Three Antenna Ranges Based on Articulated Robotic Arms at the National Institute of Standards and Technology†

Usability for Over-the-Air and Standard Near-Field Measurements

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***Abstract*—NIST has developed an antenna range that uses coordinated industrial robotic systems for measuring milli-meter wave (mmWave) antenna patterns and gain. The Configurable Robotic millimeter Antenna (CROMMA) facility employs a multi-axis articulated serial robotic arm to place probes accurately around a test article. The positional and temporal capabilities, shown by CROMMA, has become a springboard to develop two new robotic ranges for use primarily from 0.5 - 30 GHz. Both of these systems are based upon commercial-coordinated-kinematic systems with multiple degrees of freedom. The first is the dual six-axis, robotic-arm Large Antenna Positioning System (LAPS). It is designed to perform large volume scanning with an emphasis on Multiple-Input Multiple-Output (MIMO) and Over-the-Air (OTA) testing. The second system employs a seven-axis robotic arm to perform communication testing of Single-Input Single-Output (SISO) systems and will be used to establish modulated and continuous-wave field references.**

We will discuss the advantages, limitations and techniques employed to use these commercial robotic systems for accurate time-sensitive positioning and coordination with communications measurement equipment.

Keywords—antenna; measurement; OTA; near-field; gain

I. Introduction

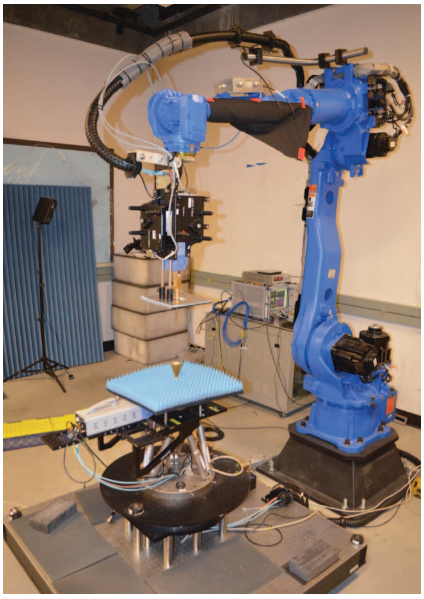
There is an expectation that the proposed commercial communications systems in the proposed 5G bands will require much more comprehensive testing to ensure that reliable multi-user connections are established and maintained [1]. Current 2G, 3G, 4G, and LTE mobile systems work on broad sectored base stations patterns and near omnidirectional antennas on mobile user equipment (UE). In July 2016, the Federal Communications Commission (FCC) opened up limited spectrum for 5G mobile radios covering 27.5-71 GHz [2]. To overcome path loss, battery-limited transmit power availability, and antenna gain limitations on UE receiver sensitivity in these frequency ranges, we expect that these new systems will incorporate dynamic beamforming to reduce link loss [3].

Conventional near-field testing systems can measure static beams, far-field systems can test moving beams over limited angles, but offer little in dynamic beam quality. Techniques such as the two-stage substitution, reverberation chamber, and boundary array or multi-probe anechoic methods (MPAC), seek to generate or simulate illumination of the UE from many directions using many antennas [1,4]. There is a need for a dynamic OTA testing method that investigates system performance while providing real-world field interactions.

