Distributed RF Design Implementation for a Multi-functional Robotic Antenna Measurement System

Kim Hassett, *Fellow, AMTA,*
Bert Schluper, *Senior Member, AMTA.*
Next Phase Measurements
Garden Grove, CA USA
kim.hassett@npmeas.com, bert.schluper@npmeas.com

Abstract—**Industrial robotic arms offering high speed, precise positioning repeatability, and a high degree of freedom in motion, are an attractive alternative positioning solution for supporting a wide variety of scan geometries using a single antenna measurement system. For multi-function and production antenna measurement applications, this makes them a cost-effective solution compared to custom designed positioner stack-ups. However, motion is not the only consideration when implementing a multi-functional measurement system. The RF system design needs to be equally flexible to accommodate different measurement topologies and operating modes. Ideally, the solution should be flexible enough to also provide a clear upgrade path to accommodate future requirements. This paper discusses the use of commercial modular multi-port Vector Network Analyzer products in the implementation of a distributed RF system for a 14-axis robotic antenna measurement system that supports multiple antenna measurement geometries with minimal manual reconfiguration. This novel RF system design has the capability of simultaneously measuring multiple antenna test ports and can be easily reconfigured to support a variety of measurement configurations and other applications.**

Keywords—Production Antenna Test, Robotic Antenna Measurements, Multi-port Measurements, Multi-function RF System

I. Introduction

The use of industrial robots has become prolific and has expanded beyond manufacturing to other applications, such as antenna measurement metrology. The National Institute of Standards and Technology was one of the first to pioneer this technology back in 2014 when they investigated the feasibility of using a 6-axis robotic arm for metrology antenna measurements, resulting in the Configurable Robotic Millimeter-Wave Antenna Facility (CROMMA) [1]. Previously limited to use in academia and R&D, this technology has matured such that it is now being employed in commercial antenna measurement applications. The robotic arm's speed, high degree of repeatable positioning accuracy, and extreme flexibility provides for an accurate, reliable, and highly reconfigurable antenna positioning system, suitable for both production and engineering environments.

Robotic systems offer many advantages over other mechanical positioning systems used in antenna measurement applications. Traditional positioning systems are comprised of single axis motion stages, combined to perform measurements in a specific coordinate system. The need to support multiple measurement coordinate systems typically requires a larger number of motion axes, which increases both system complexity and costs. Motion profiles and positioning accuracy are limited by the mechanical specifications of the individual as well as combined stages. In addition, range alignment can be challenging as it is often DUT dependent and may be limited by the positioning system motion or requiring the shimming of individual stages to achieve the desired accuracy.

The 6-axis DOF (degrees of freedom) offered by a robotic arm allows it to provide practically any motion profile within the mobility reach of the arm. A single robot can be programmatically reconfigured to perform antenna measurements in any coordinate system, at varying probe to AUT distances, and for different geometries, both conformal and non-conformal [2]. For example, a single robotic arm can perform planar near-field measurements, not only in vertical or horizontal orientations but over tilted surfaces as well. With the addition of a DUT rotation stage, this same system can now support spherical near-field measurements [3]. Though the reach of the robotic arm is somewhat limited, a single robot can be mounted atop a linear floor slide and/or outfitted with an arm extension to accommodate larger measurement area coverage. Adding a second robot to this type of configuration can provide a measurement system with a dozen motion axes or more, yielding an unlimited number of measurement scenarios [4].

Implementing an RF subsystem for such a measurement system can be challenging as it must be equally reconfigurable, adapting to a multitude of measurement scenarios without sacrificing RF performance. Due to the wide range of motion afforded by a multi-axis robotic system, cable management and phase stability due to RF cable flexure can be problematic. To accommodate different measurement configurations often requires manual reconfiguration of the RF subsystem or duplication of RF components and/or a RF switch matrix to automate this process. The later approach results in increased cost, complexity, and RF path losses, which may impact system performance.

To complicate matters further, there is a growing desire to perform simultaneous RF channel measurements for coherently acquiring both polarization senses and multiple antenna ports. While many modern-day measurement receivers support multi-port channel acquisitions, implementing this functionality on a reconfigurable system can be a challenge due to the increased number of possible measurement scenarios.

NPM has recently implemented a distributed RF subsystem for a 14-axis dual robotic antenna measurement system using distributed multi-port VNA modules to accommodate automatic RF system reconfiguration without sacrificing RF performance. The details of this novel implementation are presented in the subsequent sections.

