specify a starting position of the robot using the relative values or the absolute values.

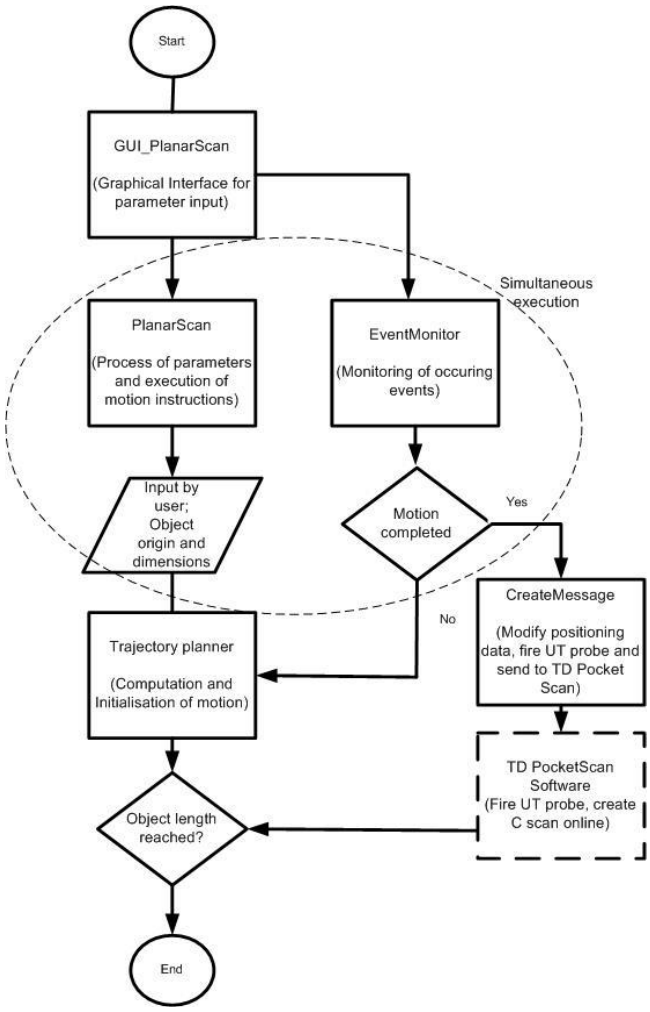

Fig. 2. Program flow of Real-time NDT scanning system

As a real-time system, the used control system using V+ computation provides complex motion to be executed quickly as continuous trajectory computation makes efficient use of system memory and is also reducing overall system complexity. The combination of event monitoring and real-time path-modification facility, where during an execution of a motion instruction the alteration of the path is enabled, is the major part of planned force control implementations. At the current stage the robotic system advantage is the simultaneous execution of different programs at the same time with at a frequency of 16 milliseconds. This feature enables resultant behaviour to be generated by concurrent execution of individual programs. In this case a program has been written, figure 2, to monitor the events of a completion of a motion for example is running concurrent to the motion execution program. On the occurrence of an event the other program is then executed. The flow diagram demonstrates the principle for a commanded planar scan. The scan is commanded on a flat surface and can be executed on a surface with slight changes in geometry. A different program has been developed where the operator can teach only several points which enable the inspection of an object with more complex surface changes. Both options are constructed for a surface scan with the compliant probe, explained in the chapter below.

The ongoing research using force control and therefore creating a more optimized behaviour will be discussed in the last chapter. The force tracking provides a constant force against the surface and a manipulator orientation only orthogonal to the surface. Joint limit avoidance, obstacle avoidance and singularity avoidance keeps the arm from collisions and singularities.

II. Surface Adaptation Using Passive Compliance

The main difficulty in automating NDT is to establish an accurate adaptation to the test surface (remotely located or of complex shape such as aircraft turbine blades that have a complex surface geometry) to obtain high quality data from possible defects. It is then necessary to respond to surface changes while going over the surface and at the same time to also orientate the NDT probe in the right way and position to get the best results.

There are several methods to profile a surface, where one of them is e.g. the use of vision sensors which has been researched in many different areas. Although this method has proved a very good performance in several industrial areas, one has to weight the suitability for this specific task. The automation of non-destructive evaluation mostly uses methods, like e.g. ultrasound, that require a permanent contact to the inspected surface throughout the evaluation phase. To receive any constructive NDT data from the end-effector, one has always to be able to keep the probe perpendicular to the surface. The implementation of a force sensor to the robotic system provides us with the knowledge of the forces in real time at the point of contact and therefore enables us to command the motions via force feedback control. Since most NDT methods require contact to the surface, the force sensor for adapting to the unknown surface is a very good option.

