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ROBOTICALLY CONTROLLED MM-WAVE NEAR-FIELD PATTERN RANGE

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ABSTRACT

The Antenna Metrology Lab at the National Institute of Standards and Technology in Boulder Colorado has developed a robotically controlled near-field pattern range for measuring antennas and quasi-optical components from 50 GHz to 500 GHz. This range is intended to address the need for highly accurate antenna pattern measurements above 100 GHz for a variety of applications including remote sensing, communications and imaging. A new concept in near-field range systems, this system incorporates the positioning repeatability of a precision industrial six-axes robot, six-axes parallel kinematic hexapod, and high precision rotation stage, integrated with a highly accurate laser tracking system. Programmable robot positioning allows the system geometry to be configured for spherical, planar, and cylindrical scans, as well as gain extrapolation measurements. Variable scan volume accommodates different test antenna sizes. Positioning accuracy better than 10 µm is predicted. Specifics of the system design, operating specifications and configurability will be presented.

Keywords: antenna metrology, calibration, imaging, millimeter wave, near-field, pattern, radiometry

1.0 Robotic Near-Field Range Concept

As science and technology efforts continue to expand into the mm-wave regimes, there is significant opportunity for improving and adapting proven antenna metrology techniques for these higher frequencies. Several areas of research rely on mm-wave metrology including remote sensing [1-4] and defense/security stand-off threat detection [5-7]. Thus there is a need for accurate and readily available mm-wave antenna metrology capability.

Near-field (NF) measurements have a well-tested legacy for being a reliable technique for characterizing antennas [8-12]. In particular, near-field techniques allow antenna patterns to be measured over a large solid angle, with high signal-to-noise as is the case for a spherical near-field range. The ability to access the large solid angle provided by a spherical NF scan is particularly advantageous where extremely low uncertainty in beam efficiency is required. The remote sensing community is particularly interested in conducting radiometric measurements in the mm-wave regime [1-4] in order to provide vital data for understanding climate change and atmospheric phenomena. It is not uncommon for radiometer characterization to require antenna beam efficiencies to be known to within 0.1 %. A spherical NF scan with its large solid angle coverage is therefore well suited for such stringent measurement specifications. Until the past 5 years commercial units for full vector-network analysis above 200 GHz were not routinely available. However current state-of-the-art mm-wave mixer sources, receivers, and analyzer designs have made it possible to routinely make full vector-network S-parameter measurements up to 1.1 THz.

In this paper we present a new robotically controlled NF pattern range for measuring antennas and quasi-optical components over the frequency range of 50-500 GHz. The use of robotics allows for a highly configurable NF range that can achieve antenna positioning that is accurate and repeatable to fraction of a wavelength.

2.0 Robotic Range Design

In performing near-field measurements it is necessary to control the position of antennas to a high degree of precision and accuracy in all six degrees of freedom. As the wavelength can be on the order of hundreds of microns over 50-500 GHz, the precise positioning of antennas poses a significant challenge. A common approach for setting up a spherical NF scanning system is to position the Antenna Under Test (AUT) axis parallel to the laboratory floor, and thus perpendicular to the force of gravity, as in a roll over azimuth design, see Figure 1. The AUT aperture is then rotated about a vertical axis relative to the probe antenna, which is held stationary. This approach is conducive to using stacked motion stages like linear rail systems and rotation stages for positioning antennas. However, in this configuration gravity is always acting perpendicular to the measurement alignment axis that joins the AUT and probe antenna aperture coordinate systems. As such the positioning systems that move and maintain alignment of the antennas are constantly working against gravity. Under the load of the antennas the positioning systems inevitably flex and sag to some measurable degree due to gravity. When the frequencies are such that this flexure and sag approaches the operating wavelength, position errors can significantly influence the NF measurement. In addition at high frequencies (>50 GHz), the AUT may more often be an entire system such as a mm-wave radiometer. In such a case, the aperture and the center of mass of the system may not coincide and thus mounting the AUT or System Under Test (SUT) becomes more difficult. In such a case having gravity working against the mounting and movement of the SUT poses significant issues for maintaining alignment during a NF measurement.

