NUTHIC: NON-CONTACT ULTRASOUND INSPECTION MACHINE OF HIGHLY INTEGRATED COMPOSITE PARTS

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Abstract. Aerospace industry is moving towards more integrated composite structures in order to reduce autoclave cycles and assembly operations, which leads to considerable cost, time and energy savings. However, the main drawback of this approach is that no inspection solution at a reasonable cost is given by ultrasound equipment in the market, because of the geometry complexity and access restrictions to those parts.

NUTHIC E! 8929 project (partially founded by Eurostar Program H2020) is aimed to develop an adaptive and fully automated air-coupled ultrasound inspection system for highly integrated composite components, whose complex geometries and difficult access prevent using state of the art equipment.

The goal of this project is to provide the aerospace manufacturing industry with an adaptive and automated non-contact ultrasound inspection solution for highly integrated composite parts

This paper presents the progress and early results of the project on Honeycomb structures, Nomex and solid components. All of them are inspected with non-contact ultrasound, avoiding water coupling and reducing inspection time by performing the inspection into the same clean environment of the production line.

1. Introduction

Manufacturing composite parts with a high integration level introduces new challenges for ultrasound inspection systems. On one hand, as integration lowers manufacturing time, inspection time should be reduced accordingly, or at least not increased, to achieve an overall reduction of production costs. On the other hand, quality requirements cannot be relaxed, and the inspection solution should provide, at least, the same performance than current systems. Furthermore, inspection of 100% of the part must be warranted, regardless of the access restrictions that these new components impose.

In aerospace industry, practically all automated inspection systems for composites use water as the coupling medium between the transducer and the part. This procedure usually requires moving the part from the clean zone of the manufacturing line to an inspection zone where water can be used, a time consuming process especially for large components. Furthermore, if a defect is found and the component has to return to the manufacturing zone, drying and cleaning procedures slow down the process even more.

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2. NUTHIC organization, main challenges and methodology.

2.1 Consortium

NUTHIC project started in the early 2015, with a duration of 36 months and a global budget around 1.6 M €. The consortium is formed by two countries (Spain and UK) and 3 companies (DASEL, ASG and INNOTECUK), with the assistance of two subcontracted research organizations (CSIC and FIDAMC), Figure 1.

SPAIN	SPAIN	SPAIN	SPAIN	UK
Dasel sistemas	CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS CSIC	FIDAMC	AUTOMATION SYSTEMS GROUP	InnoTecUK
SME	RTD	RTD	SME	SME

Fig. 1. Consortium resume: DASEL, ASG and INNOTECUK partners; CSIC and FIDMAC RTD.

2.2 Main Challenges of NUTHIC project

The challenges of NUTHIC focus on three main areas:

- Develop a novel air-coupled ultrasound array technology, with large bandwidth and low insertion losses. Such a technology is not commercially available and must be developed by the consortium. Array techniques will increase overall throughput, while allowing corrective actions for some transducer-part misalignments, not possible with conventional mono/multi-element probes. The main challenge is to adapt the high acoustic impedance of the transducer to the low impedance of air to minimize insertion losses and get an acceptable sensitivity while achieving a wideband response of the transducer and a high spatial resolution.

- Obtain air-coupled inspection techniques with resolution and sensitivity comparable to actual state of the art water coupled solutions. Although arrays themselves provide improved resolution and contrast when compared to single-element transducers, that is not enough for air-coupled applications. For example, slight misalignments or subtle changes in the component geometry, can lead to a strong modification of the ultrasound path because of the large refraction index between air and composite materials, probably producing severe signal losses. This is an important challenge for NUTHIC.

- Development of an adaptive inspection device able to move inside closed structures of changing shape. Such device will be placed inside the closed structure to be inspected and will be guided by its inner walls that act as a reference. No elbows or big change of curvatures are expected. A motorized solution will be provided to control the inspection device position inside the closed structure and a set of sensors will be used to monitor its real position in relation to the starting point. The mechanical structure will be designed to be easily adjusted/updated to different sizes of closed structures. A second inspection head will track the inner device to perform through-transmission inspection. Coordination between both devices is essential, being other of the project challenges.

