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11 Reasons to Use Automated Metrology

Robert Flynn and Carson Miller Electroimpact Inc.

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Abstract

Aerospace structures manufacturers find themselves frequently engaged in large-scale 3D metrology operations, conducting precision measurements over a volume expressed in meters or tens of meters. Such measurements are often done by metrologists or other measurement experts and may be done in a somewhat ad-hoc fashion, i.e., executed in the most appropriate method according to the lights of the individual conducting the measurement. This approach is certainly flexible but there are arguments for invoking a more rigorous process. Production processes, in particular, demand an automated process for all such "routine" measurements. Automated metrology offers a number of advantages including enabling data configuration management, de-skilling of operation, real time input data error checking, enforcement of standards, consistent process execution and automated data archiving. It also reduces training, setup time, data manipulation and analysis time and improves reporting.

This paper draws on experiences from a recent automated metrology project and examines some of the challenges and benefits of successful measurement automation.

Introduction

Your assembly process is running smoothly and every week you get reports from your metrology team assuring you that those large structures the team is building are all within tolerance. All is well, the systems are working, but one day someone suggests automating the metrology processes related to your product. Automating the process will not be easy…will it be worth it? Why would anyone make this leap?

Looking back over an extensive automated metrology project, the authors will endeavor to provide a few answers to these questions, and along the way, share a number of lessons learned, illustrate some best practices, and show a generalized architecture for an automated metrology system. We highlight some particular benefits of automation in the following. Metrology automation:

1. enables rigorous input data configuration management
2. de-skills the operations
3. reduces the intensity and length of training required
4. reduces setup time
5. facilitates real time input data error checking
6. enables enforcement of scalebar checks and other standards
7. promotes a rigorously consistent measurement process
8. insures consistency of data analysis
9. reduces time for data manipulation and data analysis
10. automates reporting
11. enables automatic storage and protection of all data and results thereby eliminating lost data

An Automated Metrology Case Study

In this particular job, the authors were developing a system which was capable of "compensating" and locating (in six degrees of freedom) hundreds of 2 and 3 axis machines. During the work on this large system, the benefits of automation were borne in with particular force. The project, which taught many of the lessons noted here, entailed the development and integration of an aerospace wing assembly application, which relied on several automated workflows. The workflows served to compensate and improve the accuracy on each of the 216 multi-axis CNC machines. Each group of 27 machines worked in coordination to set critical features in the wing fixture. After compensation, another workflow was executed for each of these 216 machines to globally locate it within the assembly fixture's coordinate system. The team also developed a workflow to do a quick "health check" on the state of each fixture. Each workflow led to some new incremental advancements or ideas on how we might improve our game on the next project.

1. Input Data Configuration Management

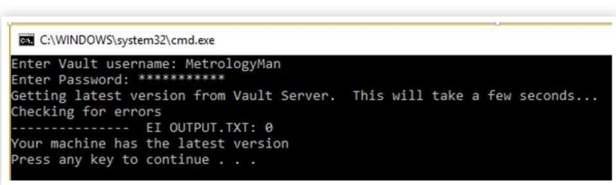
Metrology processes typically require the use of inputs such as nominal measurements, control network[1] files, text files, template files and other reference data. "Configuration Management", i.e. keeping such files all at correct versions and distributed to everyone on the team can often be a challenge. Of course, automation projects also add software elements such as C# code, scripts, Excel macros and the like, taking the complexity to a new level. Fortunately, good, off the shelf, revision control software tools exist which can be exploited to address the configuration management challenge.

The automation team was already using a commercial software revision control tool (Vault, by SourceGear) to execute software revision control so it was a natural extension of current practice to use the same tool for all related data as well. Since each installation requires many files, the team uses a simple custom software tool (GetLatestOpcom) to retrieve all the necessary files at a stroke. Using this tool, the operator now only needs a reliable internet connection in order to retrieve the latest software versions and data releases, providing rigorous software configuration and input data management.

2. De-Skilling Operations

An experienced metrologist can execute impressive measurement and analysis tasks, often very quickly. Using that metrologist to repeat those same tasks on a regular basis quickly becomes costly. On the other hand, handing the task over to someone with limited training and no metrology skills is asking for trouble…unless the operations have been "de-skilled". Developing a programmatic solution to metrology operations very significantly reduces the skill level required to conduct the operation. A comprehensive workflow can gather data to make decisions (so that the user does not have to) and guide the user down the correct path under a wide variety of circumstances. Most automation schemes also offer the user a simplified interface, which serves to make the process less intimidating. With just a little training, the typical mechanic can easily, and correctly, run a workflow containing many complex metrology operations.