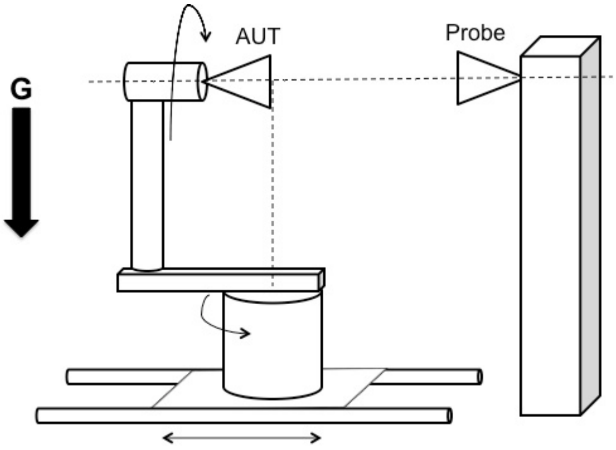

Figure 1 – Roll Over Azimuth Spherical Near-Field Range. Gravity vector, "G", is shown with arrow.

In designing this new robotic mm-wave NF range our approach was to layout the entire system so that both gravitational forces and position errors were inherently mitigated in the design. A bottom up approach was taken where gravity works to stabilize the position and movement of the AUT/SUT. Where instead of moving the AUT/SUT, the probe antenna is moved which is typically much smaller and has less mass. We then incorporated state-of-the-art, compact, six-degree-of-freedom (6DOF) robotic position systems that allow programmable movement of both the probe antenna and AUT/SUT to the *micron level or better*.

At the heart of this new system is a six-axes articulated robotic arm (see Figure 2 and 3) which has affixed to it one of the antennas used in the NF measurement (typically the "probe" antenna). The primary function of the robotic arm is to move the probe antenna along the scanning path. The programmable positioning capabilities of the robotic arm enable all 6DOF of the probe antenna to be manipulated. This allows the probe antenna position and orientation to be controlled over *any arbitrary* path within the robots working envelope. As such, using a single alignment, multiple NF scan geometries, i.e. planar, spherical, cylindrical are achieved within *the same* scanning system. In addition, the antenna path can be configured to perform extrapolation measurements [13]. Feedback from a laser tracking system is used to monitor robot position as well as to calibrate robot postures to increase position accuracy. The laser tracking system also allows for the implementation of position correction algorithms [11,12] thereby increasing the accuracy of the antenna patterns at these high frequencies.

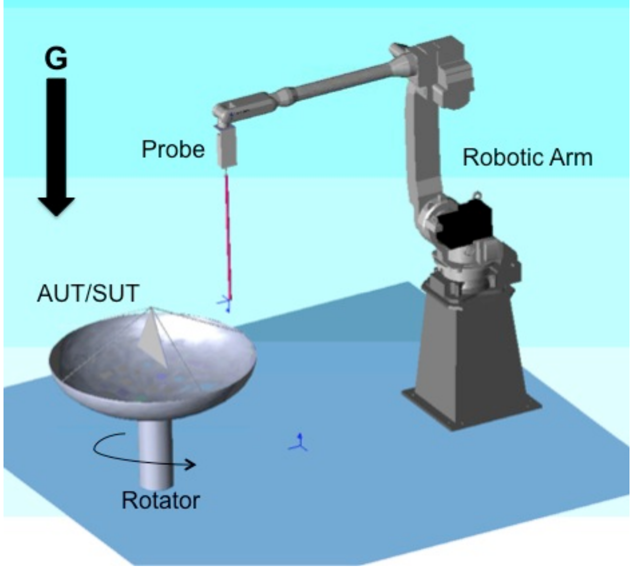

Figure 2 – Robot Range Concept. Gravity vector ,"G", is shown with arrow.

While the robotic arm is mainly used to move the probe antenna relative to the AUT/SUT such that the elevation angle is scanned, a precision rotation stage is used to rotate the AUT/SUT about the azimuthal angle. This central rotator is located under the scanning path of the robotic arm as shown Figure 2 and provides continuous rotation of the AUT/SUT over 360˚. The combination of azimuthal rotation of the AUT/SUT and the elevation scanning of the probe antenna with the robotic arm, provide the required antenna motion to perform spherical, planar and cylindrical NF scanning.