2.3 Consortium members and main tasks

DASEL is in charge of the ultrasound system development, due to its experience in the design and manufacture of inspection systems (conventional and phased array). For this task, DASEL subcontracted also the Spanish National Research Council (CSIC), who has developed an innovative process to manufacture transducers and array probes adapted for emission and reception in air. Preliminary trials have shown the potential of this technology for the inspection of composite material, with improved resolution and contrast because of their focusing and linear scan capabilities, as it is shown in this work.

INNOTECUK and ASG work together to develop a highly modular and adaptive robotics. The solution devised by the consortium is to develop a compliant robot able to travel inside the parts, while adapting to the changes in geometry, coordinated with a second inspection head that will cover the part from the outside, allowing to apply trough-transmission techniques. An objective of this project is to obtain a flexible solution that allows an easy reconfiguration for different structures. ASG receive the support of FIDAMC, a composite research centre part of EADS group that has been subcontracted.

The role of FIDAMC is to define the set of components representative of actual configurations in the aerospace manufacturing industry, to which the development of the scanning head will be first targeted in the project. This is essential to get, by the end of the project, an inspection solution ready for the composite market. FIDAMC will manufacture mock-ups with artificial defects to validate the proposed solution.

3. Preliminary results of the ultrasound system.

A first step to address the ultrasonic challenges has been the development of innovative concepts for air-coupled ultrasound. At this initial stage, this has been carried out for mono-elements, being the new technology currently extended to array probes. Since air-coupled electronics is more conventional, here we present the most innovative results.

Air coupled ultrasound faces some problems not found with the more conventional water-coupled inspections. Among them, high acoustic impedance mismatch, transducer bandwidth, spatial resolution and signal levels must be taken into account. These have been addressed in the NUTHIC project as follows.

3.1 Acoustic impedance mismatch

Most composite material presents high attenuation to ultrasound. But, with air-coupled ultrasound, the most important losses arise from the acoustic impedance mismatch between piezo-ceramics and air and between solid and air. The well known equations of the reflection and transmission coefficients as a function of the acoustic impedances Z_1 and Z_2 of the two propagation media yield a method to estimate the insertion losses.

Figure 2 shows the insertion losses for two coupling media (water and air) considering the following typical impedance values: piezo-ceramic Z_P=35 MRayls, CFRP part Z_C=5.3 MRayls, water Z_W=1.5 MRayls and air Z_A=410 Rayls.

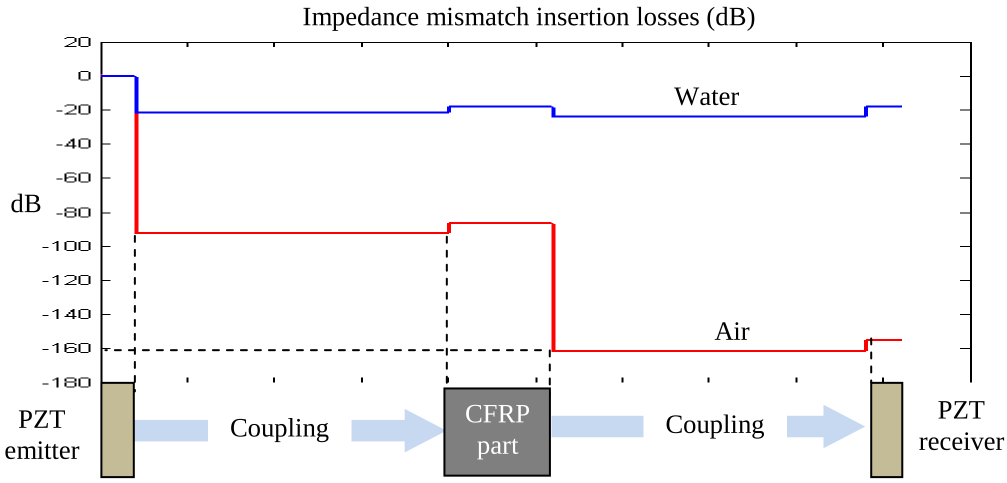

Fig. 2. Insertion losses due to acoustic impedance mismatch with water or air as the coupling medium.

This graph shows those losses due to acoustic impedance mismatch only, not considering other factors such as attenuation in the inspected part or in the coupling medium. A PZT-to-air interface produces losses above 90 dB, considerably higher than the ~20 dB found with water coupling.

