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Automated USMN Integration for Precision Robotics and Large-Scale Metrology

Seemal Asif[1[0000-0001-7048-0183]] , Emmanuel Izuwa[1[0009-0005-4822-6783]], Daniela Sawyer[2[0009-0001-0056-2578]] and Christopher Burkinshaw[2[0009-0007-5209-8248]]

[1] Centre for Robotics and Assembly, Cranfield University, Cranfield MK43 0AL, UK
[2] University of Sheffield, AMRC, Factory 2050, Sheffield, S9 1ZA, UK
s.asif@cranfield.ac.uk

Abstract. This study introduces a novel automation framework for the integration of the Unified Spatial Metrology Network (USMN) across Spatial Analyzer (SA) and PolyWorks (PW), addressing critical inefficiencies in manual metrology workflows. Traditional methods for USMN execution and data translation between platforms are labor-intensive, error-prone, and time-consuming. The proposed system automates data transfer, reference point alignment, and coordinate calibration, incorporating real-time error detection to ensure spatial coherence and enhance measurement accuracy. This approach significantly reduces processing time from days to minutes, mitigates human error, and standardizes inter-software interoperability, while maintaining residual RMS error within ≤ 0.02mm. Application of this framework to large-scale robotic systems—common in aerospace, shipbuilding, and automotive manufacturing—demonstrates improved precision in automated tasks such as assembly, drilling, and alignment. By enabling seamless integration of multiple spatial instruments, the framework enhances the robustness and repeatability of high-precision measurements. This advancement represents a pivotal contribution to metrology automation and scalable, real-time calibration in complex industrial environments.

Keywords: Unified Spatial Metrology Network (USMN), Spatial Analyzer, PolyWorks, Metrology Automation, Measurement Accuracy, Reference Point Calibration, Coordinate System Normalisation, Laser Tracker, High-Precision Metrology, Large-Scale Engineering, Robotic Automation

1 Introduction

Metrology serves as a fundamental pillar in precision engineering and manufacturing, providing essential measurement data necessary for quality assurance, process optimisation, and innovation.[1] The significance of metrology software in industrial applications cannot be overstated, as these tools provide the framework for accurate spatial measurements and data interpretation.[2]

Spatial Analyzer (SA) [3] is widely regarded as a comprehensive metrology tool, particularly due to its Unified Spatial Metrology Network (USMN) functionality. The USMN is essential in high-precision spatial measurement for large-scale engineering applications, as demonstrated in the EAST project.[4] The EAST project, a large superconducting Tokamak device, required an advanced spatial metrology network to achieve precise alignment of its intricate components. Given its complex assembly involving both internal and external structures, a unified measurement framework was essential to maintain spatial consistency and accuracy. In large-scale engineering projects, USMN ensures seamless integration of multiple measurement systems, reducing discrepancies and improving precision. It mitigates environmental influences, such as temperature fluctuations, that can impact measurement stability. SA was used due to its compliance with ISO standards, robust uncertainty analysis capabilities, and ability to integrate data from diverse metrology instruments, ensuring high-precision measurements and traceability.[4] However, the dominance of SA in the metrology sector presents challenges, particularly when integrating its outputs with other software solutions such as PolyWorks (PW).[5] The absence of USMN capabilities in PW presents significant challenges in large-scale metrology applications. USMN is essential for integrating multiple measurement instruments into a cohesive coordinate system, reducing uncertainties and ensuring precise calibration of reference points and large components. In contrast, PW, while renowned for its advanced scanning capabilities, lacks inherent USMN functionality. Consequently, practitioners often perform USMN within SA and subsequently import the data into PW for further analysis. This process is time-consuming—potentially requiring a week for USMN execution in SA and an additional two days for data integration into PW, depending on the setup size. The absence of USMN in PW necessitates a more streamlined workflow to enhance efficiency and accuracy in metrological practices.

The traditional workflow, which requires executing USMN in SA, manually exporting results, and subsequently reconfiguring them in PolyWorks, is not only time-intensive but also prone to errors that may compromise measurement accuracy. The need for an automated approach to facilitate data transfer, normalisation, and seamless software integration is evident. This paper presents a novel automation plugin that optimises this workflow, minimising human error, reducing processing time, and improving overall efficiency.

