Robotic Evaluation of Commercial Space Performance

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Abstract

The ability to consistently and repeatedly conduct comprehensive and accurate surveys of building performance has been a challenge for many years. Most building audits are accomplished by taking a few handheld measurements, and only involve measuring one component of building system performance—e.g., light levels; heating, ventilating, and air conditioning (HVAC) performance; temperature—at a time. To address this problem, the Electric Power Research Institute (EPRI) developed the Autonomous Mobile Measurement Platform (AMMP). AMMP allows for the repeatable simultaneous measurements of multiple building conditions such as lighting, thermal signatures, Electro-magnetic Interference (EMI), temperature, and air quality. AMMP uses precision LIDAR (Light Detection and Ranging) or high resolution GPS (Global Positioning System) paired with an array of sensors to fully map the space it is evaluating in a single pass. Once AMMP has been driven through a space once, it can be returned to conduct follow up measurements in autonomous mode via waypoint guides. The robotic platform can also be retooled with different sensors to collect additional data sets as needs arise. This paper will focus on how AMMP can be used to conduct highly accurate and repeatable building surveys to measure changes or anomalies in building performance. These surveys can help identify how the building can be adjusted to better align with codes and standards, and identify potential efficiency improvements. In addition, AMMP surveys can provide a means to identify sources of problems, such as EMI or air quality, that may arise within a space.

Background

Comprehensive and highly accurate surveys of the many aspects of building performance are needed to fully understand conditions and factors that affect building energy performance. Unfortunately, such detailed and thorough surveys are rare because they are expensive and time-intensive. As a result, the majority of building surveys are completed using single-function, hand-held meters or devices to make a few sparse measurements within the space. These few data points are then often extrapolated by the surveyor to create a model for the entire space. These surveys thus have limited accuracy, which can be exacerbated when re-surveys are required – especially if the location of the original measurements were not well documented. This type of survey and reporting can lead to inaccuracy in findings and gaps within models and surveys. In addition, because some space conditions may not be measured at all, problematic conditions or abnormal performance characteristics may not be accurately identified or located. As a result, there is often a need to conduct additional or multiple surveys to identify, fully evaluate, understand and address issues within a building. Repeating surveys result in wasted hours and effort by utility engineers, building owners, contractors, and tenants.

The difficulties associated with conducting field surveys are an important issue, because highly accurate, highly efficient, repeatable and complete surveys are needed by utilities, building owners, contractors, government officials, and researchers for a range of needs, including:

- energy efficiency evaluation
- verification of building performance
- certification of buildings for regulation and standards purposes
- creation of accurate building models
- measurement of changes in product or system performance over time
- location of problematic or inferior performing technologies or systems
- identification of conflicting technologies or systems
- the accurate evaluation of the impact of technologies pre and post retrofit

Additionally, with the automation of the survey process, accurate and complete building surveys may assist with identifying and addressing unsafe or unhealthy conditions. This benefit can be especially useful when the risk is unknown at the time of survey.

EPRI is a 501C which has conducted collaborative research for the utility industry in a range of areas for over 40 years. Some of the areas in which EPRI conducts research include:

- power generation, transmission and distribution
- nuclear generation
- energy utilization, including the impact of end use technology on power quality, radiated and conducted emissions, and energy efficiency
- demand response and energy storage
- environmental conditions such as air quality

To support these varied types of utility research, EPRI has been required to conduct a large number of field surveys and field tests in recent years. Given this requirement and the challenges discussed above, EPRI identified a need for a robotic platform capable of conducting highly accurate and repeatable building energy surveys. To ensure quality findings, EPRI determined that such a robotic platform would need to be capable of collecting large amounts of data while still being flexible enough to provide a detailed understanding of the operation and performance of a range of technologies and products within a space. Since nothing like this was commercial available, EPRI began its own effort to build a system to meet these needs.

In recent years, EPRI has received a large number of questions from utilities regarding the operation and performance of light-emitting diode (LED) based lighting. Many of these questions revolve around the real-world performance of LEDs, as well as their color stability and lifespan. To address these and other questions regarding LED street and area lighting, EPRI developed a high-accuracy robot named "Scotty[1]" in 2009. Scotty is an outdoor lighting measurement tool which an engineer remotely controls to measure light in a precise grid. This precision is achieved by use of a high resolution, survey-grade global positioning system (GPS), which allows an operator to return with Scotty numerous times and accurately plot multiple light readings to determine differences in light output. This reliance on high resolution GPS signals results in Scotty being most effective when used in outdoor locations with clear access to the sky; the system is not as useful in dense urban or indoor environments. As a result, Scotty

[1] Named after the robotics system architect and primary user during the project.

has been used primarily to plot light levels of LED streetlights. In spite of its limitations, Scotty has successfully generated a wealth of valuable information regarding real-world LED performance and operation, some of which has been used by the U.S. Department of Energy (DOE).