This research is aiming to obtain a sound adaptation using force control which can be compared to the NDT results from the manual inspection. Additionally it is also very attractive to research the quality of the NDE using passive compliance. Compared to active compliance this option is much simpler and can also be compared to the results of the evaluation using force control. In systems equipped with passive compliance devices, there is no interaction between the control system of the robot and the compliant device. The compliant device simply compensates the emerging forces and moments by deformation. Depending on the design of the compliant device, only the end of the robot is moved for adaptation. In active compliance nevertheless it is the whole robot which moves to reach the same desired orientation, the information of the sensor is then processed by the control unit and motion instructions are sent to the various motors to correct the trajectory and to annual the forces and moments.

The following will demonstrate the design and present as well as discuss the NDT results obtained form the findings using passive compliancy. The digitised results are displayed as a C, B and D-Scan defect maps for further analysis.

The first layout of the first compliant NDT probe is introduced compliance in a singular orientation of the Z axis. This probe is only suitable for flat surfaces and not applicative for complex shaped objects because of the single axis of compliance. Thus it doesn't provide enough flexibility for the tool tip to align the ultrasonic probe to a curved surface. This has been confirmed by test scans which indicated several measurement data losses due to slight lift-off of the probe caused by changes in the configuration of the arm and slight changes in surface angles of the test object. This can also result in too much contact force being applied which stresses the robot's gears and motors and detunes the control systems resulting in tool oscillation. With this method additional teaching routines are essential and therefore object shape and environmental space have to be known, which doesn't suit our research aim. For that reason a different probe has been developed which adds two further degrees of freedom to the end of the tool, see figure 3 and 4. This method indicates a potential to approach a sufficient adaptive behaviour for qualitative NDT results acquisition. The performance of this technique can then further compared and discussed with further NDT data obtained from the system using the force control technique.

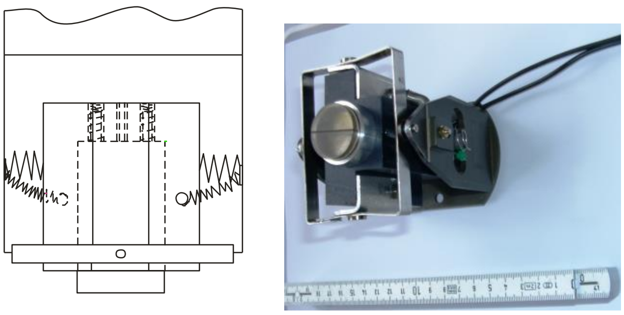

Fig. 3. Frontal view of the developed NDT probe holder; conceptional design and picture

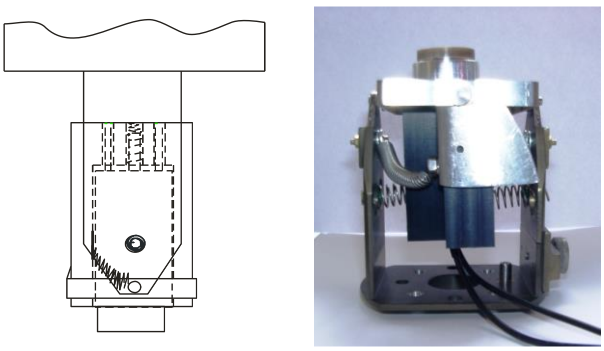

Fig. 4. Lateral view of the developed NDT probe holder; conceptional design and picture.