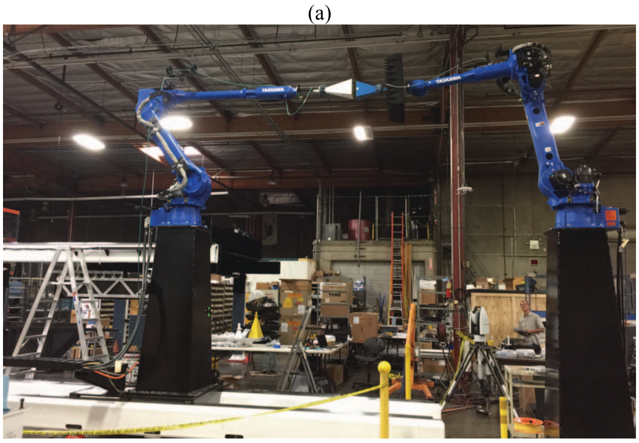
The aging antenna facilities at the National Institute of Standard and Technology (NIST) were being replaced and the new design philosophy was focused on long term relevance for general communication and radio frequency (RF) measurements. While a need for standard near-field testing was required to support probe calibrations, gain-extrapolation and polarization reference measurements, a large consideration for these new ranges was the ability to perform much more arbitrary testing than in previous systems. To address the potential need for testing dynamic beamforming systems and simulated MIMO style tests, the new ranges were based on full 6 degree of freedom (6DoF) articulated robots augmented by external axes. CROMMA showed that coordinated motion in 6DoF can greatly reduce control overhead and perform corrected dynamic positioning of antennas over a large volume, specifically ±0.03 mm accuracy over a 3 m diameter volume [5,6]. The experience gained with CROMMA was leveraged into the design of two additional ranges: the LAPS and the SISO/Reference range.

Fig. 1 shows the three robotic ranges NIST is installing. Two, CROMMA and LAPS, will be collocated in the same anechoic chamber of the Advanced Communications Metrology Laboratory (ACML) at NIST. The SISO/Reference field range is being deployed into an existing anechoic facility to create a low noise environment for generating standard fields and high isolation to limit interaction from potentially high electromagnetic field-levels with other external experiments.

The combination of large volume, velocity, and range of motion in LAPS, the high frequency capability of CROMMA, and the limited intrusion of the SISO/Reference facility will give NIST the ability measure dynamic communications systems while supporting basic metrology required for reference antenna measurements on a common measurement platform.



(a)



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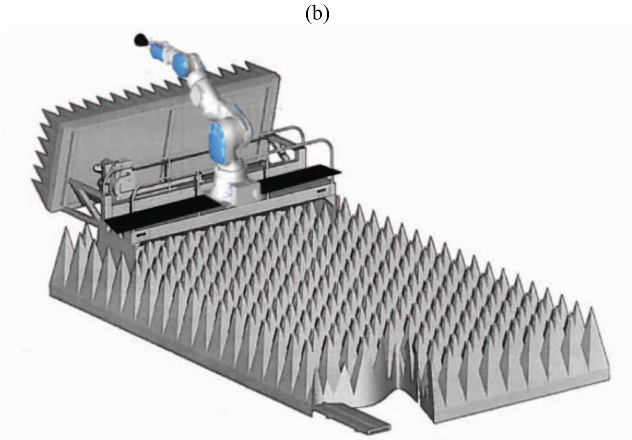

(c)

Figure 1. The three robotic ranges designed for NIST: CROMMA, (a), performing a 73 GHz gain measurement, the LAPS, (b), undergoing repeatability, accuracy and RF stability tests at the factory, and the new SISO/Reference Field facility, (c), that will be used to place and scan antennas with minimal field perturbation using a 7-axis robot mounted on a 4.5 m rail.

II. The Use of Commercial Robotic Systems for Antenna Measurements

A. Repeatability Versus Accuracy

Most commercial articulated robotic arm manufacturers are geared toward improving repeatability and speed. The ability to repeat a process with minimal deviations at high speed is a driving need of most articulated robotic arms. Path repeatability is more important than point accuracy, e.g. a command between a list of specified poses in a given order is repeated very well while a command for going to a point at a specific pose is less accurate. So, the use of industrial versus antenna specific positioning hardware requires a change in system control philosophy. Instead of moving individual axes, e.g. $\boldsymbol{\phi}$ axis movement during a spherical measurement or a $\boldsymbol{y}$ axis step during a planar scan, all six degrees of freedom are continually commanded to move to a specific path via a series of corrected 6DoF, x,y,z,Rx,Ry,Rz, poses [7].

