A Novel Near-Field Robotic Scanner for Surface, RF and Thermal Characterization of Millimeter-Wave Active Phased Array Antenna

Rodrigo M. Lebrón, *Student Member, IEEE,* Jorge L. Salazar, *Senior, IEEE,* Caleb Fulton, *Member, IEEE,* Damon Schmidt, Simon Duthoit, Robert Palmer, *Senior, IEEE*

***Abstract*—This work describes the concept and current development of a novel automated system to characterize active phased array antennas. The proposed system, called an RF Scanner, has been conceptualized and developed by the Advanced Radar Research Center (ARRC) at the University of Oklahoma (OU). This system enables the full characterization of electromagnetic, surface, and thermal properties of an active phased array antenna. An industrial 6-axis articulated robot is used to move a sensor suite to perform near-field measurements as well as surface and thermal inspection of the antenna under test (AUT). The sensor suite consists of a mechanical fixture supporting an infrared camera, a high-precision laser, a high-definition camera, and an antenna array probe. The AUT, the robotic manipulator, and the sensor suite are located inside of an environmental chamber. This environmental chamber enables characterization of the AUT under controlled temperature and humidity. The combination of the high precision robot, sensor suite, environmental chamber, and vector network analyzer (VNA), along with a software interface, allows fully automated characterization of an active phased array antenna from 1 GHz to 18 GHz, up to 60 GHz if the VNA is upgraded, over a temperature range of 0°C to 50 °C.**

***Index Terms*—active phased array antenna, automated measurements, robotic arm, thermal characterization, near-field calibration**

I. Introduction

Active and electronically scanned phased array antennas are attractive options for atmospheric radar applications. Their fast scanning performance, high reliability, and multifunction capabilities make this new technology an ideal candidate for next generation weather radars systems [1]. One of the biggest challenges of using this technology are the strict requirements for dual-polarized measurements. Accurate differential reflectivity in weather radars requires high degree of beam pattern matching (below 0.1 dB), and high cross polarization isolation (below -40 dB) between H and V polarizations [2]. Such specifications can be achieved by utilizing a high performance antenna array and applying a precise antenna calibration that takes into account the overall performance of the active element patterns as a function of its temperature.

For dual-polarized phased array radars (PAR) devised for atmospheric applications, large temperature gradients induce significant phase errors, which affect the accuracy of the calibration process in the antenna array. In the case of low frequency and large phased array systems that operate in S- and C-bands, the maximum allowable temperature gradient across the array is on the order of 15 °C [3], [4]. However, for a PAR that operates at higher frequency bands (for example W-

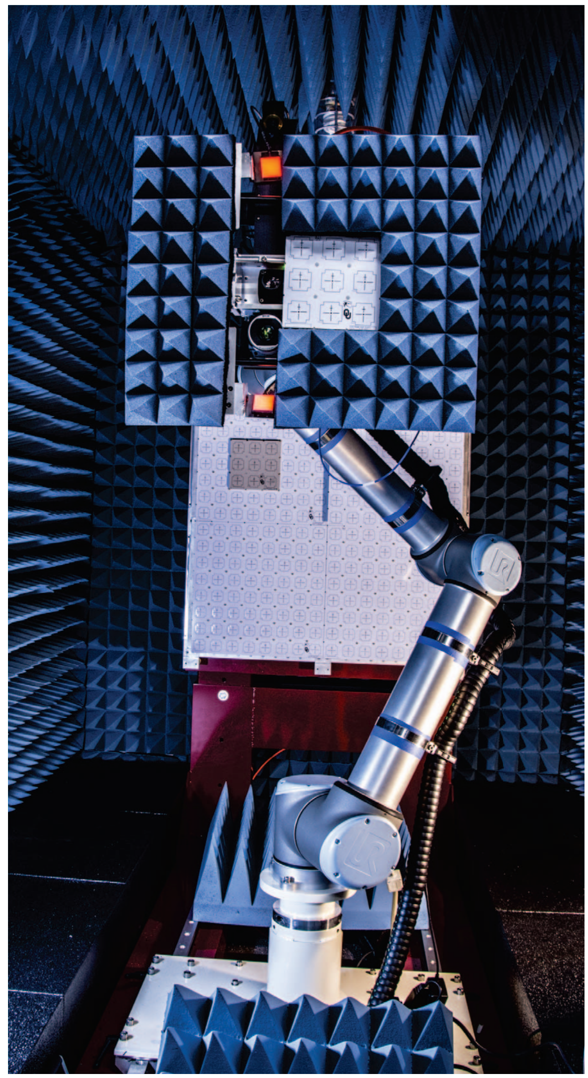

Fig. 1. Picture of a robotic arm carrying an arrangement of specialized sensors, which are fundamental components of the automated characterization system of active phased array antennas being developed by the ARRC.