II. SYSTEM OVERVIEW

The 14-axis dual robotic antenna measurement system is comprised of two 6-axis DOF robotic arms, each mounted atop parallel linear floor slides to allow greater range of motion and positioning within the test chamber, is shown in Figure 1. The system has the capability of supporting both spherical and planar measurement conventions, with a total of six possible system configurations.

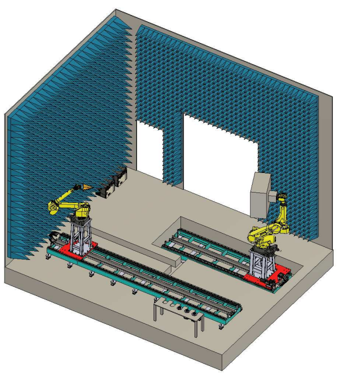

Figure 1. Robots R1 (shown on the left) and R2 (shown on the right) provide positioning of the probe and AUT respectively.

The RF system for this application was required to operate over the frequency ranges of 0.1– 50 GHz and 50- 75 GHz. A common RF system implementation would be to use a benchtop Vector Network Analyzer (VNA) with distributed frequency up and down conversion RF components located close to the probe and AUT to combat excessive RF cable losses. However, this type of RF system design is typically frequency bandwidth limited by these distributed RF components, requiring different operating bands with varying parameter settings and/or paths to cover the entire 0.1 to 50 GHz operating range. To accommodate multiple antenna port measurements or full S-parameter measurement capability, an RF switch matrix is typically used, adding control complexity and requiring additional device characterization for calibration of the various RF paths.

To overcome these limitations, an alternative RF system design using distributed Keysight P500xB Streamline Series USB Vector Network Analyzer modules was implemented. These small, faceless VNA modules provide full S-parameter functionality and performance of a standard benchtop PNA in a compact form factor, allowing them to be remotely located close to the antennas. The P5008B model, used for this application, operates from 100 kHz to 53 GHz, is available in 2-, 4-, or 6-port variants, and weighs less than 3.2kg (7.0 lbs) [5].

A single VNA module can be used in place of a benchtop VNA or combined with other VNA modules to facilitate simultaneous multi-port measurement capability and future system expandability. Figure 2 illustrates how a 6-port VNA system, consisting of a 4-port and a 2-port module, can be easily expanded to a 10-port VNA system with the addition of another 4-port module.

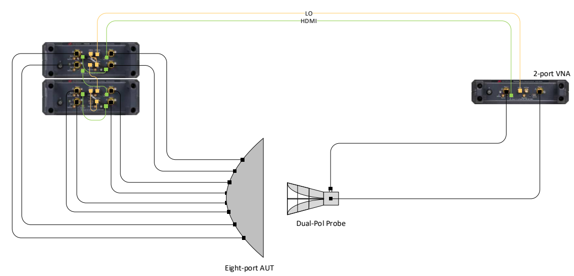

Figure 2. Block diagram of 10-port VNA system using SVNA modules.

III. IMPLEMENTATION

The 0.1 to 50 GHz baseline system was implemented using a 2-port and a 4-port Keysight P5008B Streamline Vector Network Analyzer (SVNA) module to support dual polarization measurements of a 4-port AUT. An additional 4-port module was used to support a stationary gain calibration tower located at the end of the chamber and configured with four standard reference antennas to support automated gain calibration measurements. A wiring diagram of the dual robotic RF system is shown in Figure 3.

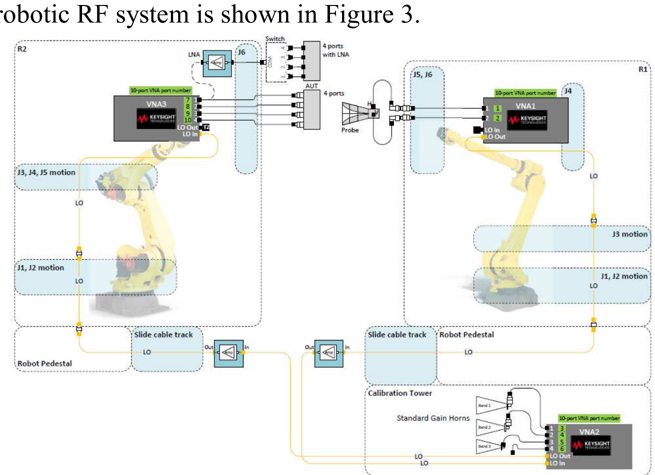

Figure 3. Dual Robotic RF System Wiring Diagram

A common LO signal, generated by VNA1, is distributed to the other VNA modules to provide phase coherency between all the measurement channels. Limiting amplifiers were used in each of the LO paths to provide the appropriate LO power level at VNA2 and VNA3 over the entire frequency operating range. The resulting RF system configuration provides 10-port VNA functionality with 100 S-parameter and 32 transmission measurement possibilities as illustrated in Figure 4.