Although Scotty's performance is exceptional, the robot's usefulness is limited in scope and scale. The ability to take measurements indoors, as well as outdoors, is important in many applications. Additionally, with the expansion of the number of deployed and connected loads, it has become critical to evaluate the interactions of various technologies and systems. This type of flexibility and functionality allows the surveyor or evaluator to understand, and if needed address; a range of issues in a timely fashion regardless of the application. Additionally, this type of analysis allows for the identification of conflicting devices, forces, and fields, while also verifying the performance levels to ensure compliance with local, state, and federal standards or facility requirements.

To address these issues, EPRI began working in 2015 to develop an expanded robotic platform, building on the concepts utilized in Scotty. From this starting point, EPRI team members spent several months developing an in-depth design, performance, and assembly concept. Once the scope of this new platform was established, it was noted that the new platform would be significantly different than the Scotty platform. As a result, it was determined that this platform should have a different name. The name AMMP (Autonomous Mobile Measurement Platform) was selected as it conveyed the core nature and scope of this new robot.

Because the design team was building on experience from Scotty, AMMP first focused on the indoor measurement of light levels and spectrum. However, the new platform was designed to measure a range of conditions and factors. The ability to add and remove sensors or monitors to the robot was a key project driver. Another key platform requirement was the ability for the robot to operate autonomously, allowing for quick and precise repeatable measurements at later dates. When operating in autonomous mode, EPRI recommends human supervision, *if possible*, to address obstacles like doors and unforeseen issues.

Regarding navigation and positioning, high resolution GPS was determined to still be the most viable solution for *outdoor use*. Since high resolution GPS is not a viable solution for indoor measurements, however, other means of mapping, orientation, and navigation were explored for *indoor* use. Three of the most promising methods were Wi-Fi localization, line-following robots, and LIDAR (Light Detection And Ranging) surveying technology.

Wi-Fi localization utilizes a connection between the robot and wireless access points. This solution typically delivers an accuracy of one to four meters depending on the location. Wi-Fi localization was not deemed to be accurate enough for this new platform. Line-following robots (which are designed to follow a path predetermined by the user) are highly accurate and simple to program, but require lines or tracks to be placed at each measurement site. This is inconvenient and time-consuming, and was ultimately determined to be too inefficient for this platform. Ultimately, LIDAR technology was chosen based on its accuracy and adaptability, as well as its ability to be configured to identify and avoid building occupants and movable objects. LIDAR technology also provides the ability to generate a near real-time map of the space that enable collected measurements to be plotted once a survey is complete.

Figure 1 provides an overview of the operation of AMMP and how the sensors interact with each other.