For many situations the AUT/SUT must be precisely aligned to the axis of the central rotator. To achieve this alignment all 6DOF need to be adjusted. Use of typical motion stages would require an individual system per axis of motion, i.e. three linear stages for X-Y-Z movement, and three rotation stages for yaw, pitch and roll. Therefore six stages would need to be stacked on top of one another. Stacking motion stages poses several issues for achieving precision positioning while under load. The positioning errors of each stage couple and accumulate, increasing positioning uncertainty and make accurately predicting position location complicated. In addition each motion stage must now not only support the load of the AUT/SUT but also the load by of all stages above in the stack.

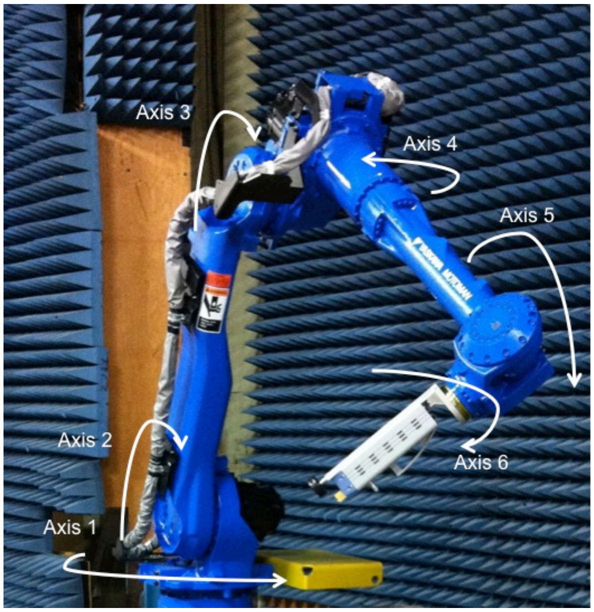

Figure 3 – 6-Axes Articulated Robotic Arm. Mm-wave mixer is attached at robot wrist joint.

To overcome stage stacking issues, a parallel robotics approach was taken for exactly positing the AUT/SUT over the rotation axis of the central rotator. The parallel robotics system uses a hexapod design with six coupled precision high load actuators that support a precision mounting platform. The motion of these actuators is coupled in parallel by a computer control feed back loop. The six-axes hexapod robot is shown in Figure 4.

By using a parallel robotics system the 6DOF motion that would be typically achieved using a heavy and error prone stack of stages is replaced by a very compact, accurate, and precise hexapod system. There are several key features provided by computer control parallel positioning, such as virtual pivot point definitions and high stiffness. System specifications will be discussed in further detail in section 3.

The phase and amplitude of mm-waves are measured via a 4-port frequency-domain vector network analyzer (VNA) and high frequency waveguide converters.

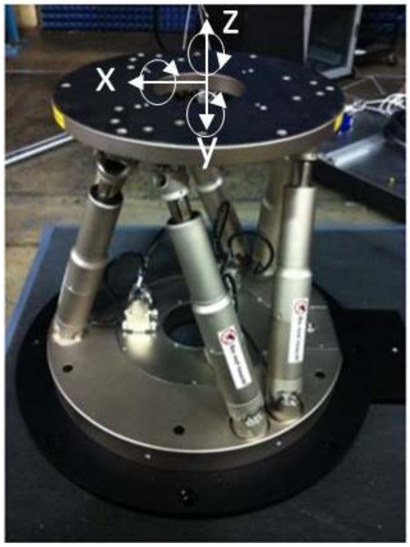

Figure 4 – Six-Axes Parallel Kinematic Hexapod Robot

3.0 System Specification

A NF measurement is a combination of electric-field metrology, position metrology and data processing that implements NF theory [8-12]. Given sound data processing, the robustness of a NF measurement directly depends on the accuracy of the electric-field and position metrology. The mm-wave and positioning subsystems in this NF range design use some-of-the most robust and state-of-the-art metrology techniques currently available. Table 1 shows a summary of system specifications. A discussion of these specifications is presented below.