R. Lebrón, J. Salazar, S. Duthoit and C. Fulton are with the Department of Electrical and Computer Engineering, and R. Palmer is with the Department of Meteorology at the University of Oklahoma, Norman, OK, 73019 USA, see http://www.arrc.ou.edu.

978-1-5090-1447-7/16/$31.00 ©2016 IEEE

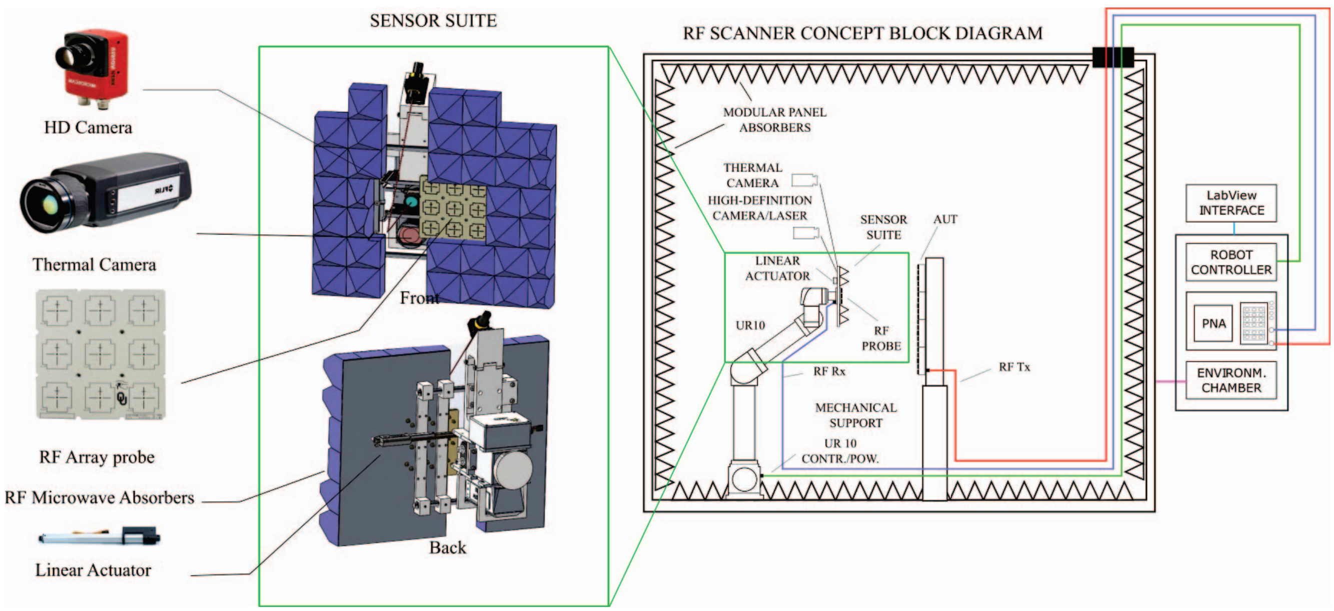

Fig. 2. Conceptual diagram of the RF Scanner. The components and wiring of the system are detailed on the right. The design of the front and back of the sensor suite are shown on the left. The locations of the sensors and actuators installed on the sensor suite are shown on the left.

band), the maximum allowable temperature gradient across the array is reduced to 1.2 °C. A reliable procedure to minimize the impact of temperature variations on the radar system, is to fully characterize the RF performance of the active array as a function of temperature, then apply a correction by calibration. In this context, the main motivation of this work is the design and current development of an automated characterization system, that will enable temperature control of the antenna environment during testing in order to inform, develop, and evaluate the on-line calibration techniques that the array will execute when it is ultimately fielded.