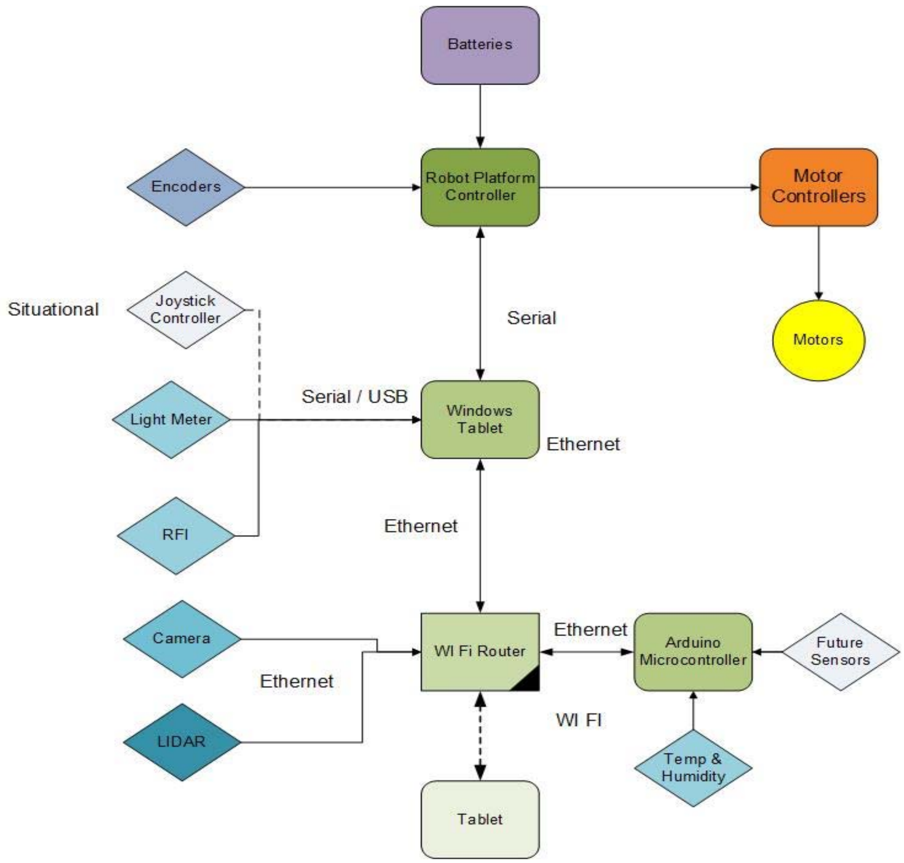


Figure 1. Overview of AMMP robot system.

Concept

EPRI's AMMP is an automated robot developed to meet the ever-expanding and changing needs of field site measurement equipment. This can include measuring ongoing performance of field technologies, intensity and spectral output of lighting, EMI emissions of technologies, thermal and humidity conditions, strength of Wi-Fi signals, air quality conditions and a variety of other parameters. AMMP provides a highly versatile and mobile platform for taking field measurements with a high level of accuracy and precision. Once the space has been initially measured by the operator driving AMMP via a wireless controller, the ability to operate autonomously allows AMMP to repeatedly and precisely measure locations with minimal human effort sans human supervision to address doors and unforeseen issues. System precision comes from the dynamic use of a LIDAR and/or GPS system that allows the platform to avoid obstacles (including people), and still reach specified measurement destinations. AMMP's repeatable precision allows for the re-visitation of locations for accurate data comparison and mapping over time. The pairing of a flexibility integrated sensor platform with the ability to repeatedly measure the same location allows for the large scale and long-term collection of data from similar field sites. This further expands the potential for data comparison.

In addition to precision measurement, AMMP has the ability to be driven by wireless control to destinations that are deemed unsafe or in which a human cannot fit. This versatility gives AMMP the capability to acquire data in places that historically have required special equipment or procedures as well as collect data in more accessible locations without interrupting building or facility operations. Figure 2 provides a photograph of AMMP.


Figure 2. AMMP prototype image.

As noted previously, AMMP was designed for interchangeability in measurement equipment. This allows the operator to easily and quickly change from one measurement device to another without completely breaking down the platform. Even after the change or retrofit of measurement equipment and/or sensors, AMMP is capable of autonomous operation using its positioning hardware and software. This functionality enables high-precision data collection with minimal human error. The AMMP platform also provides a vast amount of field data that must be digested and analyzed before being presented. This will be achieved via custom software which compiles collected data into a standard format on the onboard tablet.

In addition to these capabilities, the AMMP system is relatively simple to assemble and use, and can be packed and shipped in three cases. Overall, the AMMP system provides for precise measurement of a variety of data types. The measurement equipment outfitted on the platform provides a versatile structure to evaluate different conditions, current state, and technology performance at a variety of field sites.

Operation

Designed with portability and ease of use in mind, AMMP can be disassembled and shipped in custom shipping cases; (as noted above). A trained user can fully assemble AMMP in about 30 minutes. Once the hardware is configured, the platform software is launched. The majority of AMMP's operations are performed through the custom EPRI-developed AMMP Data Collector program. This software is designed so new measurement devices can be incorporated into the AMMP system via minor software tweaks to accommodate different data logging systems. The program provides three major functions:

- Hosting of the robot's server;
- Communicating with measurement devices; and
- Logging of incoming data.

Once the meters are connected, the user starts the robot server and is ready to begin creating a map of the space. Before AMMP can autonomously navigate through a building, the user must drive the robot through the space to create a map for navigation. Via an onboard application, the user starts a scan and drives the robot through the space using a wireless controller. This allows the LIDAR to initially plot the areas to be measured. This is the most important part of the process because, if a complete map is not created, the robot will get lost and have difficulty navigating the space on future surveys. It is generally beneficial for the user to drive the robot through a space multiple times to assure complete mapping. The length of this process obviously depends on building size, but typically ranges from ten minutes to one hour. Below in Figure 3 is an example map which shows a commercial office space. Note that walls, obstacles, hallways, and doors can be easily identified for reference. The teal dots on Figure 3 represent measurement locations within the space. Once oriented to the space, AMMP is fully capable of returning to any and all of these "dots" without human control, with minimal human supervision, and conduct additional or repeated measurements. Note, AMMP is programmed to avoid mobile or "new" objects (including humans) when in autonomous mode.

Figure 3. Example building map.