FIGURE 1 Using custom software tools to install the latest software versions and data serves to enhance software configuration management and simplify the tracker operator's job.



[1] A control network is a set of carefully measured monuments or nests, usually scattered throughout the entire volume of the work area. Foundation reference systems (monuments glued into holes cored into concrete) and jig-reference systems (nests permanently attached to tooling structures) are two examples of control networks.

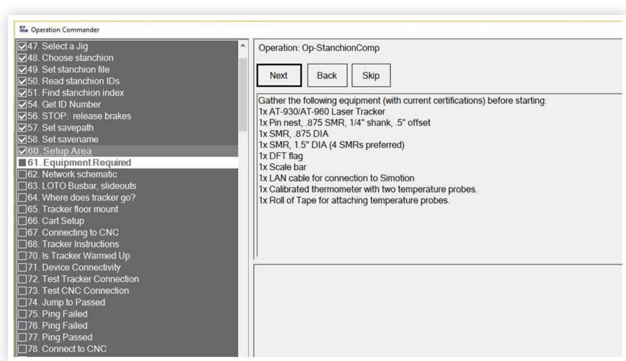
3. Reduced Training Requirements

Automating the process and de-skilling of operations adds another benefit. It reduces the intensity and length of training required for each team member. Now, rather than having to train operators on the use of metrology software, order of operations for the process and the nuances of use of the instrument used, a simple and basic training can be applied. A good workflow will guide the operator through each operational step and he will not have to remember the order of process details, much less understand the importance of uncertainties developed from weighted multi-lateration calculations and other metrology arcana.

4. Reduced Setup Time

Automating a metrology process can reduce setup time. This might seem counter-intuitive, but by including detailed setup instructions at the beginning of each workflow (see Figure 2 showing a screenshot from Operation Commander[2] [2]), the exact task requirements are always comprehensively defined. Because the task list is comprehensive and yet taken step by step the operator will not forget essential but forgettable chores

FIGURE 2 This Operation Commander window clearly lists all required equipment needed to complete this workflow.



[2] Operation Commander is a metrology-centric Manufacturing Execution Program developed by Electroimpact for automating assembly processes. Script illustrations in this document taken from Operation Commander workflows. Most metrology tools have some built-in scripting language, e.g. Spatial Analyzer (Measure Plan), Verisurf, Metrolog, and Polyworks to name a few in no particular order. The theme of this paper applies equally to any of these software tools.

such as setting the correct IP address. Any kind of failure (e.g. failure to ping the tracker) is addressed with context sensitive instructions, which are otherwise not seen. This makes setup simpler from the user point of view and helps reduce false starts and forgotten steps. A side-bonus is that it naturally works hand-in-glove with the 5S approach to manufacturing - the operator does not even see failure-case text unless the failure occurs.

5. Enabling Real Time Input Data Error Checking

Real time input data error checking…what could that involve? There are usually a few inputs on every metrology job which bear checking. For example, it is common to conduct a scalebar measurement on every metrology job on some projects. Company, NADCAP or other standards may require that the scalebar certifications on that scalebar be current.

Providing scalebar data files as part of the input data package for a job enables an automated check on the expiration date to validate that scale bar. Another example of input data checking is temperature. Shown below, in Figure 4, the operator has fat-fingered the entry of part temperature, entering 98°F rather than 68°F. This error was caught in real time, where the operator was prompted to confirm or deny the unexpected temperature. Only after the unexpected result is confirmed by the operator does the workflow progress.

This kind of real time input data error checking is a very useful tool for metrology processes.

FIGURE 3 A simple input data check, such as this where the scalebar certification date is verified - can avoid a host of problems.