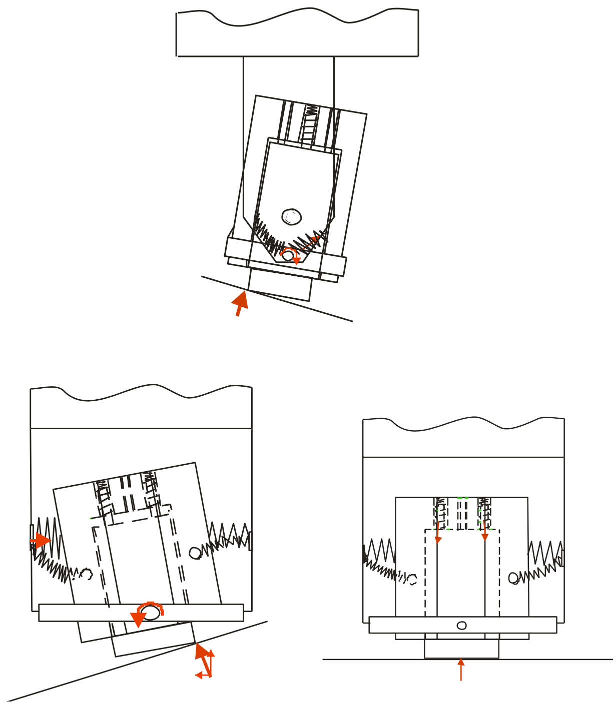

Fig. 5. Frontal and lateral view of the adaptation using passive compliance.

The developed compliant NDT probe is designed to represent a function that maps the forces applied to the manipulator into a resulting motion [4]. It accommodates the end-effector's motion with the external forces and moments by applying additional passive compliance to its end effector as well as two further degrees of freedom. At the initial movement of the robot towards an unknown object, the robot will suddenly encounter the object. The arose force will have an effect on the tilt on the tool tip and allow the sensor to position himself normal to the surface. The two side as well as frontal springs limit the movement of the NDT probe and ensure a more controlled placement onto the uneven surface and moreover avoid a flip turn of the probe.

The advantages and disadvantages of this mechanism are:

1) No additional control system necessary; simplicity
2) Ease to introduce passive compliance
1) No control over pressure onto surface
2) Can only adapt to surfaces with minor/ limited changes of the surface

Experimental test on the following plane and bend samples have resulted into the following NDE results. The digitised results are displayed as a C, B and D-Scan defect maps for further analysis. The inspection used the Pulse Echo (PE) method using a straight beam ultrasonic probe (5MHz). With a set gain of about 70.5 dB with a averaging value of 16 at sampling rate of 100000 MHz, a satisfying A-scan signal could be accomplished. The test piece has a depth of 30mm and length of 239mm. It has six defined vertical cracks at the bottom with the following parameters:

TABLE I

REAL CRACK POSITIONING AND SIZES OF TEST PIECE

Defect No.	X-Relative [mm]	Y-Relative [mm]	Defect Size [mm]
1	0	40	10
2	0	78	9
3	0	111	8
4	0	142	7
5	0	174	6
6	0	206	5

The movement chose to be along the side of the test piece which was fixed into a fixation positioned along the robots y-direction. The position values transmitted from the robot to the NDT unit are first calculated relative to the starting point of the test piece which was defined to be (0, 0) at an actual robot position of (463.32,-56.96,-171.48). The automated scan resulted into a smooth adaptation with no recorded data losses. The data acquisition was set, using one gate, to record data before (around 24mm) till including the first back wall reflection (at wall thickness of about 30mm). All six defects could be found, as shown in figure 6.

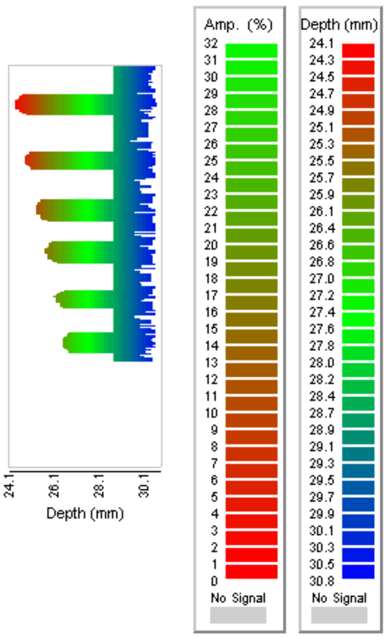

Fig. 6. D-Scan of test piece with detected six defects.

Note that the crack sizes, here decreeing, can be seen in figure 6 and 10. Looking closer at one particular crack, here chose crack number 2 (figure 7), 3 (figure 9) and 5 (figure 8).