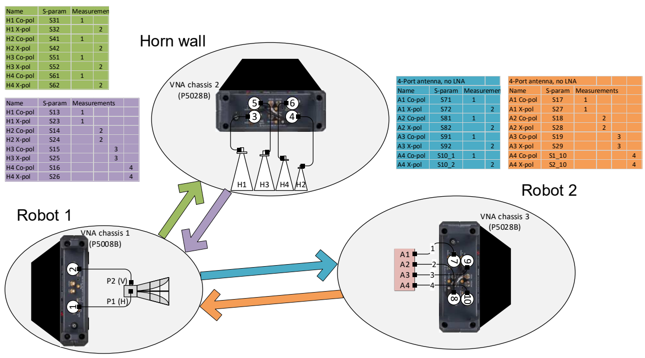

Figure 4. Multi-port S-Parameter Configuration

There are some limitations and considerations when implementing such a multi-VNA module RF system design. A Thunderbolt 3 connection provides control to the VNA modules from the measurement workstation, and HDMI is used for the measurement triggering handshake implementation. One of the modules needs to be designated as the Master for both HDMI and LO distribution to the other modules, which can be connected to the other modules using either a daisy chain or star configuration. Each module has two Thunderbolt 3 ports for connecting HDMI, either of which can be an input or output. The maximum combined length for HDMI 1.4 cable is around 15m (50ft). Exceeding this limit will result in a timing error caused by a delay between measurements using different VNA modules. This error can be overcome by disabling the Auto Gain Ranging on the VNA, and manually setting the gain to either Low or High as one of the signals on the HDMI is an auto-gain range control for each measurement point. The maximum cable length using this approach is unknown to date, but NPM has successfully tested using HDMI cable lengths up to 64m (210 ft).

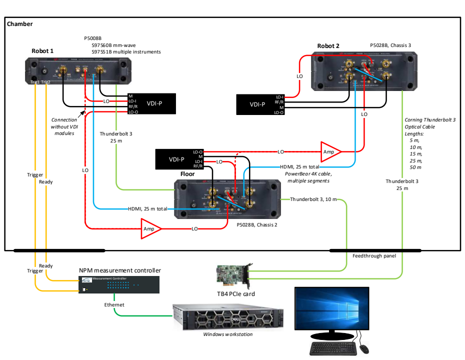

Figure 5. RF System Control Wiring Diagram

IV. MEAUREMENT PERFORMANCE

During the system design process, measurements were conducted to evaluate the performance of the SVNA versus the PNA. The results, displayed in **Figure 6** below, show the SVNA to have lower port output power but greater sensitivity than the PNA, yielding comparable dynamic range performance.

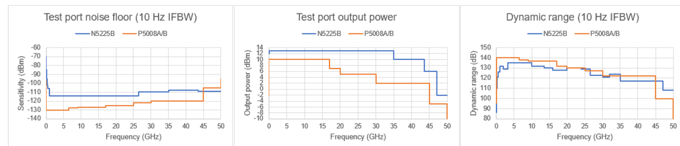

Figure 6. Measured performance comparison of PNA vs. SVNA

Next, a comparison of SVNA versus PNA-X measurement speed was conducted. A comparison of the specification indicates that in narrowband sweep mode, the SVNA measurement throughput is almost x2 that of the PNA. However, in wideband stepped sweep mode, the SVNA is almost x4 faster than the PNA [5,6].

Finally, an RF system performance evaluation of a SVNA versus PNA based system design was made by comparing the estimated RF power link budgets of a 1 – 50 GHz Robotic PNF system with a 1.5m x 1.5m (5 ft x 5 ft) scan plane. For this exercise, an antenna gain of 40 dBi was assumed and the nearfield probe was an OEWG. Four RF system configurations were compared: (1) PNA with external LNA, (2) SVNA with external LNA, (3) dual SVNAs located close to the AUT and probe, and (4) PNA combined with external amplifiers, frequency multipliers, and RF mixers. The calculated SNR versus frequency for a 1 kHz IFBW are shown in Figure 7.