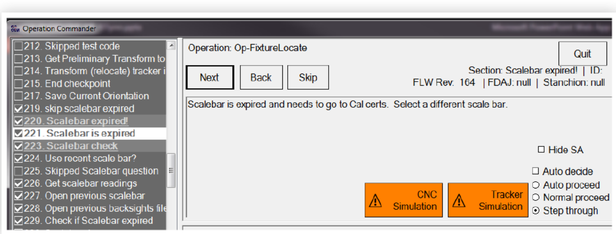
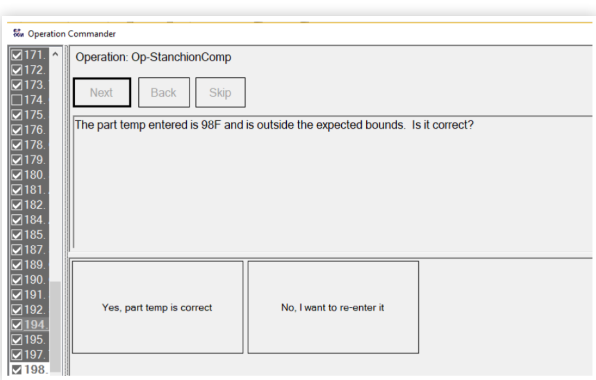


FIGURE 4 Check values in real time to help minimize errors.



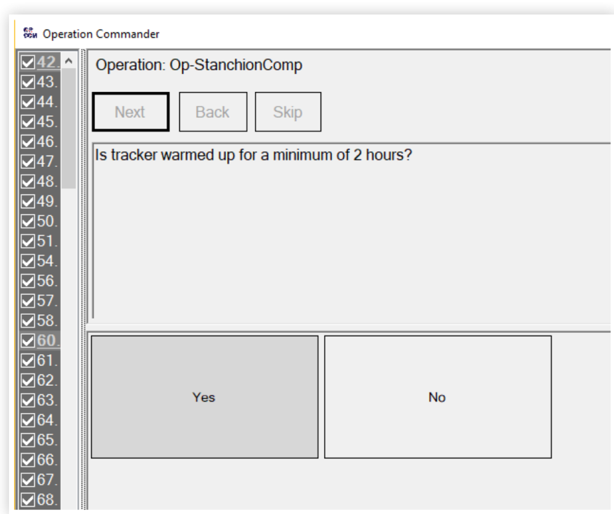
6. Enforcing Standards

As operators face pressure to keep pace with increasing production rates, routine health checks, and peripheral requirements related to company or industry standards are easily forgotten or overlooked. Common examples include required warmup periods, scalebar checks, backsight checks, and temperature readings, to name a few. Verifying instrument and scalebar calibrations are another import function. By programming these checks and standards into the workflow script, the programmer can prevent operators from neglecting to perform them. Just as important for compliance is that he can also insure that the data from the checks are saved appropriately.

7. Enabling a Rigorously Consistent Measurement Process

A consistent measurement process is extremely helpful for production operations, and yet hard to achieve manually. In a manual process, there can be infinite variety in everything from point names to feature names to order of measurement to file names, and so on. If all goes well, this may not be too problematic, but if any features are found to be out of tolerance then the first step is often to review the measurement data. This will be much harder for the engineer to do if there are differences in the process from whatever was expected. The programmatic approach to metrology resolves all such difficulties.

FIGURE 5 Here, the operator must acknowledge that the laser tracker has been warmed up for the requisite time period before any measurements are taken.



8. Ensuring Consistent Data Analysis Process

It is obvious that a consistent process is desirable for data analysis, yet simply leaving it at "desirable" is understating the case, as can be illustrated by a few examples. Suppose that a given metrology process requires a very slight rotation of a coordinate frame, followed by a point translation - how easy it is to accidently reverse those two steps! Alternatively, consider the application of temperature scaling. Temperature scaling is a common function requiring an accurate process, and one that is often troublesome in that the scaling effect is often very subtle, so errors can likewise be difficult to detect. Figure 6 illustrates a typical decision point for the user following a manual process.

There are at least three ways this could go wrong. The user could:

- Forget to bring up this window, and therefore apply no scaling at all.
- Applying the incorrect Coefficient of Thermal Expansion value.
- Misinterpret the entry points to mean "initial jig temperature" and "final jig temperature", thereby applying an incorrect scaling.
- Enter the reference temperature of 68F as the Initial Temp instead of the Final Temp, thus apply a reverse scale.

True, relying on his training the operator *might* do the right thing and enter the Initial Temp as the fixture temperature and the Final Temp as the reference temperature of 68F. Obviously,

FIGURE 6 This screen shot from Spatial Analyzer illustrates a typical decision point for an SA Operator - entering data for the shoot. Will the operator remember to enter the fixture temperature for the Initial Temp and 68F for the Final (reference) temperature?