One common solution for automated antenna RF characterization is the use of a robotic manipulator with a RF probe attached to it to perform near-field (NF) measurements. Conventionally, these types of arrangements are classified in planar, cylindrical, and spherical systems according to the scan pattern they are able to execute [5]. Moreover, these systems typically have no more than 4 degrees of freedom (DOF). Nonetheless, some of these systems need to be able to freely move the RF probe to any position and orientation in order to perform any arbitrary scan patterns. This requirement translates into the need for 6 DOF position capability. To add this versatility to the scanning setup, some researchers have included 6-axis industrial robotic arms to their NF measurement chambers. As an example, the National Institute of Standards and Technology (NIST) has developed a robotically controlled mm-wave NF scanner range, integrating a 6-axis robot, a high precision robotic hexapod, a commercial open-ended waveguide probe, and a laser tracker for accurate measurement of antenna patterns. This system allows the possibility of performing different types of scan patterns for antenna measurements all using the same testing setup [6]. Other applications where robotic arms were used for microwave imaging are presented in [7] and [8]. All of these examples have been developed for measurement of NF patterns of an AUT, mostly for high frequency antennas.

Taking into consideration the need to accurately describe the effects of temperature gradients in PAR applications, the ARRC has also adopted the idea of integrating an industrial robot into an automated phased array antenna characterization system. To perform fully active array characterization, the development of a novel *RF scanner*, Figure 1, that enables characterization of an antenna array surface, electric fields in NF region and thermal performance of the array antenna as function of temperature has been proposed. For this purpose, an industrial 6-axis robotic arm is used to move a sensor suite which contains an antenna array used as an RF probe, a HD camera, an optical laser for surface characterization, and a thermal camera for temperature monitoring. The novelty and main purpose of this proposed system is to perform not only antenna NF measurements (antenna patterns and S-parameters), but to fully characterize active phased array antennas in terms of RF, surface, and thermal properties under different temperature conditions.

II. Design Requirements

Most active phased array antennas for weather radar applications require high transmit power (from 10 kW to 100 kW) to attain the required radar sensitivity level. With sufficient radar sensitivity and polarization accuracy, it is possible to distinguish different types of atmospheric signatures, depending on the range, especially for low-level precipitation which the radar requires a high sensitivity (-10 dBz to 10 dBz) to detect. In phased array antennas, the overall transmit power is distributed over several thousand active elements, each one capable of managing 4 W to 10 W of peak power in typical systems.