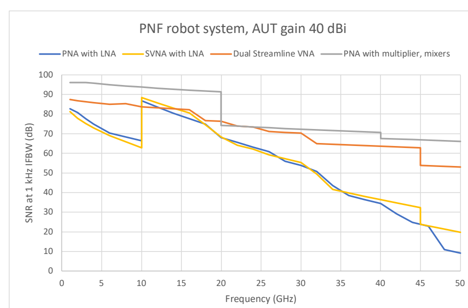

Figure 7. PNF Robot System SNR Performance Comparisons

As predicted, the performance of the PNA with LNA and single SVNA with LNA are very comparable. Comparison of the dual SVNA versus the PNA using external multiplier and mixers show that the frequency distributed PNA system has the potential of providing greater measurement accuracy. However, these types of band limited RF components restrict the continuous frequency sweep of such a system and require parsing the system operating range up into smaller frequency bands with varying operating parameters. For the dual SVNA system, the frequency sweep range is limited only by the SVNA range, which in this case is 100 kHz to 50 GHz.

Based on these evaluations and given the flexibility of the SVNA, the decision was made to use the SVNA for the dual robotic measurement system application. An RF link budget estimation for a nearfield AUT RX measurement using the RF system design described in section III is shown in Figure 8.

Frequency	0.1	1	2	4	6	8	10	15	18	20	20	25	30	35	40	45	50	GHz
RF harmonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
LO harmonic	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
VNA source power setting	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	-10.00	dBm
Cable to probe	-0.11	-0.37	-0.52	-0.75	-0.92	-1.08	-1.21	-1.51	-1.67	-1.76	-1.76	-2.00	-2.21	-2.41	-2.59	-2.77	-2.95	dB
Transmit power at probe	1.89	1.63	1.48	1.25	1.08	0.92	0.79	0.49	0.33	0.24	0.24	0.00	-0.21	-0.41	-0.59	-0.77	-12.95	dBm
Probe gain	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	dBi
AUT gain	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	dBi
Power received at AUT	-12.11	-12.37	-12.52	-12.75	-12.92	-13.08	-13.21	-13.51	-13.67	-13.76	-13.76	-14.00	-14.21	-14.41	-14.59	-14.77	-26.95	dBm
Cable to VNA	-0.25	-0.79	-1.13	-1.63	-2.02	-2.35	-2.65	-3.31	-3.66	-3.88	-3.88	-4.39	-4.86	-5.31	-5.73	-6.13	-6.52	dB
Power at VNA	-12.36	-13.16	-13.66	-14.38	-14.94	-15.43	-15.87	-16.82	-17.32	-17.64	-17.64	-18.38	-19.07	-19.71	-20.32	-20.90	-33.46	dBm
VNA sensitivity, 1 kHz IFBW	-110	-110	-110	-110	-110	-108	-107	-107	-105	-105	-105	-105	-102	-100	-100	-100	-85	dBm
VNA compression level	-12	-12	-12	-12	-12	-12	-12	-12	-13	-13	-13	-15	-15	-18	-18	-18	-25	dBm
SNR, 1 kHz IFBW	**98**	**97**	**96**	**96**	**95**	**93**	**91**	**90**	**88**	**87**	**87**	**87**	**83**	**80**	**80**	**79**	**52**	**dB**
SNR, 100 Hz IFBW	**108**	**107**	**106**	**106**	**105**	**103**	**101**	**100**	**98**	**97**	**97**	**97**	**93**	**90**	**90**	**89**	**62**	**dB**
SNR, 10 Hz IFBW	**118**	**117**	**116**	**116**	**115**	**113**	**111**	**110**	**108**	**107**	**107**	**107**	**103**	**100**	**100**	**99**	**72**	**dB**

Figure 8. Dual Robotic RF System RF Power Link Budget Estimation, AUT Rx

It should be noted that the P5008B VNA Module source output power is limited at 50 GHz and above, attributing to the drop in the SNR performance at the upper end of the frequency operating range. This can be overcome by adding an LNA and 4-port switch at the AUT output as shown in Figure 3, but at the sacrifice of performing simultaneous AUT port measurements.

Gain calibration is another consideration when evaluating the benefits of a distributed SVNA system. Multi-port AUT measurements using a traditional PNA system with a RF PIN switch at the AUT result in RF paths of different loss due to the PIN switch port tracking error. Vendor test data for a 50 GHz 4-port switch reveals this can be up to 1.5 dB difference between ports. This error must be corrected during the gain calculation process.