Unlike the rigid structures that constitute many standard near-field scanning systems, the extended nature of an articulated robot leads to gravitation droop and the serial nature of articulated arms tend to magnify pose uncertainties from hysteresis in the joints. For accurate antenna measurements, these need to be addressed. Since many antenna scanning geometries are a series of similar paths (i.e. extrapolation, spherical, planar), iteration can be used to successively improve the accuracy of paths to the repeatability level of the robot. NIST uses a laser tracker slaved to the robot to measure the location of the probe at the same time as the RF measurement. The laser tracker measures the difference between the commanded and actual pose, and the results are used to iteratively correct the probe location. With this method, there are initial "sacrificial' scans until the robot is corrected to an acceptable level [6].

B. Kinematic Model and Calibration

Most commercial articulated robotic systems can control the movement of a tool control point (TCP) in addition to individual joint rotations. The TCP is a kinematic offset from the end of the robot. For standard near-field scanning, we locate the TCP at the aperture of the probe, Fig. 2. There are several methods for determination of the TCP to robot flange [8,9]. Once determined, direct movement of the probe can be performed without the need for additional offset calculation.

In addition to direct joint control, the robots can move in direct pose control. Using the fixed X-Y-Z angle convention [7], we can calculate the $(\Delta x, \Delta y, \Delta z,\ R_x=\alpha,\ R_y=\beta,\ R_z=\gamma)$ transform from a pose {start} to {end} given by:

$$
{}^{\{end\}}_{\{start\}}T_{\{ref\}} = \begin{bmatrix} \left[{}^{\{end\}}_{\{start\}}R_{XYZ}(\alpha,\beta,\gamma) \right] & \begin{matrix} \Delta x \\ \Delta y \\ \Delta z \end{matrix} \\ \begin{matrix} 0 & 0 & 0 \end{matrix} & 1 \end{bmatrix} \tag{1}
$$

where the 3x3 rotation matrix, R_{XYZ}, in (1) is given in [7] and the common reference frame for the current location and transform is denoted by {ref}. Fig 2. shows the frames used in the iterative correction method. Since the distance offsets in (1) are relative, all that is needed is the rotation reference of the robot. From a common pose, the robot is moved and recorded with the laser tracker as translations are made in x, y and z. This results in the knowledge needed to construct a reference frame {ROBOT}.

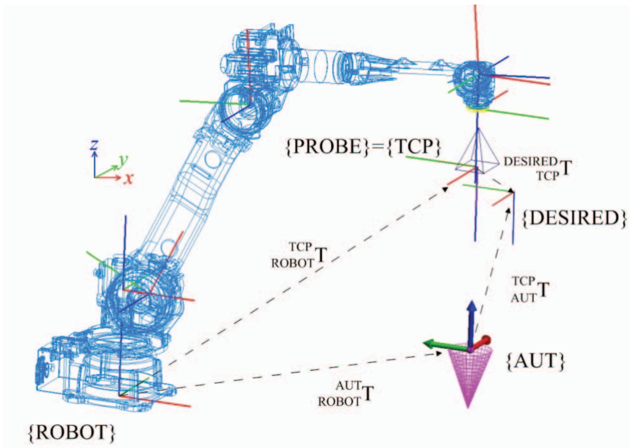

Figure 2. The relative frames for one point in a scan, {poses}, and transforms ${}^{y}_{x}T$ that are required for simple iterative correction of the robot

To perform the iterative correction, the antenna under test, (AUT), and the probe (TCP) must be spatially located [9,10]. Uncertainties and error in these poses are direct contributors to overall position uncertainties. The {DESIRED} scan geometry is constructed relative to the {AUT}. The robot is then sent to perform a rudimentary scan quite a distance from the AUT to avoid contact. This unaligned scan is measured with the laser tracker to determine the initial {PROBE} and {DESIRED}.