978-1-5090-1447-7/16/$31.00 ©2016 IEEE

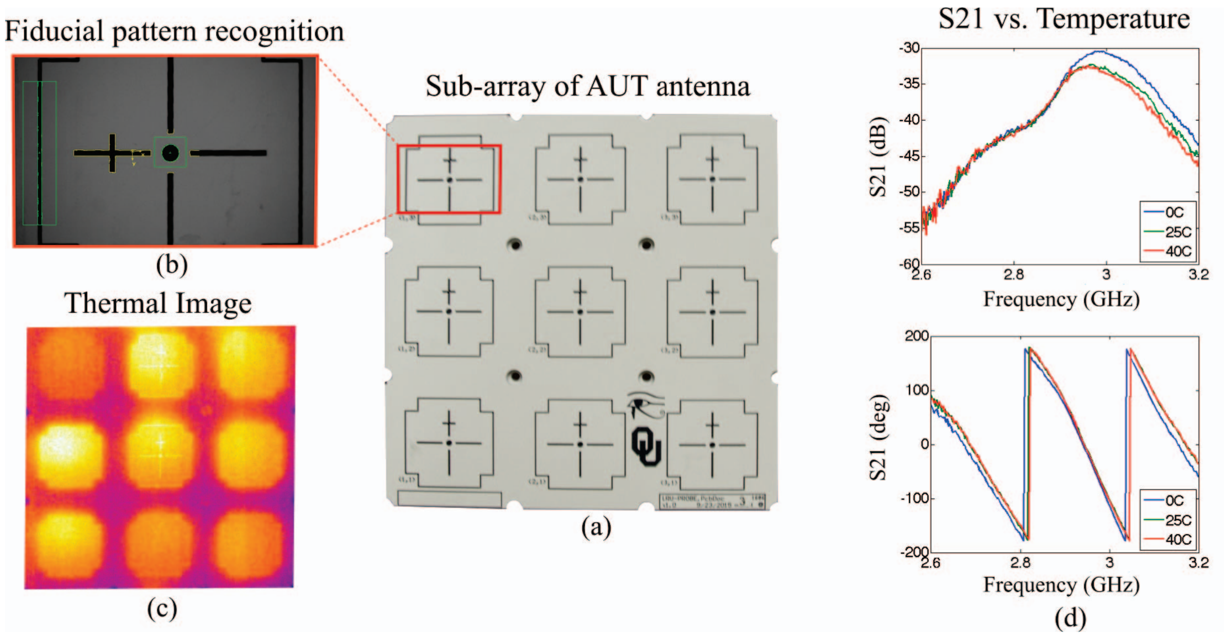

Fig. 3. Representation of the concept of the anticipated characterization capabilities of the RF Scanner. (a) Sample 3-by-3 arrangement of the AUT. Fiducial marks indicate the central point of each radiating element within the array. (b) Pattern recognition performed upon a fiducial mark of an array element. (c) Image of the 3-by-3 RF probe taken by the thermal camera. The different colors allow identification of temperature gradients on the surface of the AUT. (d) NF measurements taken by the RF probe showing the behavior of the S-Parameters in amplitude and phase at different test temperatures.

Since underneath each active element exists a high-power density T/R module, a significant amount of heat is transferred into the element from the module. The generated heat can affect the performance of the PAR due to any temperature gradient in the array surface. Characterization of amplitude and phase of each element in the array, as a function of temperature, is required to guarantee the effectiveness of any built-in calibration techniques, or to provide first-order look-up corrections vs. temperature. This is an important consideration, especially for weather applications where beam matching in the antenna co-polar patterns is required to be less than 0.1 dB and cross-polarization isolation must be below -40 dB. For this reason, the proposed scanner must have the ability to take NF measurements under controlled temperature conditions.

Commonly, the panels on phased array antennas are not perfectly flat, nor is the electronic center of each element consistently spaced by a known pitch. Moreover, as the operation temperature varies, thermal deformations of the AUT panel will change the location of its elements. Most active phased array antennas make use of multilayer structures composed of various dielectric materials. Phase stability over a temperature range with phase reference at room temperature (26 °C) is required to minimize the phase errors due to the thermal expansion. By inspecting the surface of the antenna array, it is possible to measure the distances between elements, and indirectly calculate the thermal expansion of the AUT for different ambient temperatures.

III. RF Scanner Concept and System Description

Taking into account the design requirements described in the previous section, the ARRC has proposed a suitable solution in the form of the RF scanner. The structure of the system, the components of the scanner, and corresponding parts are shown in Figure 2. The RF scanner can perform any type of scanning patterns, and is only limited by the robot's workspace volume. Additionally, the manipulator has a repeatability of 100 μm, and knowing that the positioning errors should usually be less than $\lambda/50$ for NF measurements [6], [9], the scanner is thus theoretically capable of performing NF measurements of signals up to 60 GHz. However, the current VNA's superior frequency limit is only 18 GHz. The robotic arm and the AUT are mounted facing each other on a mechanical fixture specifically designed for the scanner. Attached onto the end of the robotic arm is the *Sensor Suite*, depicted in Figure 2, which consists of a mechanical shutter where all the sensors are mounted. The purpose of the sensor suite is to serve as a support for all the sensors carried by the robot, as well as to provide the necessary equipment required for their correct operation. On the front of the fixture is the shutter mechanism on which the RF probe is attached. Surrounding the probe there are RF microwave absorbers to eliminate unwanted electromagnetic wave reflections.