2 Unified Spatial Metrology Network (USMN) Process

The Unified Spatial Metrology Network (USMN) is a robust mathematical framework implemented within Spatial Analyzer (SA) to facilitate the integration of multiple measurement instruments into a cohesive and highly accurate spatial metrology system. The primary objective of the USMN methodology is to optimise the spatial alignment of measurement devices, thereby reducing systematic errors and enhancing measurement precision in large-scale engineering applications.[6]

Large industrial robots operate over expansive workspaces, where a single measurement device, like a laser tracker or total station, cannot provide full coverage. USMN addresses this by combining multiple measurement instruments into a unified, optimized network, enabling continuous tracking of robotic movements across the entire assembly area. This is critical in applications like robotic drilling and riveting in aircraft fuselages, where even slight misalignments can lead to defects. Additionally, robot positioning errors due to mechanical flex, thermal expansion, and joint deflection can accumulate over time, impacting assembly quality. USMN mitigates these issues by optimising real-time measurement data, reducing positional drift, and improving calibration accuracy for automated systems. In adaptive manufacturing, where robots need to respond dynamically to variations in part geometry, USMN provides real-time feedback, ensuring automated assembly processes remain within tight tolerances. Moreover, in safety-critical environments, such as shipyard welding or spacecraft integration, USMN helps define precise collision avoidance zones, preventing robotic arms from interfering with other machinery or human operators. By continuously monitoring and minimizing uncertainty in robotic positioning, USMN ensures that large-scale robotic assembly processes remain accurate, efficient, and compliant with industry standards, ultimately improving production quality and reducing costly rework. Figure 1 showcase a setup of medium scale industrial robot with the metrology device. Realtime calibration of industrial robots is crucial for improving accuracy and efficiency in manufacturing, particularly in aerospace applications. [7]Traditional calibration methods often involve costly, static processes that interrupt robot operations. Recent research has focused on developing dynamic, realtime calibration techniques to address these limitations. Asif and Webb achieved error correction within 0.02 mm using a networked metrology device approach by using the laser tracker.[8] These advancements in realtime calibration techniques demonstrate significant potential for enhancing industrial robot performance and flexibility in complex manufacturing environments.

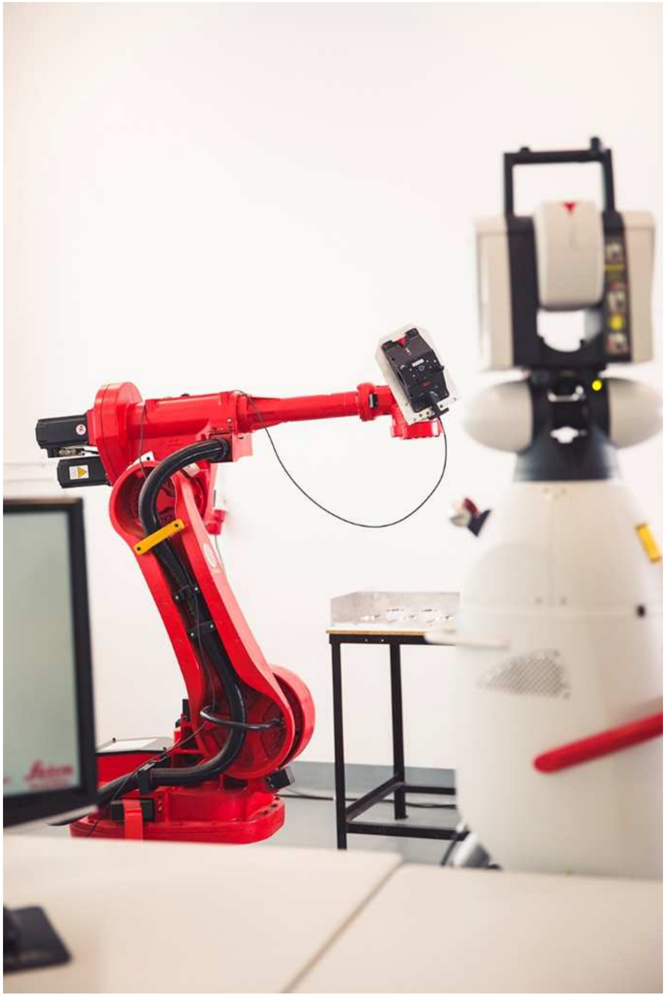

Figure 1: Metroogy setup(Lasert Tracker) with Industrial Robot (Intelligent Automation Lab, Cranfield University)