On the SVNA, each measurement port has its own S-parameter, allowing individual port calibration to be handled by the VNA. A full 10-port calibration would allow making fully error corrected transmission and reflection measurements, but at the cost of increased measurement times (as this requires both forward and reverse sweeps) and a lengthy calibration process. However, a simple response calibration of each path will not only compensate for cable frequency response but remove the difference between individual cables and VNA ports. Thus, SVNA modules provide for the capability of performing a calibration right at the AUT and probe input cables, eliminating the need to externally characterize additional devices, such as RF switches, and incorporating these corrections during gain calibration processing.

Measurements were conducted to evaluate the port-to-port tracking on a 10-port SVNA system using the configuration shown in Figure 9, with the blue path indicating the LO cabling between modules.

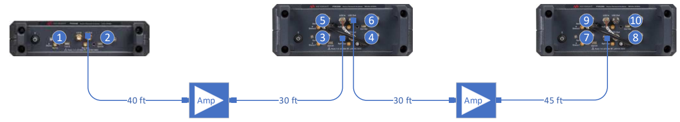

Figure 9. Test configuration for multiple SVNA 10-port tracking verification measurement

A 0.9m (3 ft) 50 GHz RF cable, -15 dBm output power, and 1 kHz IFBW were used to measure each of the S-parameter amplitude frequency responses shown in Figure 10(a). The resulting port-to-port amplitude deltas, illustrated in Figure 10(b), indicate the multi-SVNA system port-to-port tracking to be on par with the PNA and an external PIN switch.

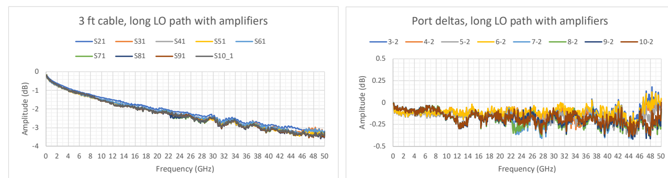

Figure 10. (a) Amplitude frequency response for 10-port VNA, (b) Port-to-port amplitude deltas.

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V. CONCLUSION

Presented here was a novel distributed RF system design concept for a flexible, highly reconfigurable antenna measurement system based on COTS SVNA modules. Multiple SVNA modules are used to provide multi-port S-parameter capability for a variety of measurement scenarios over a wide frequency operating range, eliminating the need for additional frequency band limited RF components and varying operating parameters. Locating SVNA modules close to the source antenna and AUT not only eliminates RF path loss but increases RF stability incurred by cable temperature and motion effects [7]. Not only can these modules be easily reconfigured through software, but they can also be used for performing full s-parameter calibrations and measurements directly at the antenna port(s). This scalable system architecture also provides for a cost-effective upgrade path to accommodate future measurement requirements.

REFERENCES

[1] Joshua A. Gordon, David R. Novotny, Michael Francis, Ron Wittmann, Miranda Butler, Jeffery R. Guerrieri, "The CROMMA Facility at NIST Boulder: A Unified Coordinated Metrology Space for Millimeter-Wave Antenna Characterization", *Proc. Antenna Meas. Tech. Assoc.*, 2014J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Daniël Janse Van Rensburg, Brett Walkenhorst, Quang Ton, John Demas, "A Robotic Near-Field Antenna Test System Relying on Non-Canonical Transformation Techniques", AMTA 2019 Proceedings, October 2019

[3] J. Hatzis, P. Pelland, and G. Hindman, "Implementation of a Combination Planar and Spherical Near-field Antenna Measurement System using an Industrial 6-axis Robot", AMTA 2016 Proceedings, pp. 1-6, 2016

[4] David Novotny, Joshua Gordon, Alexandria Curtin, Michael Allum, Jeffrey Guerrieri, Kim Hassett, Quang Ton, George McAdams, "A Multi-Robot Large Antenna Positioning System for Over-The-Air Testing at the National Institute of Standards and Technology", AMTA 2017 Proceedings, October 2017

[5] Kesyight Streamline Series Vector Network Analyzer (B-models), Publication 3121-1235.EN, June 14 2024

[6] Keysight 2-Port and 4-Port PNA Network Analyzer, Publication 9018-03959, August 22 2023

[7] Roland Moch, Thomas Gemmer, Dirk Heberling, "Amplitude and Phase Uncertainty Analysis due to Cable Flexing in Robot-Based Measurement Systems", AMTA 2020 Proceedings, November 2020