The New Large Antenna Positioning System for Over-The-Air Testing at the National Institute of Standards and Technology

Jeff R. Guerrieri, David Novotny, Josh Gordon, Alexandra Curtin, Michael Allman
National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305 USA, jguerrieri@nist.gov
Kim Hassett, Quong Ton, Scott Caslow
NSI-MI Technologies, 19730 Magellan Drive, Torrance, CA 90502

***Abstract* — This paper introduces the new Large Antenna Positioning System (LAPS) at the National Institute of Standards and Technology (NIST). For the last eight years NIST has been pioneering the use of robotics for antenna measurements. Starting with the development and integration of the Configurable Robotic Millimeter-Wave Antenna (CROMMA) facility. CROMMA was designed to be reconfigurable to different near-field antenna measurement geometries and perform antenna measurements from 100 to 500 GHz. Probe position repeatability of 25 µm was achieved using coordinate metrology feedback. However, the single-robotic-armed CROMMA was restricted to small antennas. To overcome this limitation, NIST developed the concept of a dual-robot system with one fixed and the other mounted on a large linear rail slide. Using characterization of the robotic arm joints and segments, the LAPS will have open loop probe position accuracies of 200 µm to facilitate antenna measurements up to 30 GHz.**

***Index Terms* — large antenna positioning system, robotic arm, antenna measurements, kinematics, 5G communications.**

I. Introduction

The National Institute of Standards and Technology (NIST) pioneered the use of robotics for antenna measurements with its **C**onfigurable **RO**botic **M**illi**M**eter-wave **A**ntenna (CROMMA) facility, shown in Fig 1. [1]. The reconfigurability of CROMMA allows for extrapolation, planar, spherical, cylindrical, and mixed-geometry scanning. CROMMA consists of a robotic arm, hexapod, and rotary positioner, when operated closed loop with coordinate metrology feedback, provides probe position repeatability of 25 µm, which meets the $\lambda/50$ requirement for antenna measurements up to 200 GHz [2]. CROMMA has been validated through numerous tests at 118 and 183 GHz, for both spherical near-field and extrapolation gain measurements [3]. While CROMMA has been proven to be a valuable tool for high frequency antenna measurements, it is limited to use on electrically small antennas.

The multiple-input, multiple-output (MIMO) and multi-beam base station antennas of new 5G communications systems require testing of adaptive antennae at arbitrary angles, testing dynamic paths, looking at Doppler effects, and testing of devices with integrated antennas, where an RF test signal cannot be injected into the system. Most of these tests are performed on systems, such as base stations, that are too large for CROMMA. NIST developed the Large Antenna Positioning System (LAPS) to address these future testing requirements. The LAPS is a dual-robot system with one robot integrated with a linear slide, and is shown conceptually in Fig. 2.

Fig. 1. CROMMA facility at NIST.

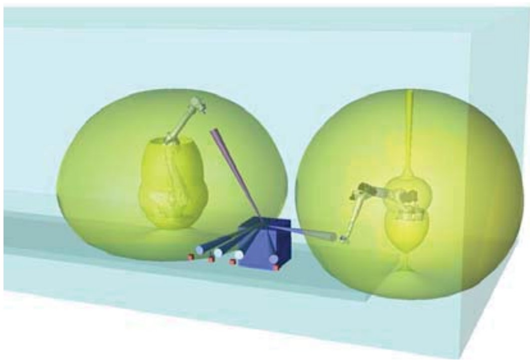

Fig. 2. LAPS conceptual design.

II. ANTENNA MEASUREMENT FACILITY

In order to accommodate space for the LAPS, NIST needed to decommission the existing multi-purpose antenna measurement facility. As a result, the LAPS also needs to replace the existing capabilities of planar, spherical and cylindrical near-field measurements and extrapolation gain needed for on-axis gain calibration services offered by NIST as a National Measurement Institute. NIST established the Antenna Measurement Facility (AMF), shown in Fig. 3 which is a Fully Shielded Anechoic Chamber (FASC) that will house the LAPS. The FASC dimensions are 17 m (L) X 7.6 m (W) X 7 m (H) and is lined with 0.5 m pyramidal absorber.