${}^{TCP}_{ROBOT}T$ is the current robot position and ${}^{DESIRED}_{TCP}T$ is the transform of the between where the probe actually is and its ideal location. As long as both of those transforms are known relative to the {ROBOT} frame, the new goal for the robot to get to the {DESIRED} location can be determined by:

$$ {}^{\{ROBOT\_NEXT\}}_{\{ROBOT\_CURRENT\}}T = {}^{\{DESIRED\}}_{\{ROBOT\}}T = {}^{\{DESERIED\}}_{\{TCP\}}T \; {}^{\{TCP\}}_{\{ROBOT\}}T \qquad (2) $$

The major advantage of using this limited correction algorithm is that only a rudimentary knowledge of the relative orientation of the robot is needed. We can also correct the major gravity deflections and localized robot movement inaccuracies. Orientation errors in {ROBOT} may reduce convergence, however, even with an orientation error of 0.5°, on CROMMA, errors are typically within 100 microns after two iterations and 50 microns after four iterations. Monitoring during the entire measurement allows for corrections to account for thermal and environment changes in the robot [6].

C. *Kinematic Model and Calibration*

Groups are working to better robot calibration techniques, by measuring each linkage in an articulated arm [10-11]. A better model of the arm with actual joint lengths, offsets, and gravity deflection models are used versus the nominal factory values. This can result in more accurate robot movement. This knowledge can shorten the alignment process, and as the operational frequency range of a system is inversely proportional to positioning errors, decreasing the physical errors allows the robot to operate open-loop at higher frequencies.

III. The Three NIST Robotic RF Measurement Facilities

NIST is installing two new ranges based on the same design principal as CROMMA: a six or seven axis articulated arm that is augmented by other motion stages to allow for accurate large volume coverage. All three ranges will be running on the same 6DoF kinematic control platform so measurement processes can be used between systems.

A. *CROMMA*

CROMMA (Fig. 1a) is comprised of two robotic systems, an articulated robotic 6DoF arm for probe positioning around the AUT [6]. A 6DoF hexapod mounted on a rotation stage allows for alignment of the AUT. The rotation stage defines the axis of rotation and the AUT direction. The hexapod aligns the AUT to the rotator. Gain-extrapolations and pattern measurements between 50 and 220 GHz have been successfully performed with CROMMA.

B. *The LAPS*

The conceptual layout of the collocated LAPS and CROMMA facilities is shown in Fig. 3. The LAPS has a stationary 2.5m reach robot and a 3.5m moving robot mounted on a 7m travel rail that creates an effective 5 m x 6 m x 10 m volume to position antennas. The LAPS corrected open-loop accuracy is designed for operation from 500 MHz to 30 GHz [12]. The dual robot configuration can be used to perform standard scanning or easily reconfigured to perform larger OTA testing and arbitrary, multi-point interrogation of RF system (see Figs. 4,5).

C. *The SISO and Reference Field Facility*

The SISO and Reference Field facility is designed to minimally perturb the fields generated within it. A seven-axis articulated arm was chosen for the probe positioner. The additional degree of freedom allows the majority of the robot could remain behind the absorber cowling when locating a probe in a field, see Fig. 1(c). The 4.5 m travel is used to separate the source and probe source and probe to limit field taper across the length of the probe.

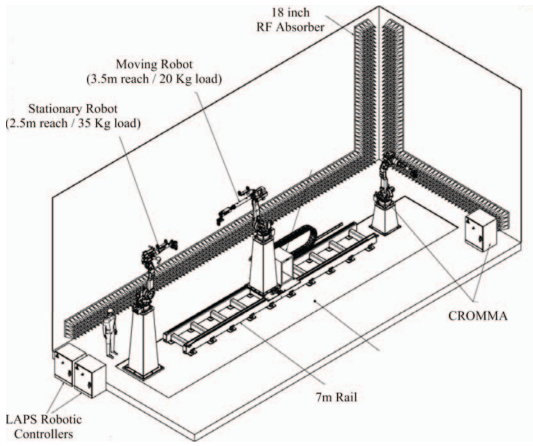

Figure 3. The Large Antenna Positioning System and CROMMA co-located in the NIST Advanced Communications Metrology Laboratory.