To deal with this problem, several approaches have been followed in the past. Most of them insert one or two matching layers to improve the emission/reception efficiency. Insertion losses of 35 dB and fractional bandwidths of 30% can be achieved with such arrangements [1-3].

3.2 Transducer bandwidth

More recently, the use of several stacked matching layers offer higher sensitivity (25 to 30 dB) and larger bandwidths for air-coupled operation, approaching the levels of transducers designed for immersion [4-5]. We have used this approach in the design of the new Sonojet and Sonowide transducers. Sonojet transducers produce collimated and wideband beams, while the Sonowide ones are not collimated.

Every matching layer in the stack is tuned to a slightly different frequency to cover the maximum bandwidth by overlapping their responses. Different designs are used for emitter and receiver transducers to make them operate at the maximum efficiency point on the complex impedance plot for their respective roles.

Figure 3 shows the temporal and spectral response of a 400 KHz air-coupled Sonowide transducer. A maximum two-way sensitivity of -30 dB is reached at 480 KHz, while the useful bandwidth extends from 340 to 580 KHz within ±3 dB (60% relative bandwidth). These figures are comparable to the levels found for immersion transducers.

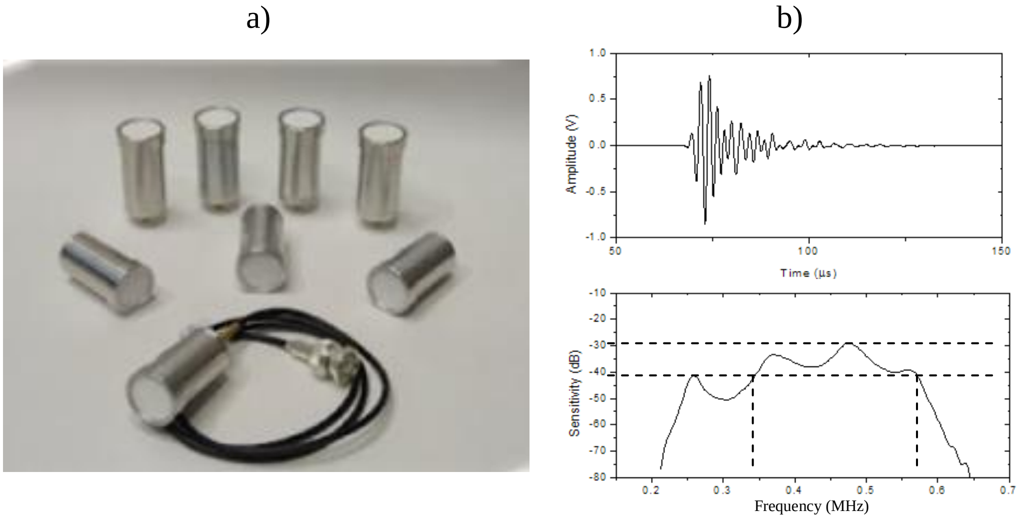

Fig. 3. a) Sonowide transducers; b) two-way temporal and frequency responses of a 400 KHz transducer.

3.3 Spatial resolution

A further issue is to satisfy the resolution requirements. Working frequency is usually kept below 1 MHz and disk-shaped piezocomposites for these relatively low frequencies have a typical diameter from 15 to 25 mm (more wide than thick to reduce lateral modes). Since the beam width is, at least, 2/3 the transducer diameter, lateral resolution becomes limited.

However, sometimes, a wide beam is desirable to cover a larger area and introduce more sound energy in the inspected part. This is frequently the case with widely spaced honeycomb cores, where spatial resolution is less important than robustness and contrast for flaw detection. This reason leaded the development of the ***Sonowide*** technology.

However, in other cases like solid CFRP laminates, resolution must be kept well below the acceptance level, typically set at 6x6 mm. A spatial resolution of 2 mm should be offered in these cases, which cannot be achieved with unfocused transducers.

Increasing resolution has been addressed in the past with a spherical transducer surface [6]. Typical focal depth ranges from 25 to 50 mm and spot size can be made as small as 1 mm. However, spherical focusing produces rays with high incidence angle. Due to the high air-solid refraction index, the critical angle is $\alpha_C \approx 6.5^o$ (CFRP).