Once the map scan is saved and processed, the user sets goal / way points on the map for the robot to autonomously traverse. Human supervision is only needed to address unforeseen issues, or doors, in follow up surveys. The user can also set boundaries and restricted areas to keep the robot from travelling outside of desired areas. The finalized map can then be uploaded and waypoints entered for autonomous navigation. Measurements are taken throughout the survey, at a rate ranging from one measurement every two seconds to one measurement every ten minutes. AMMP can also be programmed to move faster or slower depending the data detail desired. Once the robot visits all assigned waypoints, the data recording is saved for analysis.

Data is logged and saved to the onboard tablet for export and analysis. As noted above, AMMP utilizes a custom data collector program to interface and log the streaming measurement data. Figure 4 shows the spectrum data from a representative lighting measurement, and Figure 5 is an example of how collected data is formatted.

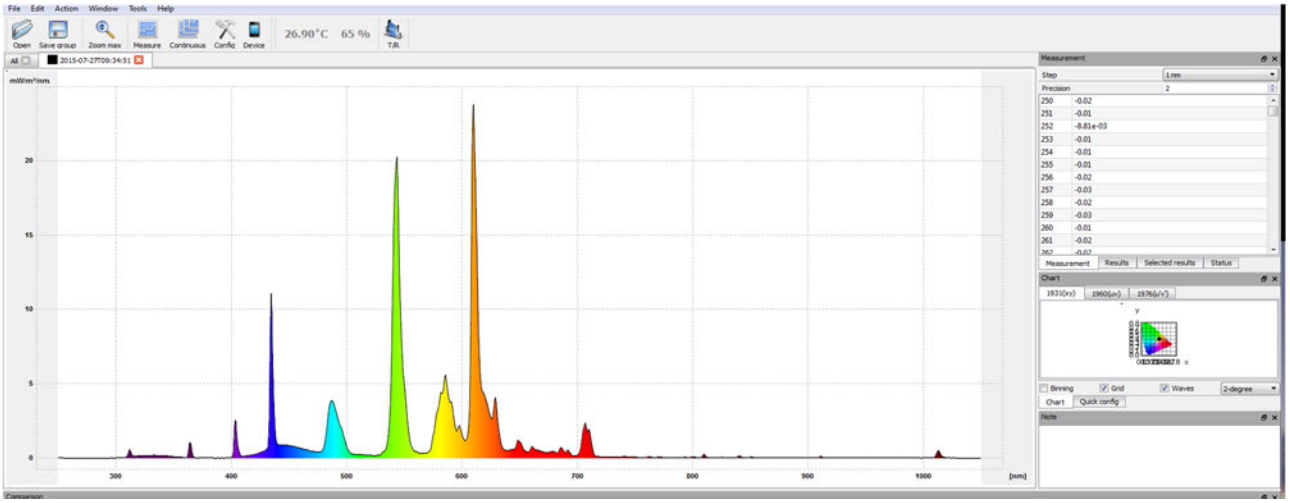
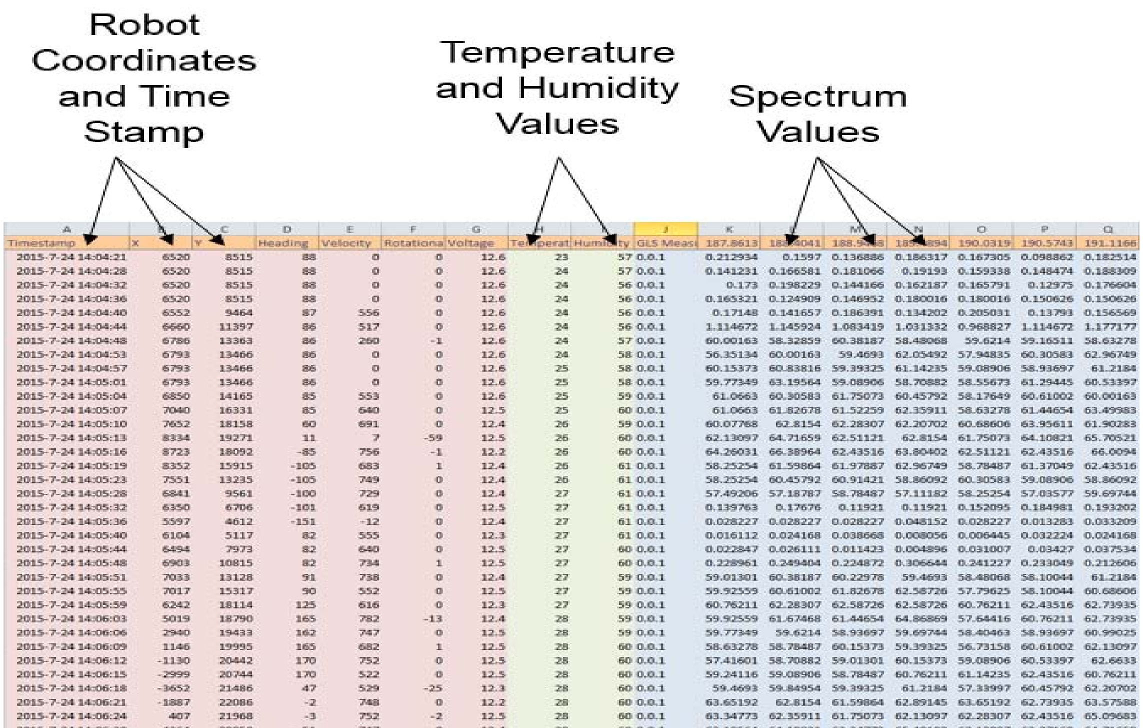