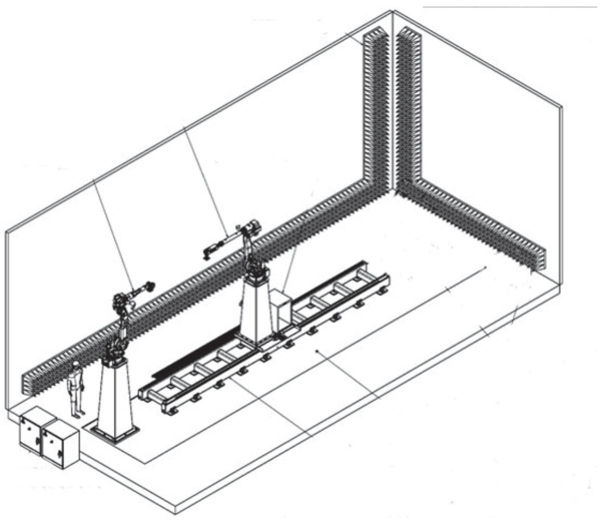

Fig. 3. Design drawing of the LAPS in the new AMF at NIST.

III. LAPS DESIGN

The LAPS was designed around two commercially available robots: one stationary robotic (SR) capable of a 2.5 m reach, and one moving robot (MR) with a 3.5 m reach that is mounted on a 7-m precision linear rail system. It is designed to have a large scan volume suitable for testing across common communications bands (500 MHz - 30 GHz) with specified absolute RMS accuracies of least 0.250 mm. This will allow for standard near–field testing, gain extrapolation, and physical separation needed to ensure reasonable field uniformity when illuminating small devices with moderate gain antennas. Multiple robots also allow for multiple bearings to a device, simultaneous emissions and immunity analysis, or interference testing.

The two robot controllers are linked together and share the same kinematic space. This allows the robots to position antennas, probes, and devices under test (DUT) either absolutely in space or relative to each other.

The two major tasks for characterizing a serial robotic system are extrinsic and intrinsic calibrations [4]. Extrinsic calibrations, shown in Fig. 4, typically remove most of the systematic measurement uncertainties, measure the robot relative to external references or where the robot frame is physically located, and define the location and orientations of base axes and antenna location or tool control points (TCP)s. This can reduce uncertainties to the millimeter level or less. However, effects from inaccuracies such as encoder/servo non-uniformity, axis warping, and motor eccentricities present practical limitations. These limitations can be addressed by characterization of each segment and axis of the robot and applying to the robot's kinematic model [5]. This approach will allow for open-loop antenna measurement without laser tracker feedback, which will provide fast dynamic movements and the ability of the system to rapidly respond to stimuli.

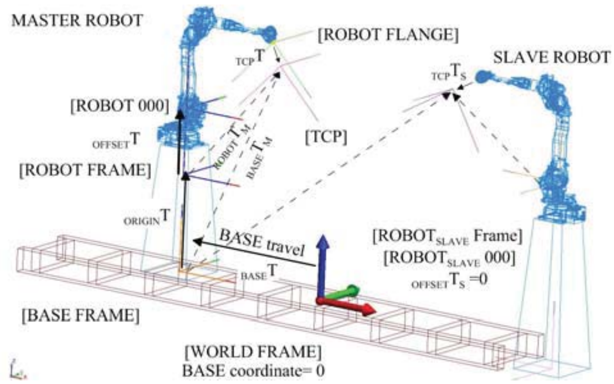

Fig. 4. Extrinsic frames and the 6D solid-line transforms between them, determined during calibration of a robot's kinematic model.

The LAPS is integrated with a Functional Safety Unit (FSU) that is aware of the unified coordinate space of the entire LAPS system. It is designed to prevent the collision of one robot with the other, itself, any attached antennas (or tooling), and collisions with the surrounding environment. The FSU also has redundant systems to protect operators. The robots can have large kinetic energy and control of that energy is integral to safe operation. The controllers are equipped with laser safety radars that stop autonomous motion when the working volume of the LAPS is encroached upon. When personnel are in the working envelope, during manual operation, alignment or mounting, enabling devices to allow robot movement must be positively activated prior to servo activation.

IV. LAPS INITIAL VALIDATION

Table 1 lists the basic physical design specifications for the LAPS. A selection of the initial validation tests results are presented in this section.

Table 1. Basic physical design specifications of the LAPS

Moving Robot (MR) and Rail	
Robot horizontal reach	3.5 m
Robot vertical reach	5 m
Robot path repeatability	0.15 mm
Robot payload	20 kg
Minimum planar scan plane size	2.5 m x 3 m
Minimum spherical radius (with a 356 mm probe)	1 m
Rail travel	7 m
TCP wobble at scan plane center (deviation from best fit line)	RMS: 0.25 mm
TCP wobble at scan plane center (deviation from best fit line)	MAX: 0.5 mm
Stationary Robot (SR)	
Robot horizontal reach	2.5 m
Robot vertical reach	4 m
Robot path repeatability	0.07 mm
Robot payload	35 kg
Minimum planar scan plane size	2 m x 2.5 m
Minimum spherical radius (with a 356 mm probe)	1 m

The TCP wobble specifications in Table 1, are a major component of positional uncertainty and is difficult to correct. It is affected by MR posture and loading, rail flatness, cart motion, the MR riser stiffness, and rail deflection under varying load conditions. The influence of the rail variations are magnified by the distance from the rail to the MR TCP.