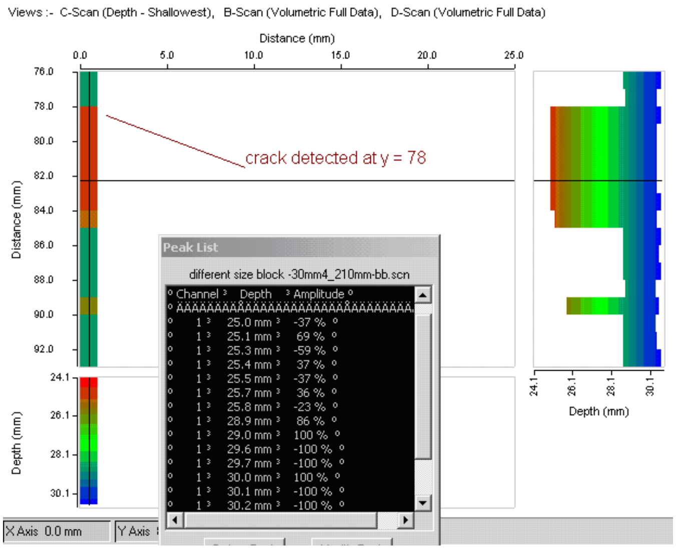

Fig. 7. C, B and D-Scan of test piece looking at defect no. 2.

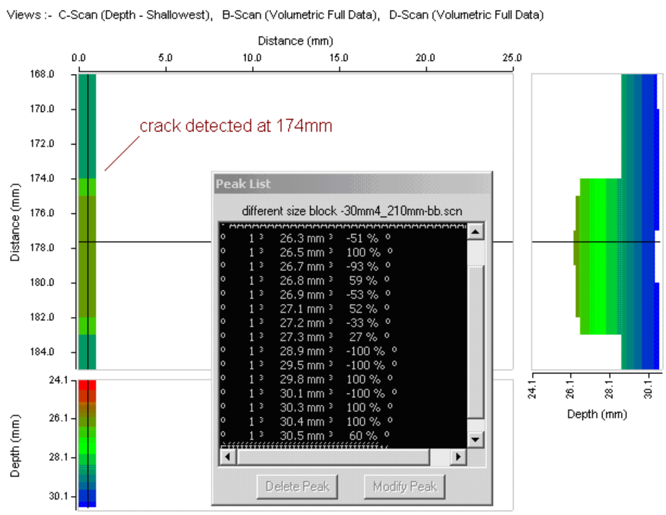

Fig. 8. C, B and D-Scan of test piece looking at defect no. 5.

As the decided frequency is at every 1mm scanning, the accuracy can be seen as sufficient enough as can be seen from the following figures compared to table 1, cracks are detected at 78mm (figure 7), 111mm (figure 9) and 174mm (figure 8). The peak list of e.g. crack no. 2 indicated the several amplitudes of the signal at that time of detection. This shows us in figure yy (figure 7) that values from a depth of 25.0 (37% amplitude) to 30.5 (100% amplitude) basically describe the distribution of sound reflections, which basically should give indications about the distance to the crack. The values bigger then 28 mm can be seen as reflections from the back wall. The value most interesting to us is the lowest value or the values near to it. From averaging or weighting of these values the correct depth values can not precisely be found. As for example of defect no. 3, the position of this defect is indented to be found at 111mm with a size of 8mm. Therefore with a depth of 30mm, a strong reflection should be at about 22mm depth. The values of the peak list however indicate values starting from 25.4mm to around 30.4mm. Therefore the location as well as the approximate size and in particular the size differences can be seen satisfactory.

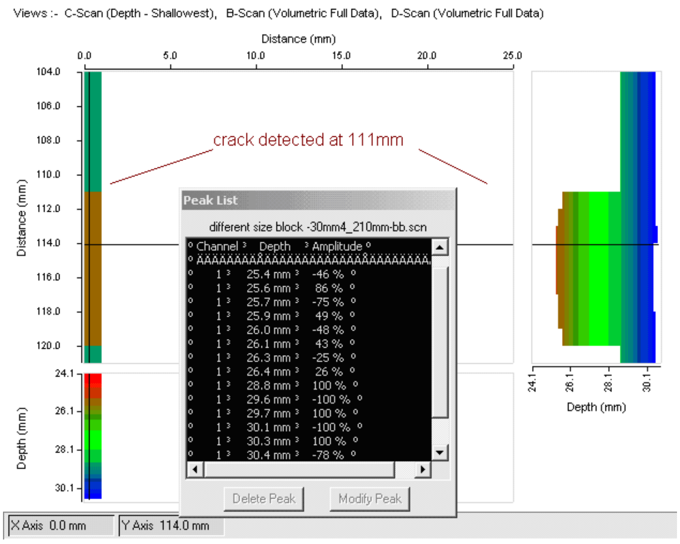

Fig. 9. C, B and D-Scan of test piece looking at defect no. 3.