Figure 4 shows this effect for a 25 mm diameter transducer spherically focused at 48 mm and a laminated CFRP part at this range. Rays shown in red arrive at angles above α_C and, thus, become reflected. Besides, a fraction of the incident sound entering the part (shown in green) is refracted away. Only a small part of the rays entering the inspected part arrive to the receiver. This arrangement, although providing good resolution, is not quite efficient. With air-coupled ultrasound, there is no room for transducer inefficiencies.

We addressed this problem in a different way. We designed a mirror arrangement that behaves like a Cassegrain-Newtonian telescope to collimate (instead of concentrate) the beam. The collimated beam produces a plane wavefront whose angle of incidence is nominally 0^o and does not present the problems above. We call this kind of air coupled transducer ***Sonojet***, mimic its behavior as a collimated sound jet.

Figure 5 shows the working principle of a 400 KHz Sonojeet transducer (a), field amplitude (b), lateral profile (c) and phase (d). Mirror parameters were tailored to produce a 2 mm wide collimated beam, obtaining a 2.1 mm wide beam at -6 dB, (panel c). Sidelobes with a transient excitation are lower than these shown. The collimated nature of the beam is evident in panel (b) and, particularly, in panel (d): phase in any direction normal to the propagation axis is constant within the beam extent, characteristic of a plane wave. Further, the design is compact and relatively easy to align in through-transmission configurations.

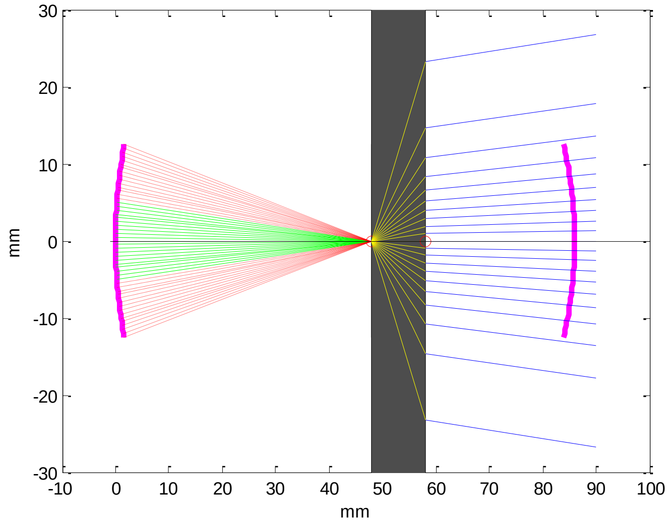

Fig. 4. Only a part of the sound produced by a spherically focused transducer reaches the receiving end.