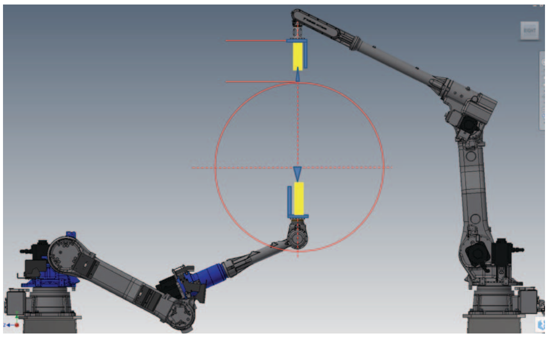

Figure 4. The LAPS setup for traditional scanning. The robot kinematics can account for mounting offsets and misalignments.

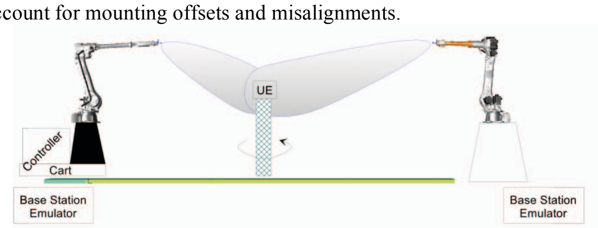

Figure 5. A depiction of multiple interrogation of a beam-forming system with the LAPS. Both robots are illuminating the UE in a MIMO fashion from multiple orientations.

IV. System Validation and Measurement Results

A. LAPS Deviation from Linear Movement

The LAPS was tested at the factory to determine its uncorrected straightness and effect on the TCP as it travelled along the rail, Fig. 6. Testing the lateral movement of the antenna with the arm extended (Fig. 1(b)) showed maximum deviations of less than 200 µm which corresponds to a λ/50 error over 30 GHz. This sets a practical frequency limit for open loop (uncorrected) operation for extrapolation measurements.

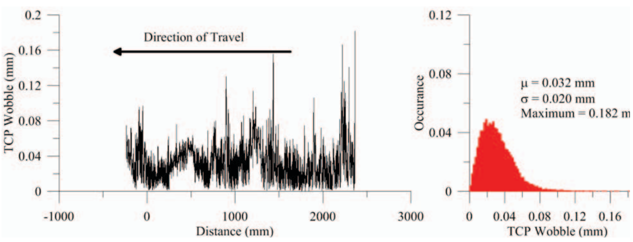

Figure 6. TCP/Antenna wobble at the end of the robot during a 2.6 m move at 23 mm/s

B. CROMMA Stability

To validate stability, we require a canonical geometry that provides a known RF response relative to position. An extrapolation scan should have a linear unwrapped phase change with distance. We have experienced phase errors due to cable stresses. As our mmWave systems employ harmonic up conversion, any phase errors in feed cables are multiplied by this up-conversion factor. The robots have a cable path with minimal stress for the motor and tool control [6]. We run our phase-sensitive local oscillator (LO) cabling along this path. At 118 GHz, we have an LO up-conversion factor of six. The results, Fig. 7, show that over a 560 mm displacement (~225 λ), the 118 GHz phase errors are less than 8°. This means we are controlling LO phase errors to ~1.3°. The full-length movement of this scan is generally more aggressive than we see on a typical 1 m spherical or planar scan. We can use this to infer that typical phase errors are approximately 1° at base LO frequencies.