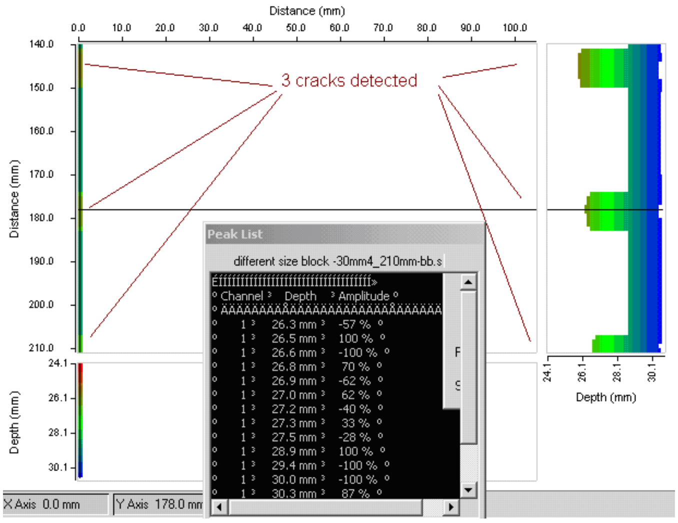

Fig. 10. C, B and D-Scan of test piece looking at defect no. 5

The added compliance assured a good contact force to the surface and good ultrasonic data when the actual surface differed by a small amount from the planned scanning trajectory.

III. Non-Destructive Testing Using Force Control Adaptation

Robot with force control has the advantage of being versatile and programmable for different applications, it requires a more advanced control system and adapted programming to specify how the robot should interact with external constraints. On the other hand difficulties, as mentioned previously, encountered using passive compliance as well as the precise knowledge processing of the end effector forces would increase safety issues and has the potential to result into a more automated optimized NDT inspection system.

Many intelligent control methods have been investigated, but super-imposing slow force control on position control has typically resulted in poor performance. The emerging work intends to control the position and orientation along the unconstrained coordinate axes by a position control subsystem while controlling the orientations along the constrained coordinate axes by a force control subsystem. [6]

First force testing, figure 11, performing straight line motion with an attempt to maintain a constant contact force showing first indications of the systems potential.

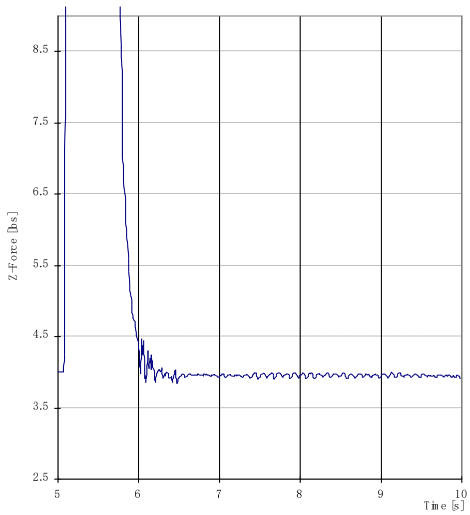

Fig. 11. Force measurements during straight line motion in guarded mode.

The force sensor is first approaching the surface in guarded mode, as soon as a trip condition occurs the motion is instructed and the control system regulates the contact force. The system shows a good force control. Further work needs to improve the system towards keeping a required contact force on a uneven surface with additional control structure to adjust the NDT perpendicular to the surface. The current system shows potential of successful accomplishment.

The consecutive work is using a task based approach where different sequential and parallel processes are executed together to accomplish a larger task. A motion task, as an example, could utilize a trajectory generator to generate the nominal approximate trajectory while force control adds prioritized perturbations to adjust for errors between the planned trajectory and the physical system motion. [7] Real-time path-modification can then be established using the ALTER instruction as soon as the force control commands a change of the trajectory. [8] Two different operation modes have to be considered. One of them is the contact transition where the end effector moves in free space and makes contact with the surface. The second mode where is active when the manipulator is placed on the surface and is performing adaptation. It is then necessary to respond to surface changes while going over the surface and at the same time to also orientate the NDT probe in the right way and position to get the best results. The adaptive control system will have learning capabilities to cope with unpredictable changes in the manipulator or environment. To accomplish a real time surface scan on a complex surface, several turbine blade samples provided by Rolls Royce will be used to recognize the previously known defects. The 7 degree of freedom robot arm will be used to obtain NDT results. These are then compared with results obtained manually and from inspection using passive compliance. The optimisation of the parameters (such as servo speed, contact speed and contact forces, rotation and placement of probes) is then required to obtain a reliable system.

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