The mm-wave subsystem uses a 4-port VNA able to provide fundamental frequencies up to 50 GHz. High-frequency waveguide converters operating in standard waveguide bands provide frequencies from 50-500 GHz that can be extended up to 750 GHz. Achievable system dynamic range varies from over 100 dB at 50 GHz to 70 dB at 500 GHz, with a maximum dynamic range of 110 dB over 75-110 GHz. Waveguide components and coaxial cables provide phase stability on the order 5° up to 500 GHz.

The robotic components used for manipulating antennas provide exceptional positioning range of motion with high accuracy and repeatability. The six-axes robotic arm provides 6DOF positioning for a payload up to 35 kg (70 lbs) with an un-calibrated manufacturer-supplied repeatability of 70 µm. The repeatability can be improved to 15 µm by laser tracker calibration of robot postures specific to a particular NF scan geometry. The movement of the robotic arm can be further improved to 8 µm by using real-time feedback from a laser tracker to correct position and orientation errors. Another approach to decreasing position uncertainty is by using external encoders on the rotation joints of the robotic arm. However these do not take into account lost motion from flexure in the beam sections between robot joints. The robotic arm provides a working volume up-to a 1.5 m radius allowing many different sized AUT/SUTs to be measured. Arbitrary coordinate system frames and path trajectories can be defined anywhere in the arm working volume allowing many NF scan geometries to be implemented on the same system. This allows for multiple measurements on the same antenna. Such capability makes it possible to explore which scan geometry is best suited for the particular AUT/SUT in order to optimize measurement time, solid angle coverage, and processing time. Figures 5 and 6 show laser tracker data of the robot arm movement for a planar scan path and an arc path, respectively. Scan volume can also be varied to accommodate different sized test antennas. The ability to precisely rotate the probe antenna by any orientation to accommodate any field polarization makes the use of rotary joints unnecessary. This directly addresses an issue of using rotary joints that operate above 100 GHz which can be very challenging and costly to manufacture. Virtual pivot points can also be defined allowing antenna scans to be performed about any point on the AUT/SUT to within tens of microns. Separate and independent systems are used for motion control and position query, with one system dedicated to commanding robot joint movement and one system dedicated to reading out robot position location. Therefore the speed at which robot positions are queried does not affect robot positioning, thus making for robust and accurate antenna positioning and position data acquisition.

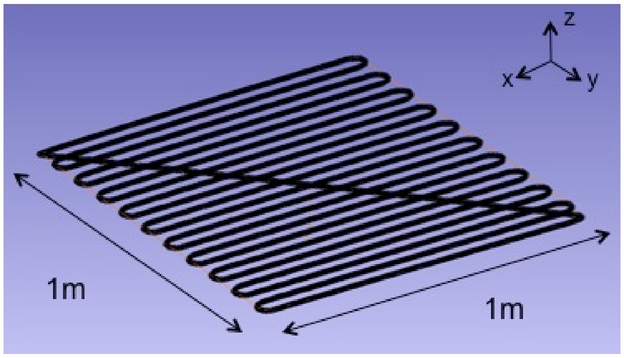

Figure 5 – Planar scan path pattern generated by robotic arm.

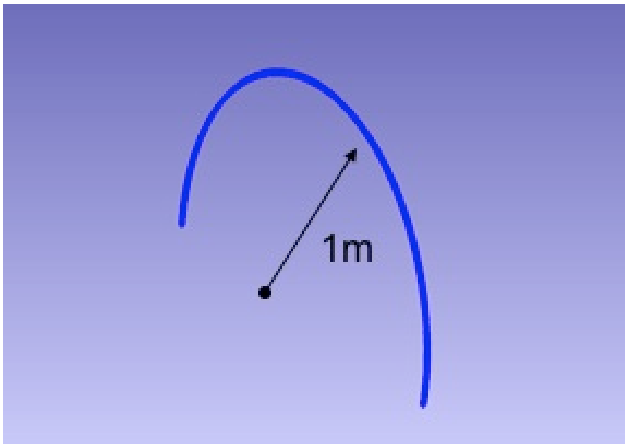

Figure 6 – Arc scan path pattern generated by robotic arm.