Figure 4. Light spectrum data.



Timestamp	X	Y	Heading	Velocity	Rotationa	Voltage	Te[illegible]perat	Humi[illegible]ty	GLS Meas	187.8613	18[illegible]4041	188.9[illegible]8	18[illegible]894	190.0319	190.5743	191.1166
2015-7-24 14:04:21	6520	8515	88	0	0	12.6	23	57	0.0.1	0.212934	0.1597	0.136886	0.186317	0.167305	0.098862	0.182514
2015-7-24 14:04:28	6520	8515	88	0	0	12.6	24	57	0.0.1	0.141231	0.166581	0.181066	0.19193	0.159338	0.148474	0.188309
2015-7-24 14:04:32	6520	8515	88	0	0	12.6	24	56	0.0.1	0.173	0.198229	0.144166	0.162187	0.165791	0.12975	0.176604
2015-7-24 14:04:36	6520	8515	88	0	0	12.6	24	56	0.0.1	0.165321	0.124909	0.146952	0.180016	0.180016	0.150626	0.150626
2015-7-24 14:04:40	6552	9464	87	556	0	12.6	24	56	0.0.1	0.17148	0.141657	0.186391	0.134202	0.205031	0.13793	0.156569
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2015-7-24 14:04:57	6793	13466	86	0	0	12.6	25	58	0.0.1	60.15373	60.83816	59.39325	61.14235	59.08906	58.93697	61.2184
2015-7-24 14:05:01	6793	13466	86	0	0	12.6	25	58	0.0.1	59.77349	63.19564	59.08906	58.70882	58.55673	61.29445	60.53397
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2015-7-24 14:05:13	8334	19271	11	7	-59	12.5	26	60	0.0.1	62.13097	64.71659	62.51121	62.8154	61.75073	64.10821	65.70521
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2015-7-24 14:05:19	8352	15915	-105	683	1	12.4	26	61	0.0.1	58.25254	61.59864	61.97887	62.96749	58.78487	61.37049	62.43516
2015-7-24 14:05:23	7551	13235	-105	749	0	12.4	26	61	0.0.1	58.25254	60.45792	60.91421	58.86092	60.30583	59.08906	58.86092
2015-7-24 14:05:28	6841	9561	-100	729	0	12.4	27	61	0.0.1	57.49206	57.18787	58.78487	57.11182	58.25254	57.03577	59.69744
2015-7-24 14:05:32	6350	6706	-101	619	0	12.5	27	61	0.0.1	0.139763	0.17676	0.11921	0.11921	0.152095	0.184981	0.193202
2015-7-24 14:05:36	5597	4612	-151	-12	0	12.4	27	61	0.0.1	0.028227	0.028227	0.028227	0.048152	0.028227	0.013283	0.033209
2015-7-24 14:05:40	6104	5117	82	555	0	12.3	27	61	0.0.1	0.016112	0.024168	0.038668	0.008056	0.006445	0.032224	0.024168
2015-7-24 14:05:44	6494	7973	82	640	0	12.5	27	60	0.0.1	0.022847	0.026111	0.011423	0.004896	0.031007	0.03427	0.037534
2015-7-24 14:05:48	6903	10815	82	734	1	12.5	27	60	0.0.1	0.228961	0.249404	0.224872	0.306644	0.241227	0.233049	0.212606
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2015-7-24 14:05:55	7017	15317	90	552	0	12.5	27	59	0.0.1	59.92559	60.61002	61.82678	62.58726	57.79625	58.10044	60.68606
2015-7-24 14:05:59	6242	18114	125	616	0	12.3	27	59	0.0.1	60.76211	62.28307	62.58726	62.58726	60.76211	62.43516	62.73935
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2015-7-24 14:06:21	-1887	22086	-2	748	0	12.2	28	60	0.0.1	63.65192	62.8154	61.59864	62.89145	63.65192	62.73935	63.57588
2015-7-24 14:06:24	407	21968	-3	752	-2	12.5	28	60	0.0.1	63.34773	62.35911	61.75073	62.13097	62.28307	62.43516	65.09683
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Figure 5. Formatted AMMP data.