There are various methods for evaluating measurement system uncertainty. Calkins and Salerno [9] propose a practical approach using bundled observations from multiple instrument locations to determine uncertainties in spherical measurement systems. Damasceno and Couto provide an overview of methodologies, including the Guide to the Expression of Uncertainty in Measurement (GUM) and Monte Carlo methods.[10] Muelaner et al. (2015) introduce a hybrid approach combining Measurement Systems Analysis (MSA) with uncertainty evaluation, particularly useful for in-line measurements in industrial settings.[11] Keller and Sharpe (1992) describe a methodology for estimating uncertainty in electrical signal measurements using comparative measurements with reference meters.[12] These methods aim to quantify measurement uncertainties, considering factors such as environmental effects, operator technique, and instrument performance. The approaches presented offer practical tools for evaluating measurement uncertainty in various fields, from metrology to industrial applications.

The SA software employs the USMN method, which has been adopted through the pioneering work of New River Kinematics (NRK). This method is fundamentally based on the doctoral research of James Calkins[13], as presented in his dissertation on quantifying coordinate uncertainty fields in coupled spatial measurement systems. The USMN method utilises an iterative least-squares optimisation approach to integrate multiple coordinate acquisition systems while rigorously quantifying and propagating uncertainty. By assigning relative uncertainty weights to residual errors, the method ensures that higher-accuracy measurements exert a greater influence on the computed coordinate values. Unlike traditional sequential transformation methods, the USMN employs simultaneous bundle adjustment, dynamically updating the uncertainty fields as new measurements are introduced.[9] This approach enhances metrological precision by optimising the spatial relationships between instruments and measured points, making it particularly effective in large-scale measurement applications where multiple systems, such as laser trackers, photogrammetry, and total stations, must be combined into a unified dataset with robust uncertainty quantification. Following are the steps in the USMN Process:

Step 1: Data Collection from Multiple Instruments: Measurements are gathered from different coordinate measurement systems (e.g., laser trackers, theodolites, CMMs). These instruments may capture overlapping data points to ensure redundancy. The collected data includes spatial coordinates, angles, and distances, which form the basis for further processing. Each instrument introduces some level of uncertainty, which needs to be accounted for in later steps.

Step 2: Aligning Measurements into a Common Reference Frame: Since each instrument operates in its own coordinate system, all collected data must be transformed into a single reference frame. This is done by identifying common points measured by multiple instruments and using them as alignment references. Errors in instrument positioning, orientation, and environmental factors are considered during this process. The result is a unified dataset where all measurements correspond to the same spatial framework.

Step 3: Error and Uncertainty Analysis: Each instrument has inherent measurement errors due to factors such as precision limitations, operator handling, and environmental variations (e.g., temperature, vibrations). USMN evaluates these errors and determines how they propagate across the measurement network. This step ensures that the uncertainty associated with each measurement is quantified and can be corrected or minimised in the next stage.

Step 4: Optimisation of Measurements: Mathematical optimisation techniques are applied to minimise discrepancies between overlapping measurements. This involves refining instrument positions and orientations to reduce residual errors. The process iterates through multiple solutions to find the best alignment that results in the least amount of uncertainty. This step ensures that the final dataset is as accurate as possible by leveraging redundancy in the collected measurements.

Step 5: Final Uncertainty Calculation: Once optimisation is complete, the final uncertainty values are computed for all measured points. These values represent the confidence level in the accuracy of the measurements. The uncertainty map provides insight into which areas have high precision and which might need additional verification. The final dataset is now ready for decision-making, ensuring that the combined measurements meet industry standards for precision and reliability.

3 Methodology

The ability to generate USMN have made SA the metrology software of choice for many engineering applications. However, when using other metrology software and the USMN is required for a given workspace, it can be performed in SA and the USMN composites can be imported to the metrology software of choice. Figure 2 illustrates the flow of the process:

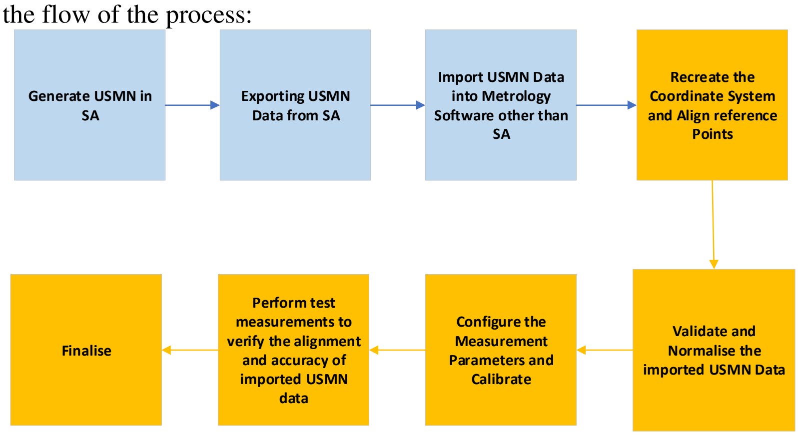

Figure 2: USMN Importing Workflow Steps from SA to anyother metrology software

The USMN integration workflow involves a combination of manual and automated steps to streamline the process of transferring and utilising USMN data in other metrology software. The process begins with generating USMN in SA, followed by exporting the USMN data from SA, and then importing the data into other metrology software (all of these steps, in light blue, require manual execution). It was ensured that the last position for the USMN was desired tracker position in the PolyWorks workspace. This can be any position with a good line of sight to the targets. Once the data is imported, the coordinate system is recreated, and reference points are aligned (yellow), a step that can be automated. Following this, the system can validate and normalise the imported USMN data (yellow), ensuring spatial consistency. The process then moves to configuring measurement parameters and calibrating the setup (yellow), which can also be automated to reduce manual intervention. Once calibrated, test measurements are performed to verify the alignment and accuracy of the imported USMN data (yellow), ensuring that the system meets the required precision standards. Finally, the process is finalised, marking the completion of the USMN integration workflow (yellow). The automation of the yellow-highlighted steps significantly reduces human effort, minimizes errors, and enhances overall measurement accuracy.

Using PolyWorks metrology software as a case study, the USMN for an assembly cell has been generated in SA and the results saved as a text file. This paper looks at the process required to automate the USMN data importation process.
The macros (modular programs) have been written to work with any open PolyWorks workspace like the one seen in the Figure 3 below:

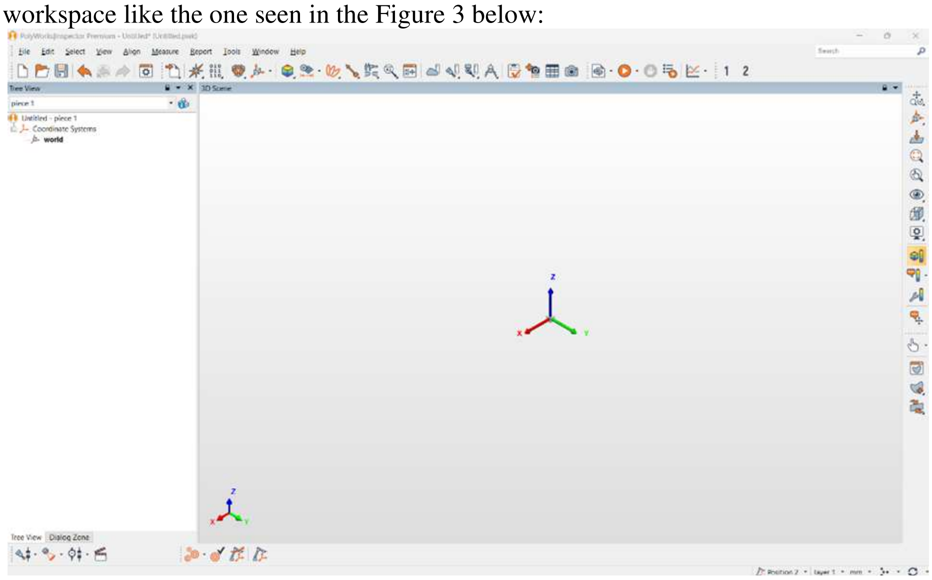

Figure 3: PW Workspace

The operator clicks on button 1 highlighted in Figure 4, the system opens a window, allowing the operator to select the directory where the USMN composite from SA is saved.