Laser tracker targets were mounted to the MR pedestal and near the TCP of the MR in an extended pose, shown in Fig. 5. They were tracked as the MR was moved through a 2-m span of the rail at a constant rate of 23 mm/sec. The pedestal-mounted target deviation from the best fit line was 14 ± 7 µm, with a 61 µm maximum, and the TCP mounted target was 32 ± 20 µm deviation with a 182 µm maximum, as shown in Fig. 6. This result shows the basic mechanical capabilities of the system are adequate for λ/50 (200 µm) operation at 30 GHz.

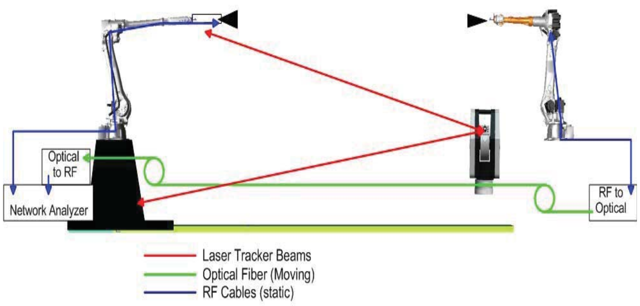

Fig. 5. Laser tracker and spherically mounted retroreflector (SMR) setup and RF measurement setup for initial validation tests.

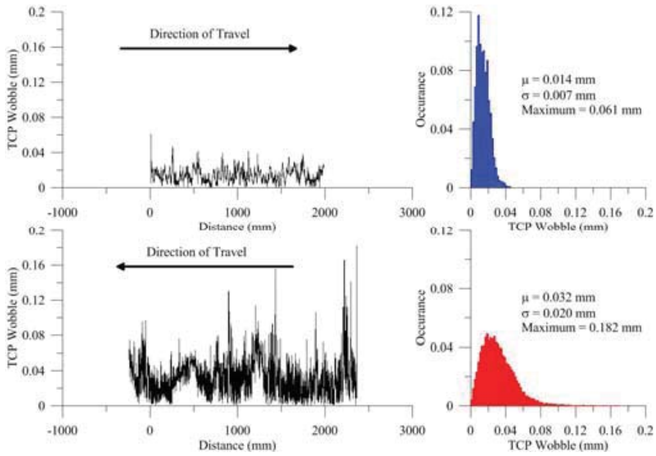

Fig. 6. Base wobble and distribution for the target on the MR base (top) and the TCP wobble and distribution for the target on the robot arm (bottom).

The system will be used for testing during motion, which requires coordination between the timing of the RF system and the motion of the LAPS. Standard gain horn antennas were mounted to each robot and aligned parallel to the axis of movement along the linear rails using the laser tracker. A vector network analyzer (VNA) based measurement system was setup to measure the insertion loss between the antennas at 9 GHz. By measuring more than 4 points per wavelength, RF_i, the RF separation is determined by taking the phase of the insertion measurement, unwrapping the phase vs. distance and then converting phase to distance [6]:

$$d_{phase} = \operatorname{atan}\left(\frac{\operatorname{Re}(RF_i)}{\operatorname{Im}(RF_i)}\right)\frac{\lambda}{2\pi}360$$

The laser tracker was setup to measure the target mounted near the TCP. The MR was moved in 2.5 mm steps at a speed of 30 mm/sec along the rail, stopped, RF insertion data and laser tracker data were taken over a 1 sec time window, and then the motion restarted. The expectation was that the rapid-stop motion in different directions would highlight the vibrational modes of the system. The setup of the measurement is shown in Fig. 5.

The results of the RF insertion measurement, shown in the top half of Fig. 7, and the corresponding laser tracker measurements, shown in the bottom half, display good correlation as the separation gets larger. At close distances, the phase variations from linear distance increase noticeably at greater separations than the amplitude. The correlation of laser tracker and RF inferred distance show that the robot and cabling are not experiencing excessive movement during the position and velocity changes. These initial test results met the required specifications, and the LAPS was delivered and installed at NIST, as shown in Fig. 8.