A HD camera is used in conjunction with a laser to inspect the surface of the antenna. The setup is able to measure the position of each radiating element of the AUT, relative to the others, using machine vision. A printed fiducial mark located exactly at the center of each element is used to facilitate the recognition of each element and its position by the machine vision system, as shown in Figure 3.a. The HD camera is capable of pattern recognition from the scanned images of the fiducial marks, shown in Figure 3.b. Therefore, it is possible to locate the X, Y position of the center of an element and

978-1-5090-1447-7/16/$31.00 ©2016 IEEE

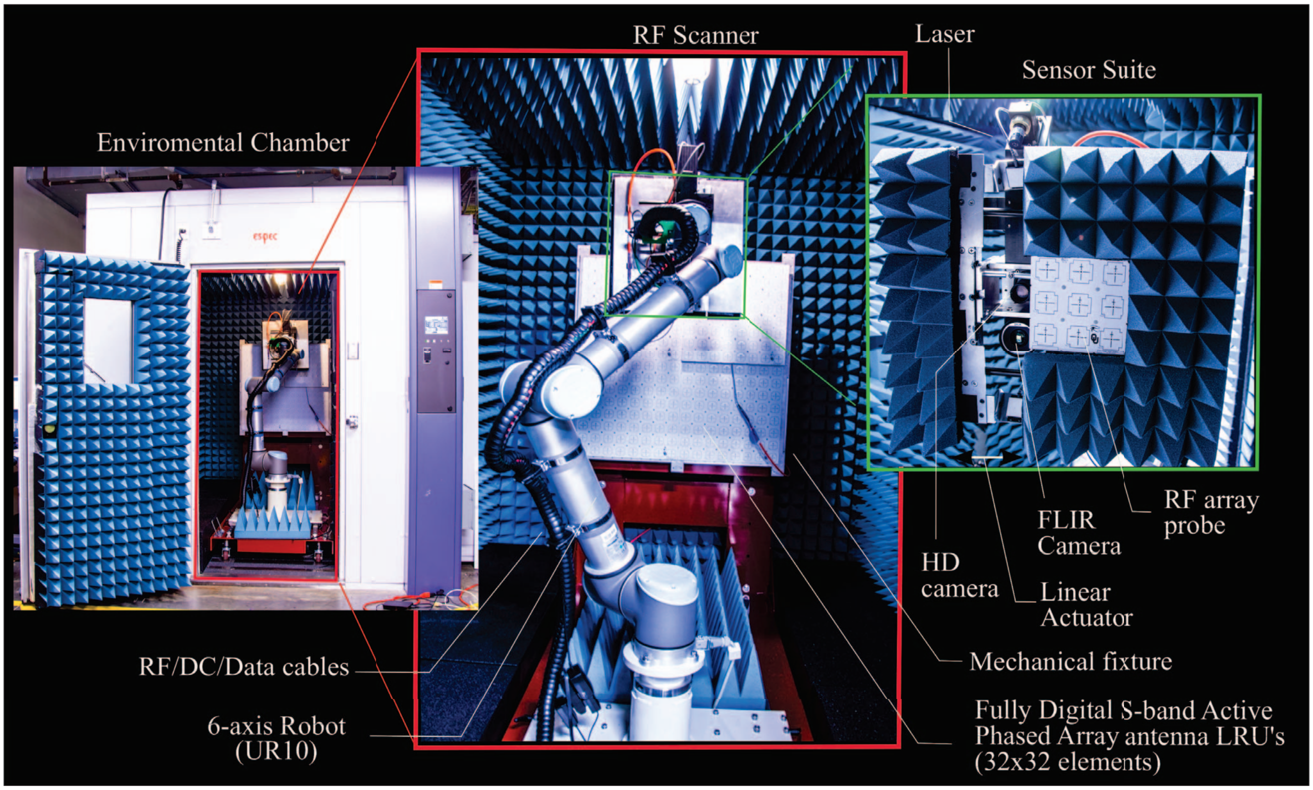

Fig. 4. ARRC's RF Scanner in its current state of development. The robotic arm and the sensor suite, both mounted on the mechanical fixture, are shown sitting inside of the environmental chamber.

quantify the rotation angle of the plane of the element, both with respect to the current position of the sensor suite. With this technology it was proven that a location measurement resolution of 24 μm can be attained. In addition, a laser mounted on the top of the sensor suite is used to indirectly measure the Z coordinate of the element, i.e., the distance between the sensor suite and the element on the surface of the AUT. The laser draws a reference line on the surface of the antenna, which by techniques of optical triangulation executed by the machine vision camera, can be used to determine how far the surface of the AUT is from the sensor suite. In effect, using machine vision allows measurement of the X, Y and Z coordinates of the center point of the element, and the misalignment angle between the RF probe and antenna element. Future work will involve taking several images of the surface of the antenna and stitching them together to generate a mosaic of the entire panel. This mosaic will allow accurate characterization of the distances between elements, according to the temperature gradient on the array surface. This will also allow ARRC engineers to better decide upon the gaps that should be intentionally placed between sub-arrays for operational systems.