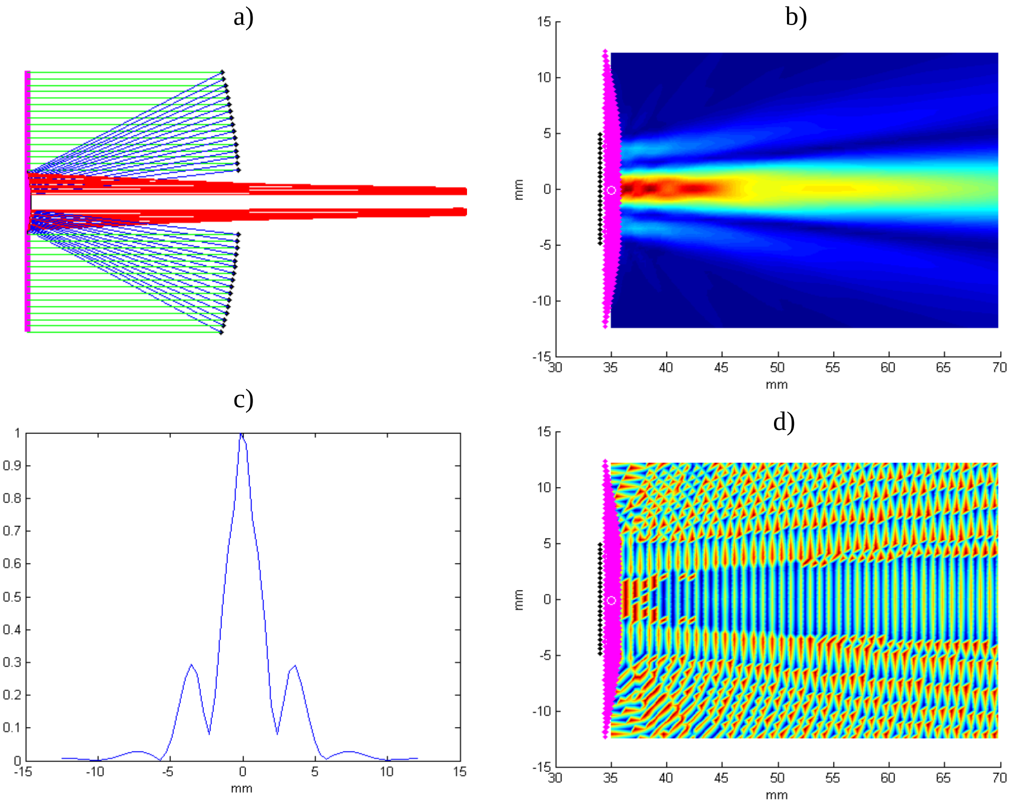

Fig. 5. *Sonojet* transducer: a) Working principle; b) Sound field intensity; c) Lateral beam profile; d) Phase.

3.4 Signal levels

Due to higher losses in air, signal levels at the receiving transducer are significantly lower than those found in water- or dry-coupled ultrasound. The aim is to obtain a good enough signal-to-noise ratio (SNR) to get signals well above the noise level. Most of it is due to electromagnetic interference (EMI), in the form of white and impulsive noise.

Conventionally, at the electronics equipment front-end, filtering reduces the noise content of the signals. In some cases, averaging is used to improve, at most, 3 dB of SNR every time the number of averaged A-scans is doubled. However, this has adverse effects on the scanning rate, since many A-scans must be acquired at every spatial position. We have addressed these issues by implementing two techniques:

1. Integration of an ultra-low noise (< 1nV/√Hz), impedance matched, 48 dB pre-amplifier in the receiver. Since it is directly connected to the piezo-element terminals, induced EMI noise is very small, further improved by the shielding of the transducer case and the internal filtering adapted to the transducer bandwidth.
2. Using our EMI filtering real-time hardware. This technique cancels impulsive EMI noise with only two or three A-scan acquisitions, merely affecting the scanning rate. EMI noise filtering is based on keep only those signals remaining at the same position in the 2 to 3 acquired A-scans and removing all indications not verifying this condition. This procedure has shown to be very effective in reducing impulsive EMI noise and is standard in all our equipment.

4. Some experimental results

Figure 6 shows the measured acoustic field of a 400 KHz *Sonojet* transducer. The beamwidth (2.1 mm) and the non-diverging region (~50 mm) are as expected.

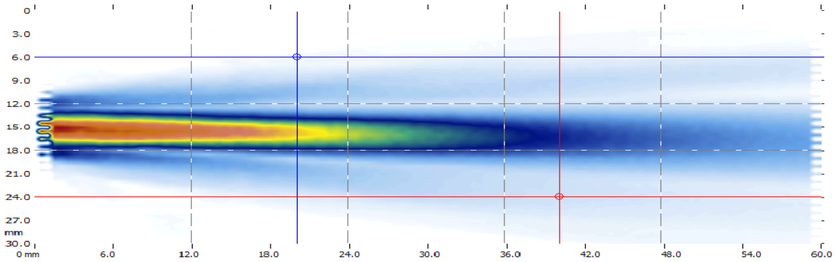

Fig. 6. Measured field of a 400 KHz Sonojet.

Up to date developed NUTHIC technologhy has been used to inspect a large set of parts made of honeycomb cores and solid CFRP laminates. Normally, honeycomb cores are better inspected with *Sonowide* transducers, which provide increased sound intensity entering the walls of the core. *Sonojet* transducers are most adequate for high resolution inspections of solid CFRP laminates, due to their collimated beam.

a) b) c)