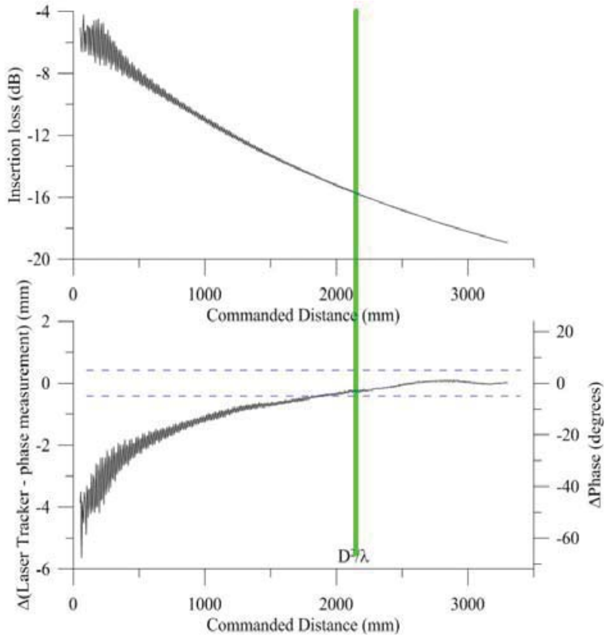

Fig. 7. RF insertion measurement (top), and laser tracker measurement (bottom) comparison results.

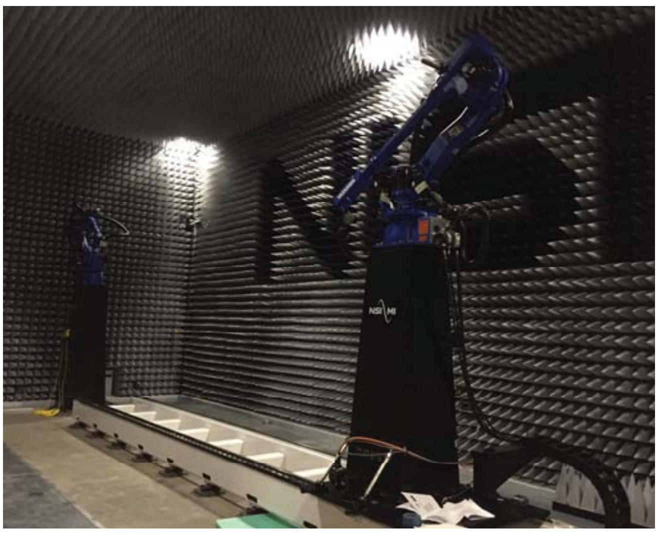

Fig. 8. The LAPS installed at NIST.

V. LAPS CAPABILITIES

The LAPS will perform the traditional near-field scanning geometries and hybrid geometries, which involve moving both robots and interrogating communications systems from multiple positions. Figures 9 and 10 demonstrate the spherical and planar scanning geometries of the MR, while Figures 11 and 12 show same geometries for the SR.

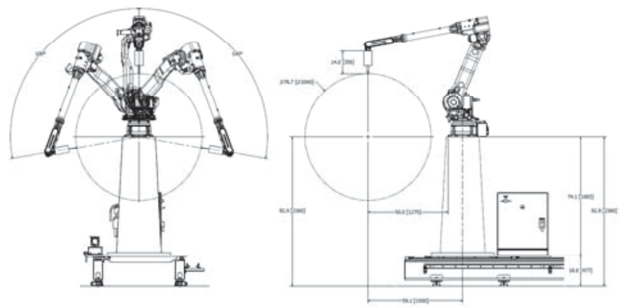

Fig. 9. MR typical spherical scanning geometry.

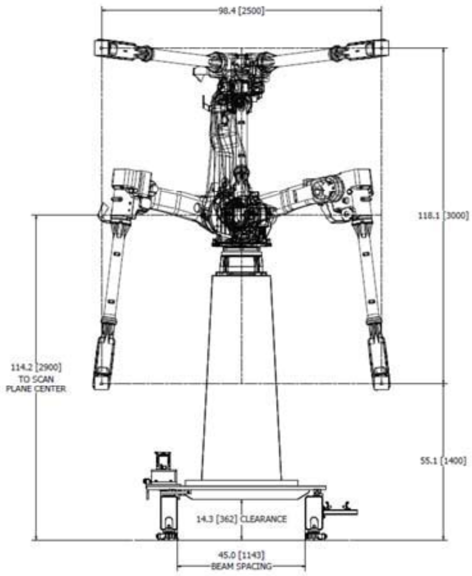

Fig. 10. MR typical planar scanning geometry.