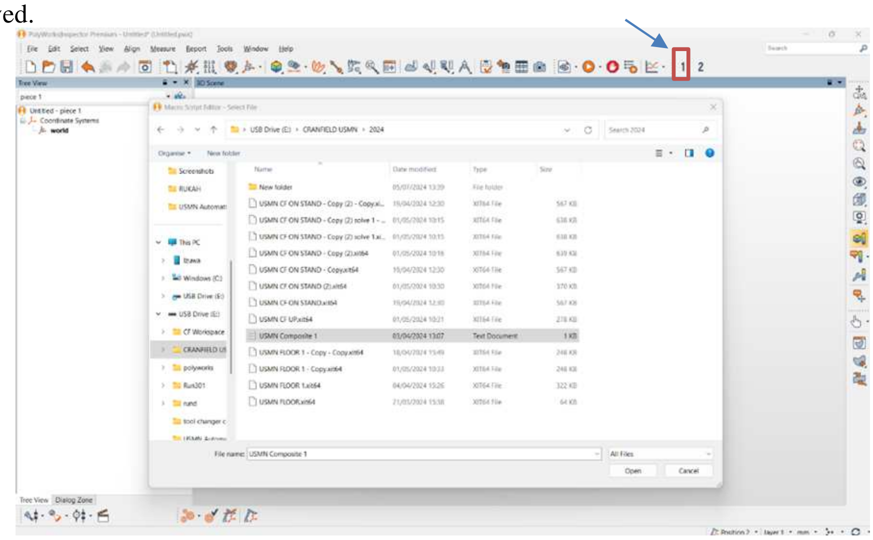

Figure 4: USMN Composite Selection process

The USMN points are imported automatically into the PolyWorks workspace as elements as seen in the Figure 5 below.

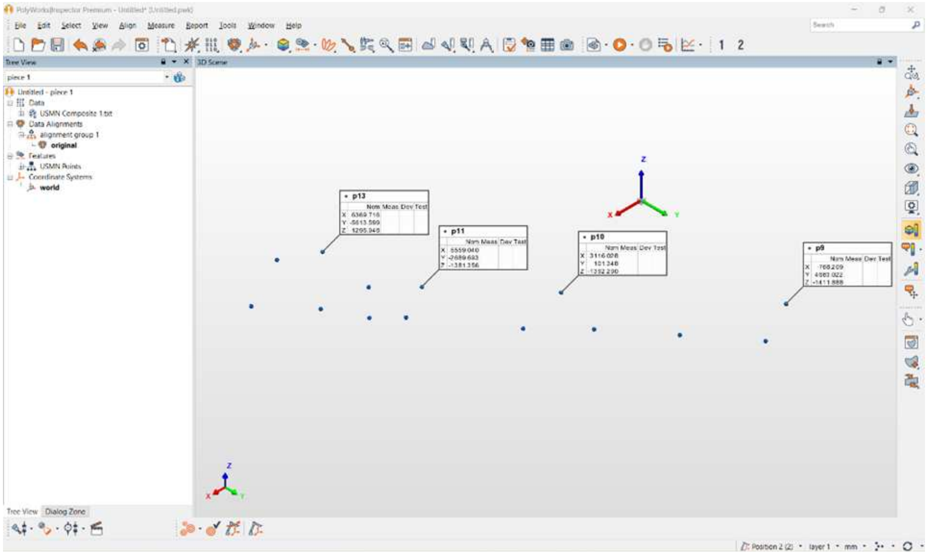

Figure 5: Creating points from USMN Composite point cloud (elements)

The elements are used to create points. These points are grouped and then imported into the device position setup using the “Create global primitives from centers” option.

This imports the points as targets that can be used to create a new device position. The laser tracker is completely unaware of the positions of the targets in space at this point. Hence, there is a need to create a new device position to help lock it onto the targets. For this pupose, operator then click on the button 2. To aid in selecting the targets in the cell, the system activates the camera on the laser tracker as seen in Figure 6 below. This helps eliminate the need to manually move the laser beam from target to target.

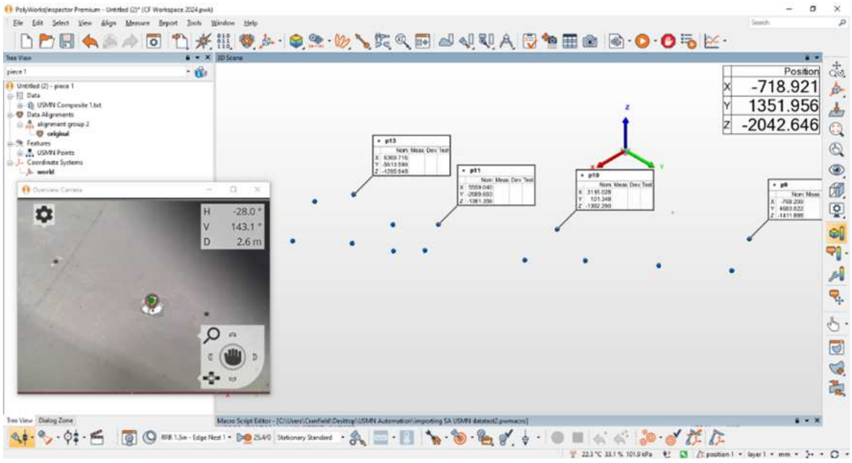

Figure 6: Using laser tracker camera to select reflectors (Point targets)

Then the system then activates the new device position creation process. Combined with the laser tracker camera, the operator can select the targets in the workspace as seen in Figure 7 below.