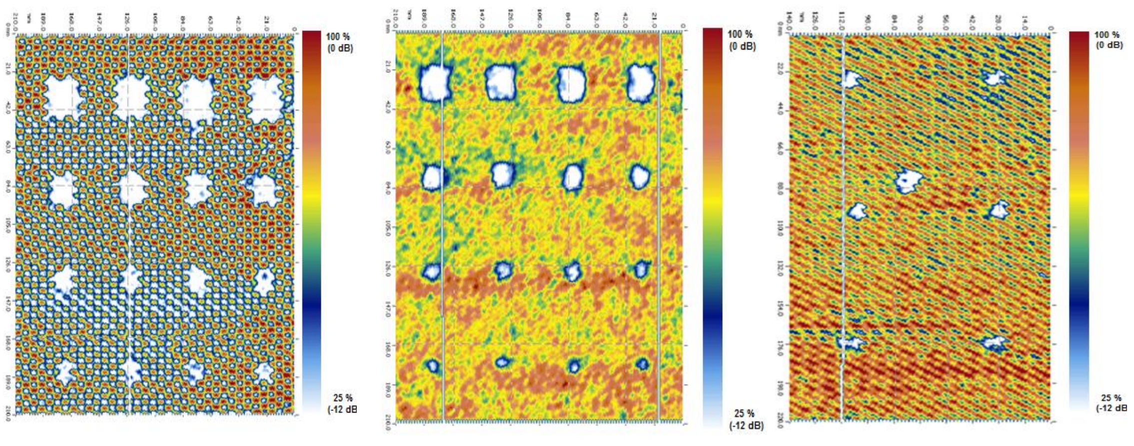

Fig.7. Inspection of honeycomb cores with a couple of Sonowide transducers in through-transmission. Cores of: a) ¼", b) 1/8" and c) 3/16".

Figure 7 shows an example of a inspection of several honeycomb cores with artificial flaws. All of them were accurately detected with a contrast of -12 dB, as can be seen from the color scale, significantly higher than the -6 dB typically specified. Resolution is good enough to accurately determine the extent of the flaws.

a) b)

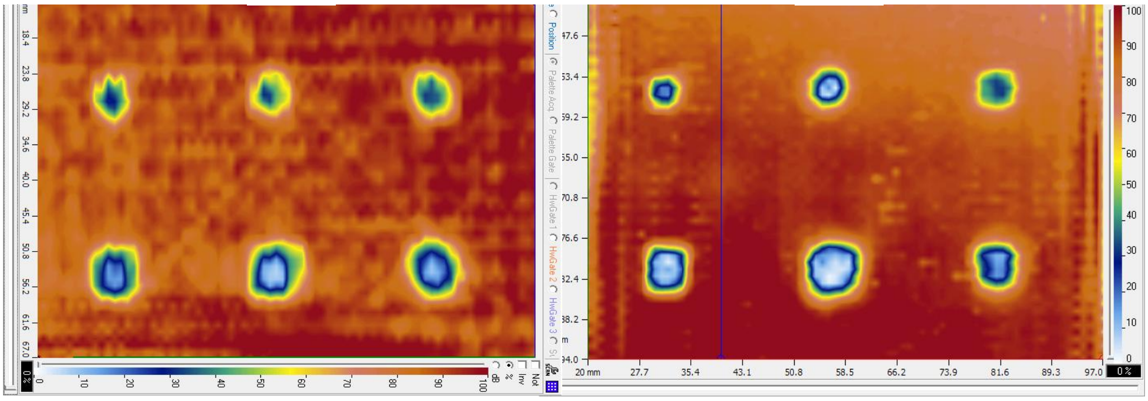

Fig.8. Inspection of solid CFRP laminate of 7 mm: a) AirScope inspection with SonoJet transducers b) Conventional pulse-echo with a 5 MHz transducer in immersion.

Figure 8 shows a further example of the inspection of a solid CFRP laminate with thickness of 7 mm with artificial flaws placed in three different positions: 1/3 thickness, 1/2 thickness and 2/3 thickness. In this case, *Sonojet* transducers were used in through transmission, with an excellent spatial resolution and contrast. With an excellent spatial resolution and contrast, (Fig. 8a) comparable to that obtained with a conventional pulse-echo technique in immersion at 5 MHz (Fig. 8b).

Conclusions

NUTHIC E! 8929 project aims to develop an advanced technology for an adaptive and fully automated air-coupled-ultrasound testing system of integrated parts for the aerospace manufacturing industry. This paper shows some of the innovative designs to get a high performance ultrasound system. Results show that we are in the good pathway.

NUTHIC yet requires work to extend the results to array technology, robotics and real-time misalignments correction. The consortium is currently addressing these subjects.

Finally, mention that NUTHIC is open to those aerospace component manufacturers willing to test the new technology capabilities.

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