After the survey has been completed, the user can open the raw data file to verify that the correct data was captured. EPRI is working to develop enhanced visualization and embedded reporting software to aid in data analysis.

The visualization software will be designed so the user can examine the entire map of the measured building with the measurement data overlaid. The user will be able to alternate between which collected data sets (temperature, light levels, etc.) are overlaid on the map. Additionally, the user will be able to manually select a range or limitation where only data over/under the limit is shown. This software will enable the user to quickly draw conclusions. The EPRI team also plans to develop additional software to provide a site report – including maps and graphics – soon after survey completion.

Results

Previous sections of this document have explained the concept, design and operation of AMMP. The following section will show the results of the data collected and developed during AMMP's evaluation and testing process. These images represent just a portion of the potential measurements that AMMP can make, but they provide insight to the potential of AMMP.

Figure 6 combines the location data provided by AMMP with light level data collected from the onboard spectrometer. This combination of data produces a map of light levels within a space. The axis on the left represents lux levels within the space and the bottom axes represent the location (X-Y coordinates) of the measurement. This type of measurement can be used to locate areas that are above or below the required standards or the design guidelines.

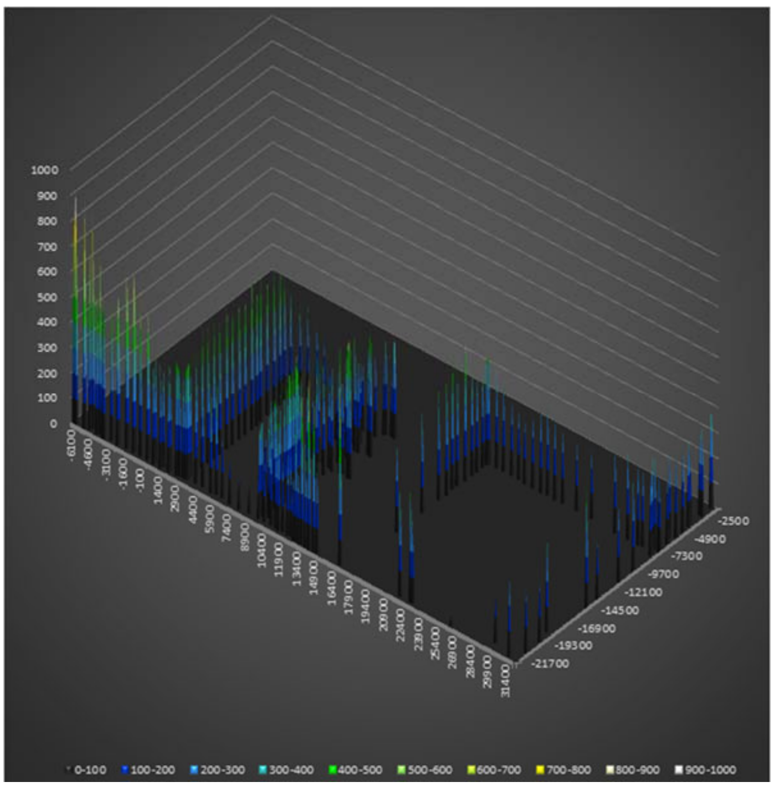

Figure 6. Plot of light (lux) levels within a space – represented in X/Y coordinates.

Below are two maps generated by AMMP as it surveyed a space. Note that the maps show the locations of walls, doors, spaces and furniture and other obstacles. AMMP's LIDAR identifies these objects (including building occupants which it is programmed to avoid) and then uses this raw data to create the map of the surveyed spaces. Each measurement point shown on the maps below contains more than 1100 points of sensor data; the survey data sets thus each contain more than 100,000 data points. Once initially mapped, each follow up autonomous survey took approximately 20 minutes to complete.

The first image/map (Figure 7) shows the X and Y coordinates in relationship to assigned measurement points or waypoints, represented by red dots, to which AMMP can be sent back autonomously. This map shows a building which is approximately 50,000 square feet and is a mixed use facility with office and warehouse space. The second image (Figure 8) shows a similar AMMP generated map. This image covers a sub-portion of the space in Figure 7, and includes the overlapping positioning of three runs of AMMP to check accuracy and repeatability. Each survey run is shown by a different color data point on this map.