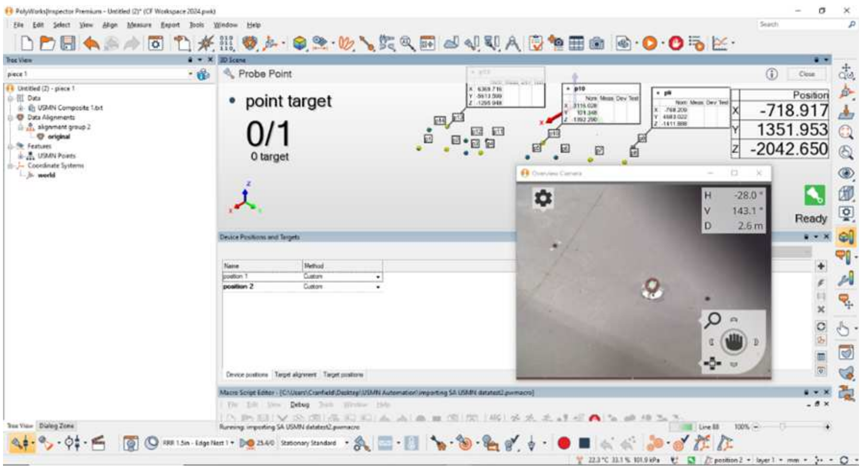

Figure 7: Fitting the points to the Device Position

At this point, the laser tracker is fully locked into the cell and can now be used to take measurements.

The process is illustrated below in Figure 8 consists of both operator-executed and system-driven steps to streamline measurement workflows. The process begins with the operator initiating USMN in SA to execute calibration and establish reference points (orange). The operator then clicks button 1 in PW to import the USMN text file (or-ange). Once imported, the system seamlessly automates alignment creation, generating alignment points in PW (blue). Following this, the operator clicks button 2(blue) in PW to create a device position on the imported points and group them, this is performed automatically. The system then prompts the operator to select targets on the screen (orange). Finally, the automated process locks the laser tracker onto the selected targets, enabling precise measurement (blue). The system then automatically normalise/fit the device (laser tracker) based on the USMN. This structured workflow minimises manual intervention while ensuring high accuracy in large-scale metrology applications.

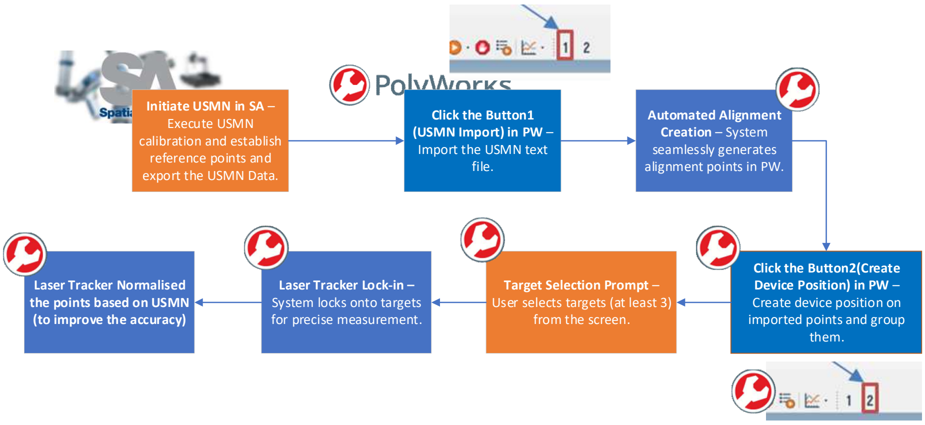

Figure 8: Automated Process Setup

The developed automation significantly optimises the workflow for USMN execution and integration with PW, addressing inefficiencies in traditional manual processes. The key features of the automation are as follows:

- Seamless USMN Data Transfer: The automation enables direct and structured import of USMN data from SA into PW, eliminating manual file conversions and reducing data loss risks. It ensures a consistent and standardised format, enhancing interoperability between the two platforms.
- Automated Reference Point Calibration: The automation facilitates precise alignment of reference points and large components within the coordinate system. It ensures uniform spatial consistency, reducing the need for manual reconfiguration in PW.
- Reduction in Processing Time: By eliminating redundant manual steps, the automation significantly shortens the USMN execution timeline. The integration process, which previously took several days, is now completed in a fraction of the time, improving workflow efficiency.
- Minimisation of Human Errors: Manual data handling introduces inaccuracies due to potential misalignment, incorrect data input, or configuration errors. The automation mitigates these risks by implementing an error-checking mechanism that ensures data accuracy before integration.
- Enhanced Measurement Consistency: The automation maintains spatial integrity across different measurement systems by preserving original USMN parameters. It provides uniform calibration across multiple measurement setups, improving repeatability and reliability.

- User-Friendly Interface and Process Simplification: The automation features an intuitive interface that allows operators to execute USMN operations with minimal technical intervention. It streamlines the process, enabling metrology professionals to focus on high-value analysis rather than data handling.
- Scalability and Future Adaptability: The automated system is designed to accommodate various metrology setups, allowing for scalability across different measurement environments. It provides a foundation for future enhancements, including AI-driven optimisations and expanded software compatibility. By integrating these features, the automation significantly enhances the efficiency, accuracy, and usability of USMN execution within PW, making it a transformative solution in large-scale metrology applications.

4 Discussion & Conclusion

To test the system, it was important to compare the normal (manual) method and the new automated method using the same USMN run. The workspace for the test was set up, and reflectors were placed in position. The USMN was performed in SA using 11 stations, as seen in Figure 9 below.

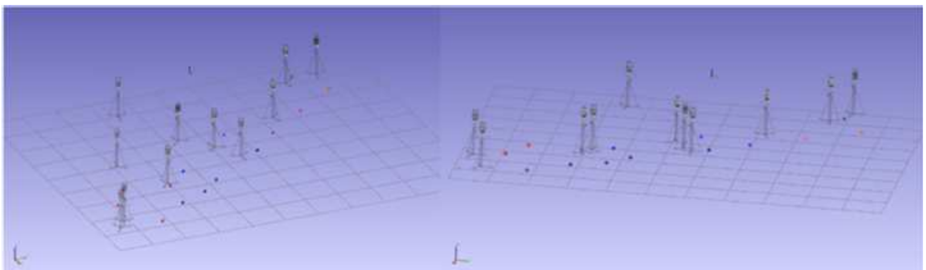

Figure 9: USMN Workspace

Before exporting, the overall RMS was 0.03. The USMN composite was exported and imported manually using the stated procedure; the RMS in PolyWorks was 0.037. Due to the manual tasks involved in this process, the time taken to complete the import was approximately 36 minutes. The same task was performed using the automation program. The RMS after importing to PolyWorks was 0.029. And this only took about 4.5 minutes. The workspace used for this test is a relatively large space, but this can be replicated for smaller workspaces as well. The laser tracker used for this test was the Leica AT960. It was observed that the syntax in the PolyWorks macro editor required modification when running the program on a different tracker. One key feature that contributes to significant time savings is the AT960's built-in camera, which can automatically lock onto reflectors. This functionality is difficult to implement on earlier models, such as the AT901-MR, as observed during testing. Figure 9 showcase the comparison of both mathods.

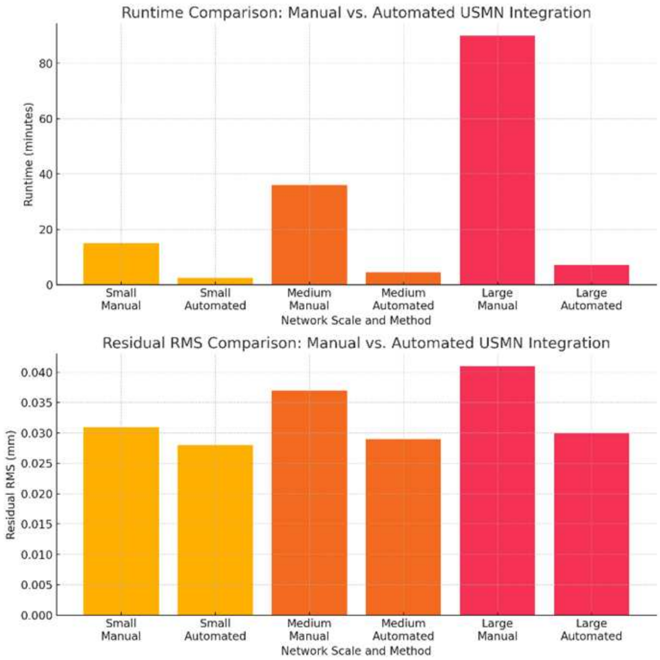

Figure 9: Comparison Manual vs. Automated USMN Integration

The automation framework for USMN integration has markedly improved the efficiency, accuracy, and reliability of spatial metrology workflows. Tasks that previously required up to two days—such as importing USMN data into PW and aligning components—can now be completed in minutes, significantly enhancing productivity and reducing downtime.