Below the high-definition camera on the sensor suite, sits a state-of-the-art thermal imaging camera. The thermal camera is used to detect the thermal state of the radiating elements of the antenna array. This type of camera uses infrared technology to capture the heat radiation of a target, producing a thermal profile. The thermal image can be processed by computer software to obtain correct temperature values for characterization of the array. Consequently, the function of the camera is to provide the information needed to characterize the thermal gradients along the surface of the antenna. Figure 3.c shows an image of a 3-by-3 sub-array of the AUT taken by the thermal camera. The different colors represent different temperatures.

For NF measurements, a 3-by-3 antenna array is used as an RF probe. The design of this probe was optimized to minimize the potential impact on the NF measurements accuracy that can be affected by the coupling between the probe and AUT. The design also takes into consideration the reduction of the payload of the robotic arm (UR10), which is important for position accuracy. The probe is connected to a low cost 2-port vector network analyzer (VNA). The other port of the VNA is connected to the phased array antenna. The probe and the VNA allow the system to take S-Parameters measurements as shown in Figure 3.d.

Finally, an environmental test chamber is used to control and monitor the test environment temperature during the antenna array characterization. An environmental chamber can be described as a closed room, thermally isolated, with an air conditioning system for controlling and tracking the temperature and humidity inside the chamber. The environmental chamber implemented in this application allows a range of temperature testing of -30 °C to 85 °C, however the specifications of the sensor instruments are limited to operative conditions of 0°C to 50 °C. Having the AUT and sensors located on the inside of the chamber, as indicated in Figure 2, it is possible to test the AUT performance under different temperature conditions. For

978-1-5090-1447-7/16/$31.00 ©2016 IEEE

this project, the interior of the chamber has been completely covered with absorbers, as shown in Figures 1 and 4, to make it a suitable location for NF measurements. The current state of the scanner in development is illustrated in Figure 4.

IV. Scanner Operation

The RF scanner developed by the ARRC is designed to perform three stages of the process of characterization: surface characterization of the antenna panel, RF characterization of each element in the AUT, and temperature characterization of the antenna panel. All the stages are to be performed under conditions of controlled temperatures.

A. Surface Characterization

The first stage of operation is the surface characterization of the AUT. The scanner registers the position of each element of the array using the high-definition camera and laser, which are also used to register the absolute position of each element across the array.

During this stage, the robotic manipulator is used to move the sensor suite across the array. First, the robot positions the sensor suite parallel to the AUT panel, at a location where the range of vision of the HD camera can capture the fiducial mark of an element. The scanner proceeds to open the shutter to enable the operation of the camera/laser system. The camera will take a picture and later process it to calculate the position of a fiducial mark, as well as the misalignment angle between the RF probe and antenna panel. From this analysis it is possible to measure distances among adjacent radiating elements, and the angle of the sensor suite with the AUT. By iterating this procedure, the positions and misalignment angles of all the elements of the array can be measured relative to each other. Furthermore, since the environmental chamber is controlled by the user interface, the surface characterization stage allows the system to characterize the thermal expansion of the AUT panel as a function of temperature.

B. Thermal Characterization

The main purpose of the thermal characterization stage is to register the temperature gradients of the antenna surface. To accomplish this goal, the thermal camera and the robotic manipulator are used simultaneously. First, using the location data of the radiating elements obtained from the surface characterization stage, and while having the shutter open, the robot will position the thermal camera in front of the element. Next, the thermal camera will capture an image of the thermal profile of the area surrounding the radiating element. By processing this image, the temperature gradients along the surface of the antenna can be characterized. This measurement is fundamental to associate the adverse effect of the temperature gradients over the surface dimensions and RF performance of the larger antenna array.