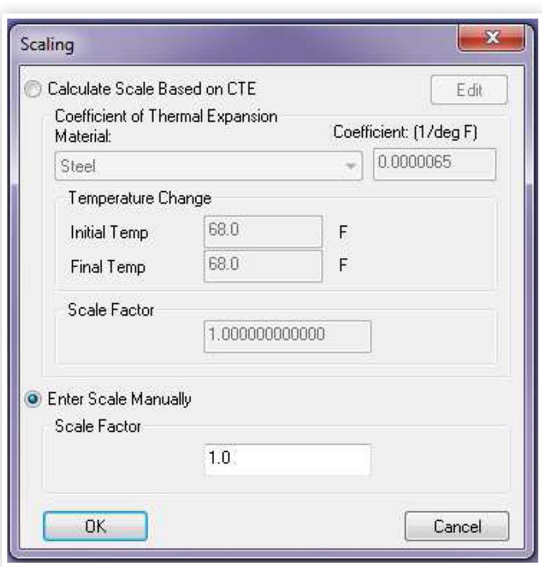
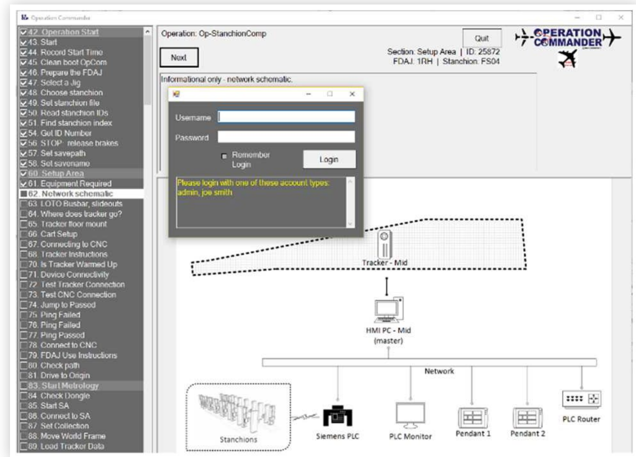


FIGURE 7 Changes to workflow order of execution can be limited to authorized persons.



in a production environment it is desirable to reduce the potential for such errors and rely less on what the operator *might* do. Avoid all of these sources of error by taking a programmatic approach to the metrology, such as with a scripted workflow.

A key characteristic of scripted workflows is that work progresses in a linear manner where the order of execution of steps is controlled. This level of control does much to keep the operator on the "straight and narrow" so that the outcome is predictable. If occasional deviations from the required path may be desirable, tools exist to allow exceptions, given proper authorization, as illustrated in the example in Figure 7, where the user is attempting to skip to another point in the workflow.

An authorized username and password is required to change the order of operation. This kind of security insures proper adherence to the workflow while ensuring flexible operations where there is a need.

9. Reduces Time for Data Manipulation and Data Analysis

An obvious benefit of programmatic metrology solutions is that all data manipulation (scaling, relocating, fitting, plane, sphere (and other object) creation, etc. all happen almost instantaneously, typically with no user input. Likewise, most or all of the data analysis can be conducted automatically and nearly instantly leaving the user with an executive level green "up" or red "down" for the process.

10. Enables Consistent Reporting

The report is one of the products of most metrology operations. A fixed reporting format (whether in the native metrology software, Microsoft Excel, tables, graphs, .txt file or any combination of these and other types) and consistent reporting methodology results in a better understanding of the report results by the reader, and so is generally a requirement for production processes. An automated process lends itself to rigorously consistent reporting formats, wherein no elements are forgotten and where the presentation and meaning of the data is always identical. Of course, there is also the time savings attendant to an automated process.

11. Automated Storage & Protection of Data and Results

Anyone whose has spent much time around laser trackers has probably experienced his own "where's the data" moment. Trackers are typically operated on a laptop out on the factory floor where the measurement files and reports exist locally. After the operations are complete, the user is responsible for manually copying - sometimes via sneakernet and a thumb drive - the critical data to a server.

This methodology leaves plenty of opportunities for failure:

- Forgetting to copy to the thumb drive.
- Copying the wrong data to the thumb drive.
- Losing the thumb drive.
- Copying the wrong data from the thumb drive.
- Copying
  the data from the thumb drive to an incorrect folder.

Automated data archiving offers a way out of the lost-data mess.

Automated Data Archiving

Automated archiving is simply programmatically copying all the relevant data and reports to a consistent, established location - typically a server. When this is done in the context of a larger process script it can be done without any further user

FIGURE 8 Though functional, "Sneakernet" is not an ideal way to handle data transfer and storage.