Beyond accelerating workflow, the system reduces human error by standardising data transfer and alignment processes. Automated integration preserves spatial integrity and repeatability while real-time error detection mechanisms identify discrepancies early, improving overall measurement reliability.

The framework also enhances interoperability between SA and PW, enabling a consistent and scalable solution adaptable to diverse industrial environments. By removing manual dependencies, it ensures uniformity across varying metrology setups.

In summary, the proposed system offers a transformative step forward in large-scale metrology, delivering faster execution, improved accuracy, and robust process standardisation. Future work will explore algorithmic optimisation and cross-platform compatibility to extend its applicability across broader engineering contexts.

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References

[1] K. A. Olu-lawal, O. K. Olajiga, E. C. Ani, A. K. Adeleke, and D. J. P. Montero, “The role of precision metrology in enhancing manufacturing quality: a comprehensive review,” *Engineering Science \& Technology Journal*, vol. 5, no. 3, pp. 728–739, 2024.

[2] J. Jamshidi, A. Kayani, P. Iravani, P. G. Maropoulos, and M. D. Summers, “Manufacturing and assembly automation by integrated metrology systems for aircraft wing fabrication,” *Proc Inst Mech Eng B J Eng Manuf*, vol. 224, no. 1, pp. 25–36, 2010, doi: 10.1243/09544054JEM1280.

[3] Spatial Analyzer, “Overview of SpatialAnalyzer.” Accessed: Feb. 13, 2025. [Online]. Available: https://www.kinematics.com/spatialanalyzer/

[4] C. Liu, Y. Gu, Y. Zheng, S. Qin, and J. Wang, “Study on precision spatial measurement network of EAST,” in *Ninth International Symposium on Precision Engineering Measurement and Instrumentation*, J. Cui, J. Tan, and X. Wen, Eds., SPIE, 2015, p. 94462C. doi: 10.1117/12.2181108.

[5] InnovMetric Software Inc, “3D Dimensional Analysis and Quality Control SW.” Accessed: Feb. 13, 2025. [Online]. Available: https://www.innovmetric.com/products/polyworks-inspector

[6] New River Kinematics (NRK), “Unified Spatial Metrology Network (USMN).” Accessed: Feb. 13, 2025. [Online]. Available: https://www.kinematics.com/spatialanalyzer/usmn.php

[7] S. Asif and P. Webb, “Realtime Calibration of an Industrial Robot,” *MDPI: Applied System Innovation*, 2022, doi: 10.3390/asi5050096.

[8] S. Asif and P. Webb, “Managing Delays for Realtime Error Correction and Compensation of an Industrial Robot in an Open Network,” *Machines*, vol. 11, no. 9, 2023, doi: 10.3390/machines11090863.

[9] J. M. Calkins and R. J. Salerno, “A practical method for evaluating measurement system uncertainty,” in *Boeing Large Scale Metrology Conference*, 2000.

[10] J. C. Damasceno and P. R. G. Couto, “Methods for Evaluation of Measurement Uncertainty,” in *Metrology*, Anil, Ed., Rijeka: IntechOpen, 2018, ch. 2. doi: 10.5772/intechopen.74873.

[11] J. Muelaner, A. Francis, M. Chappell, and P. Maropoulos, “A hybrid Measurement Systems Analysis and Uncertainty of Measurement Approach for Industrial Measurement in the Light Controlled Factory,” 2015.

[12] A. S. Keller and D. T. Sharpe, “A practical methodology for estimating uncertainty in electrical signal measurements,” in *[1992] Conference Record IEEE Instrumentation and Measurement Technology Conference*, 1992, pp. 623–628. doi: 10.1109/IMTC.1992.245064.

[13] J. Calkins, “Quantifying Coordinate Uncertainty Fields in Coupled Spatial Measurement Systems,” 2002.