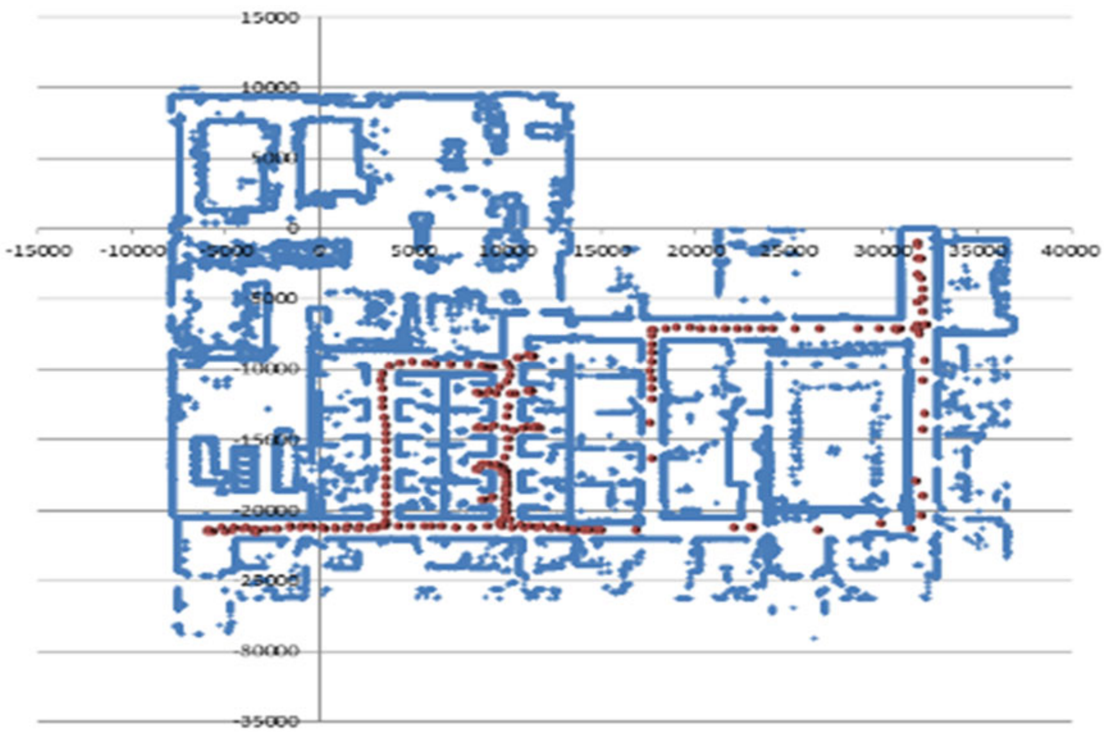

Figure 7. Building plot represented in X/Y coordinates – with waypoints designated.

Figure 8. Partial building plot with multiple measurement paths plotted.

The following images show a range of maps and findings generated using AMMP data. Figure 9 is a generated map along with an assigned path for measurement (shown by teal dots). This map shows the results of an AMMP survey of the same space that was shown in Figure 7, but in full autonomous mode. Note that this map also includes an area of outdoor space in the lower portion of the image, and shows the shrubbery and vehicles along the front of the building. This ability to include interior and exterior areas in the same survey demonstrates AMMP's versatility. During this survey, AMMP stopped at each assigned point and conducted a full series of measurements before moving on to the next. Figure 10 shows the generated map of a warehouse/laboratory space in which light levels are noted. On this map the red dots represent light levels around the 400 lux level, green dots represent light levels around the 60 lux level, and blue dots represent light levels around or below the 30 lux level. This map also shows the software's ability to assign color shades to show variance. On the final image in this series, Figure 11, the same warehouse/lab space was evaluated for variance above or below a set Kelvin temperature. On this map, the darkest dots represent about 4500K CCT light, where the lightest dots represent 3500K CCT light. This map was generated using the same map as Figure 10, but with a different set of criteria selected for comparison. These figures illustrate how one survey can be used to measure a range of conditions or values by changing the data being compared. Furthermore, the maps show the systems potential for repeated measurement and comparison over time.

Figure 9. AMMP generated map with measurement path highlighted.

Figure 10. Map of light levels above or below target.

Figure 11. Map of color temperature variance within a space.

Recently, AMMP has also been expanded to measure radiated EMI by integrating an on-board spectrum analyzer. Initial tests and measurements have been completed and the data is being analyzed. The team is working on visualization methods for the recorded EMI data. Spatial recording of EMI spectrum data is expected to be very useful in helping to pinpoint, diagnose and solve EMI issues in industrial, commercial, residential, and power generation settings. Furthermore, this will allow for verification that the EMI issues have been mitigated after corrective measures have been taken. The expansion of AMMP's measurement capabilities into the EMI realm illustrates the flexibility and potential of this platform.