C. RF Characterization

The last stage is the RF characterization, which measures the radiation performance of the PAR. At this stage, the scanner will close the shutter, placing the RF probe exactly in front of the center of the element. Next, the system will trigger the VNA to measure the S-parameters at the current configuration.

D. Operation control

For every stage, all the processes are commanded by a LabView master program that includes a visual user interface. This software allows the user to select the elements to be characterized and set the ranges of frequency and temperature operation while monitoring in real time the measured values. This software is also responsible for setting the temperature inside the environmental chamber in order to evaluate the performance of the AUT as a function of the operation temperature. Eventually, this software will interface with the active array controller to evaluate its performance of the array's internal calibration procedure, using the RF scanner as the ”ground truth” estimator of amplitude and phase errors.

V. Conclusion

A novel RF scanner for phased array antenna characterization has been presented. It is expected that the RF scanner will be capable of completely characterizing the performance of phased array antennas in terms of surface, electromagnetic, and thermal properties. By implementing a robotic arm as a probe manipulator, the scanner can perform many types of raster patterns. Moreover, the robotic arm's repeatability of 100 μm allows for NF measurements of up to 60 GHz. Precise alignment is possible by using a high-definition camera. Thermal expansion of the antenna panel can be quantified. The thermal camera allows correlation of the measured values of NF and surface characteristics to the temperature gradients across the panel. The combination of an environmental chamber with thermal imaging camera permits the scanner to evaluate the performance of the AUT and its internal calibration processes at different temperatures of operation. Ultimately, the developed scanner will provide relevant information on the behavior of the AUT during operation at different temperatures.

Acknowledgment

This work was partially supported by NOAA's National Severe Storms Laboratory under CIMMS cooperative agreement NA11OAR4320072.

The authors would like to thank the assistance of Parker Hewitt and Tom Brennan from Artemis Vision during the implementation of the machine vision system. In addition, the authors recognize the help of Robert Baines, Oskar Paredes, Brian Brown, Alessio Mancini, Daniel Feland and Jonathan Christian for conditioning the environmental chamber for electromagnetic isolated testing.

References

[1] D. S. Zrnic, J. F. Kimpel, D. E. Forsyth, A. Shapiro, G. Crain, R. Ferek, J. Heimmer, W. Benner, T. J. McNellis, and R. J. Vogt, “Agile-beam phased array radar for weather observations,” *Bulletin of the American Meteorological Society*, vol. 88, no. 11, pp. 1753–1766, 2007.

[2] Y. Wang and V. Chandrasekar, "Polarization isolation requirements for linear dual-polarization weather radar in simultaneous transmission mode of operation," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no. 8, pp. 2019–2028, 2006.

[3] D. N. McQuiddy Jr, R. L. Gassner, P. Hull, J. S. Mason, and J. M. Bedinger, "Transmit/receive module technology for X-band active array radar," *Proceedings of the IEEE*, vol. 79, no. 3, pp. 308–341, 1991.

[4] J. L. Salazar, "T/R Modules for Active Phased Array Radars," *IEEE Radar Conference*, 2015.

[5] D. Gray, "How to choose an antenna range configuration," *Proceed. Antenna Measurement Techniques Association*, 2002.

[6] J. A. Gordon, D. R. Novotny, J. B. Coder, J. R. Guerrieri, and B. Stillwell, "Robotically Controlled Mm-Wave Near-Field Pattern," *Proc. Antenna Meas. Tech. Assoc.*, vol. 34, pp. 384–389, 2012.

[7] L. Boehm, F. Boegelsack, M. Hitzler, and C. Waldschmidt, "An automated millimeter-wave antenna measurement setup using a robotic arm," *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, vol. 2015-Octob, pp. 2109–2110, 2015.

[8] N. Petrovic, T. Henriksson, N. Joachimowicz, and M. Otterskog, "Robot controlled data acquisition system for microwave imaging," *European Conf. Antennas Propagat. (EuCAP)*, pp. 3356– 3360, 2009.

[9] D. Novotny, J. Gordon, A. Curtin, R. Wittmann, M. Francis, and J. Guerrieri, "Antenna Measurement Implementations and Dynamic Positional Validation Using a Six Axis Robot," *AMTA 37th Annual Meeting and Symposium*, 2015.