The six-axes robotic hexapod system provides 6DOF motion for orienting an AUT/SUT to the axis of the main rotator and can accommodate loads of up to 30 kg. The hexapod provides in-plane X-Y motion over ±50 mm and ±25 mm along the Z-axis. Each uncoupled actuator in the hexapod system has a resolution of 16 nm, resulting in the combined coupled repeatability of 500nm. The hexapod provides rotation of ±15° about the X-Y axes and 30° about the Z-axis with repeatability of 0.0004° and 0.0007° respectively. A larger hexapod can be used to accommodate AUT/SUT payloads greater than 30kg.

The main rotator provides continuous rotation of the AUT/SUT with an angular resolution of 0.36 arc-sec and accuracy of 20 arc-sec and a 300 kg payload capability.

Depending on NF measurement accuracy requirements, knowledge of antenna positioning anywhere from 1/20th to 1/50th of a wavelength may be required. At 500 GHz $\lambda/50 \approx 12\ \mu m$. To meet these stringent positing requirements a high accuracy laser tracking system is used to track the position and orientation of antennas during a NF scan. In addition to X-Y-Z position data, the laser tracker system can be integrated to a photogrammetry system to provide full 6DOF tracking of the robotic arm, and any antenna fixed to it, with typical accuracy of ±5 µm + 2.5 µm/m in X-Y-Z and 0.01° in yaw, pitch, and roll.

The laser tracking system can be used in several ways to improve the accuracy of NF measurements. Passive position and orientation data can be measured during a NF scan which can then be used in applying position correction algorithms [11-12]. The laser tracker can also be used in a feedback loop to the robotic arm as a 6DOF optical encoder for real-time position and orientation correction of robot postures.

Table 1. Robotic Near-Field Range Specifications

mm-Wave	Frequency Domain Vector-Network Analyzer: 50-500 GHz Extendable to 750 GHz
Robotic Arm	Scan Volume: 1.5 m radius Positioning: Six Degrees of Freedom Repeatability: <70 µm Payload: 35kg
Hexapod	Linear Motion: Range: X-Y axis, ±50 mm, Z axis ±25 mm Repeatability : 500nm Rotation Motion: Range: ±15˚ about X-Y Repeatability: 0.0004˚ Range: ±30˚ about Z Repeatability: 0.0007˚ Payload: 30kg
Rotator	Motion: Continuous Rotation Resolution: 0.36 arc-sec Accuracy: 20 arc-sec
Laser Tracker	Linear Accuracy (X-Y-Z): ±5 µm + 2.5 µm/m Angular Accuracy (Roll, Pitch, Yaw): 0.01˚

4.0 Future Work

The NIST antenna metrology lab is currently in the process of validating this system over the 50 GHz-500 GHz frequency range. An intensive NF measurement campaign of several standard antennas will be made in order to validate this system. Antennas previously calibrated on other NF ranges as well as extrapolation ranges will be measured with this new system and data compared. As the stages of the validation process are completed, detailed measurement results will be reported in the literature including uncertainty analysis. The antenna metrology laboratory at NIST, Boulder CO is excited to bring this new system online and be able to offer such antenna metrology capability.

5.0 Summary

In an effort to address the need for highly accurate antenna measurements above 100 GHz, the Antenna Metrology Lab at the National Institute of Standards and Technology in Boulder Colorado has developed a robotically controlled near field pattern range for measuring antennas and quasi-optical components. This new near-field range will operate from 50 GHz to 500 GHz and be able to be extended up to 750 GHz. A new concept in near-field range systems, this range incorporates the positioning repeatability of a high-precision industrial six-axes robotic arm, and six-axes parallel kinematic hexapod integrated with a highly accurate laser tracking system. The ability to precisely program robot positioning allows several types of NF scans to be accomplished with the same system. Positioning repeatability is predicted to be better than 10µm. The robotic NF range concept is introduced, and an overview of the system design, specifications, and configurability are presented.

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