Current Status and Next Steps

As noted in this report, AMMP is still being developed. However, even at this stage its potential to conduct highly accurate building performance, energy efficiency, environmental, emissions, and thermal surveys has been clearly demonstrated. Regardless of the sensors attached, the amount of data that AMMP collects is several orders of magnitude above that delivered by a traditional site survey. For lighting, this allows the user to more accurately monitor the degradation of light over time, which is specifically important for assessing the lifetime of LEDs. For EMI, this level of data allows for the accurate location of problematic and offending emissions. As a result, AMMP allows the surveyor to determine where emissions emanate and how far they radiate. For temperature and humidity measurements, areas that are not being properly conditioned can be precisely located. This highly accurate level of data collection alone is impressive, but the fact that AMMP can measure and collect data on several conditions simultaneously -- while allowing engineers to identify any interactions between conditions and operations -- is what makes AMMP truly unique. Another key factor is AMMP's ability to quickly incorporate new sensors with minimum compatibility checks and simple modifications to AMMP's data collection program. Combined this functionality and versatility provides utilities, building surveyors, building managers, and engineers with the ability to identify areas, systems, and issues within building operations which can be targeted for energy savings, for operational improvements, or for evaluation over time to monitor changes. These findings can lead directly to noticeable energy savings, cost reductions and verification of value.

The next steps in AMMP's progress will include the development of an easy to use software interface for data compilation, data processing, and report generation. As noted, EPRI is also actively working to expand the number of sensors and meters which work with AMMP. These steps will further expand the versatility and usefulness of AMMP, while allowing EPRI to better understand the market value of a AMMP survey. This process is on-going, and EPRI has submitted a proposal to DOE to accelerate this work and also to pair AMMP with other systems to create even more highly detailed surveys in a more efficient and high speed manner.

Conclusions

As noted earlier, most site surveys today are simple processes utilizing hand-held devices that measure a single condition. AMMP's focus is to replace this process by quickly and repeatedly measuring a range of conditions at random or specific locations with high accuracy via robotic means. This flexibility and uniqueness means AMMP can be used to carry out simple to complex projects that require precise measurements at designated locations.

Today, AMMP is a viable, but developing, platform well positioned to provide a base for autonomously measuring and storing vast amounts of repeatable and verifiable measurement data at precise locations, in a range of conditions and situations, and from a range of sensors or measurement tools simultaneously. This results in a system that utilities, building owners, efficiency engineers, integrators, and government agencies can utilize to identify and address spaces, systems, technologies, and conditions that can be improved from an efficiency, codes, or operational perspective. AMMP also provides a means for the repeated measurement of systems and technologies to determine the impact of changes and retrofits.

The identification of these efficiency opportunities, code variances, installation inconsistencies, and technology variations, as well as the ability to perform repeated survey's over time, should allow for reduced energy usage and overall improved building performance. As a result, facility managers, building owners, space occupants and utilities all receive benefit, while achieving equal or improved conditions within the evaluated space. This is achievable as a result of the adaptability and versatility of the AMMP system, which allows it to perform various functions easily by interchanging meters, sensors, and components on the chassis.

Currently, AMMP enables the measurement of select conditions: light, EMI, and temperature/humidity. EPRI is working to add additional functionality to AMMP such as measurement of CO^2, SO^2 level assessment, air quality values, high accuracy temperature readings, thermal imaging, radiation detectors, and other various detectors. The speed and priority of these expansions will be driven by utility, industry and business needs, but will result in a robust system capable of a wide range of measurement and evaluation. These platform expansions will also help EPRI learn the market value of using AMMP in the field, as currently AMMP is used exclusively by EPRI for in-house projects.

This expanded functionality, combined with the remote controllability of AMMP, may also allow the platform to safely measure hazardous or toxic areas with limited to no human exposure. An example of this would be AMMP entering, measuring and returning from a toxic air environment while being remotely guided using onboard video. AMMP can also be used to take environmental readings of air quality, or other factors, to assure compliance with Occupational Safety and Health Administration (OSHA) standards. Similar measurements could also be performed around waste ponds, generation facilities, sanitation plants, agricultural facilities, and chemical processing plants to ensure general safety. Business and industry could use such measurements to ensure that air quality levels meet the requirements for delivering consistent production (i.e., clean rooms and other environmentally controlled spaces) and safety (e.g., hospital rooms, nursing homes). To conduct these and other, quality, safety and security measurements, the current chassis would only require minimal changes or additions of equipment. It should also be noted that EPRI has already begun the work of conceptually designing other AMMP platforms based on the current design which can accommodate sensor packs and elements which cannot fit the current chassis due to payload limitations.