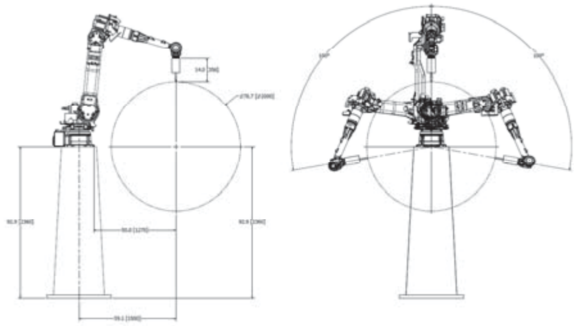

Fig. 11. SR typical spherical scanning geometry.

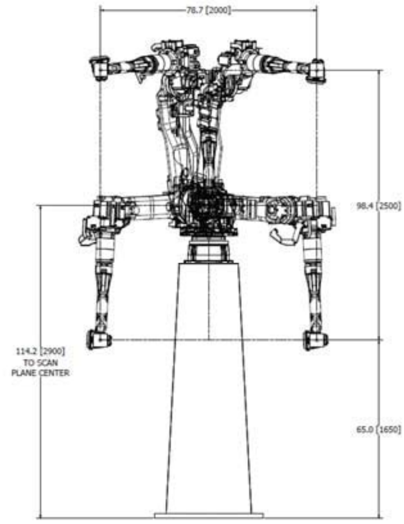

Fig. 12. SR typical planar scanning geometry.

Since the MR and linear rail are kinematically linked, coordinated motion between the two can be controlled to perform large planar near-field measurements, as illustrated in Fig. 13.

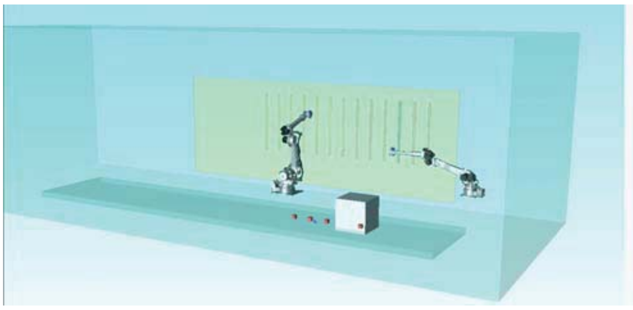

Fig. 13. The LAPS large planar scanning configuration.

The real advantage of the LAPS will be the ability to perform active over-the-air (OTA) interrogation of future communication systems. Fig. 14 illustrates a scenario for testing a beam-forming network by sampling the high signal-to-noise ratio (SNR) region while simultaneously and coherently measuring off-axis performance. By sampling the emissions coherently, in the near-field, pattern analysis can be made without the injection of an RF test signal into the system. This is a more realistic test, where, the system itself is used as the stimulus and response.

Figure 15 depicts two base station emulators interrogating a single DUT, performing a MIMO test. Utilizing the reach of the robots and the rail, a suitable uniform field could be generated to illuminate the DUT under conditions resembling the far field. This might also be used as a platform to develop OTA MIMO tests with rapidly varying spatial and Doppler conditions.

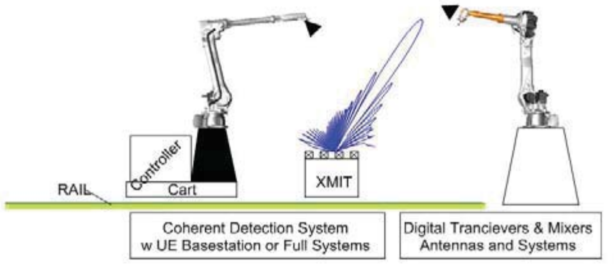

Fig. 14. A depiction of simultaneous measurements of a beam-forming system with the LAPS, SR (right) is measuring the main beam while the MR is probing off angle performance.

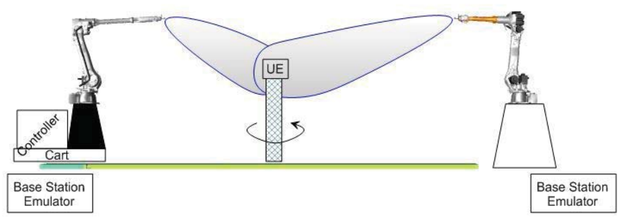

Fig. 15. A depiction of multiple interrogation of a beam-forming system with the LAPS, SR (right) and MR are illuminating the UE in a MIMO fashion from multiple orientations.

VI. Conclusion

While the LAPS can perform standard antenna pattern and gain testing, the ultimate goal is to perform dynamic OTA system tests. Initial validation of the LAPS at the factory show that basic mechanical operation of the system is within the specified design tolerances for static and dynamic testing to at least 30 GHz. The LAPS has been installed at NIST and is going through final validation testing.

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