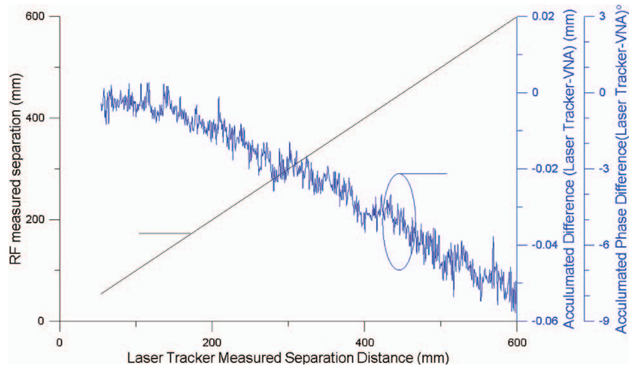

Figure 7. Distance inferred by phase change during a 118 GHz RF insertion measurement compared to the distance measured directly by a laser tracker.

V. Conclusion

NIST's use of industrial coordinated motion robotics has shown usefulness in a metrology setting. To realize the full accuracy that these systems can deliver, a coordinate metrology analysis and path optimization for scans have been developed. We have performed highly accurate, feedback-based scans using an *in-situ* laser tracker and open-loop methods at lower frequencies where positional needs are less stringent.

References

[1] M. Fogelle, "Advances in Over-the-Air Performance Testing Methods for mmWave Devices and 5G Communications," *Proc. of the Antenna Measurement Techniques Assoc.*, Nov 2016.

[2] *Use of Spectrum Bands Above 24 GHz For Mobile Radio Services*, FCC order 16-89A, July 2016.

[3] K. A. Remley *et al.*, "Measurement Challenges for 5G and Beyond: An Update from the National Institute of Standards and Technology," *IEEE* Microwave Magazine, vol. 18, no. 5, pp. 41-56, July-Aug. 2017. doi: 10.1109/MMM.2017.2690882.

[4] M. Rumney *et al.*, "Testing 5G: Evolution or Revolution?," *Radio Propagation and Technologies for 5G (2016)*, Durham, 2016, pp. 1-9. doi: 10.1049/ic.2016.0067.

[5] D. Novotny, J. Gordon, J. Coder, M. Francis and J. Guerrieri, "Performance evaluation of a robotically controlled millimeter-wave near-field pattern range at the NIST," *2013 7th European Conference on Antennas and Propagation (EuCAP)*, Gothenburg, 2013, pp. 4086-4089.

[6] D. R. Novotny, J. Gordon, M. Francis, R. Wittmann, A.E. Curtin, J. Guerrieri, "Antenna Measurement Implementations and Dynamic Positional Validation Using a Six Axis Robot," *Proc. of the Antenna Measurement Techniques Assoc.*, Nov 2015.

[7] J. J. Craig, *Introduction to Robotics: Mechanics and Control*, 3rd ed., New York, NY, Pearson Education, Inc, 2004, ISBN 9780201543612.

[8] J.A. Gordon, D.R. Novotny, A.E. Curtin, "A Single-Pixel Touchless Laser Tracker Probe," *J. of the Coordinate Measurement Soc. Conference*, vol. 10, no. 2, pp. 12-22, Autumn 2015.

[9] *DX100 Instructions: FOR NORTH AMERICAN (ANSI/RIA) STANDARD*, Part No. 155494-1CD, Rev. 2, Yaskawa Electric Corporation, pp 8-23,29.

[10] S. Droll, "Real-Time Path Correction of Industrial Robots with Direct End-Effector Feedback from a Laser Tracker," *J. of the Coordinate Measurement Soc. Conference*, vol. 10, no. 1, pp. 20-25, Spring 2015.

[11] M.S. Allman *et al.*, "Serial Robotic Arm Joint Characterization Measurements for Antenna Metrology," in *Proc. of the Antenna Measurement Techniques Assoc.*, Nov 2017 (in process).

[12] D. Novotny *et al.*, "A Multi-Robot Large Antenna Positioning System for Over-The-Air Testing at the National Institute of Standards and Technology," *Proc. of the Antenna Measurement Techniques Assoc.*, Oct 2017 (in process).