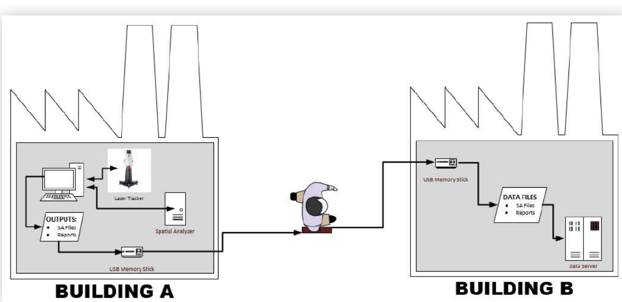


FIGURE 9 Leaving file naming and storage to the user is suboptimal: a tired or careless user may choose an "almost correct" file name. Finding the misnamed folders later can often be a time-wasting challenge.

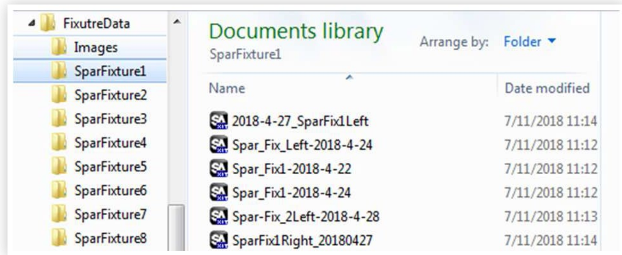
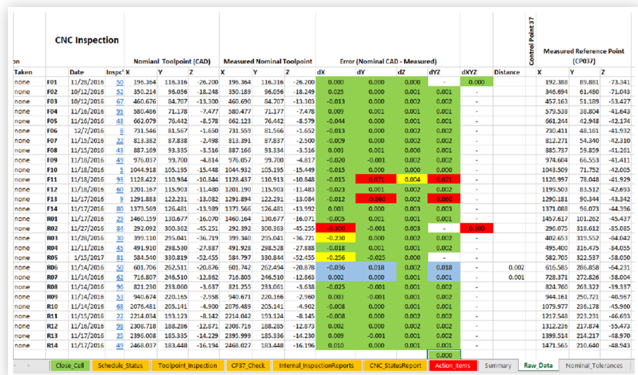


FIGURE 10 Large complex systems, such as a wing assembly jig may necessitate the development of a single comprehensive Excel file (or worksheet) used for summarizing data, and planning future work.



on	CNC Inspection			Nomianl Toolpoint (CAD)			Measured Nominal Toolpoint			Error (Nominal CAD - Measured)						Control Point 37	Measured Reference Point (CP037)		
Taken		Date	Inspc'	X	Y	Z	X	Y	Z	dX	dY	dZ	dYZ	dXYZ	Distance		X	Y	Z
none	F01	11/28/2016	50	196.364	116.316	-26.200	196.364	116.316	-26.200	0.000	0.000	0.000	-	0.000			192.388	89.881	-73.341
none	F02	10/12/2016	52	350.214	96.056	-18.248	350.189	96.056	-18.249	0.025	0.000	0.001	0.001	-			346.694	61.480	-71.043
none	F03	10/12/2016	67	460.676	84.707	-13.300	460.690	84.707	-13.303	-0.013	0.000	0.002	0.002	-			457.163	51.189	-53.427
none	F04	11/16/2016	95	580.486	71.178	-7.477	580.477	71.177	-7.478	0.009	0.001	0.001	0.001	-			579.538	38.804	-41.643
none	F05	11/16/2016	43	662.079	76.442	-8.578	662.123	76.442	-8.579	-0.044	0.000	0.001	0.001	-			661.244	42.948	-42.174
none	F06	12/7/2016	8	731.546	81.567	-1.650	731.559	81.566	-1.652	-0.013	0.000	0.002	0.002	-			730.411	48.161	-41.932
none	F07	11/15/2016	22	813.382	87.838	-2.498	813.391	87.837	-2.500	-0.009	0.000	0.002	0.002	-			812.271	54.340	-42.310
none	F08	11/15/2016	43	887.169	93.335	-3.516	887.166	93.334	-3.516	0.003	0.001	0.000	0.001	-			885.737	59.859	-41.261
none	F09	11/18/2016	49	976.037	99.700	-4.814	976.057	99.700	-4.817	-0.020	-0.001	0.002	0.002	-			974.604	66.553	-41.411
none	F10	11/18/2016	5	1044.918	105.195	-15.448	1044.932	105.195	-15.449	-0.015	0.000	0.000	0.000	-			1043.509	71.752	-42.005
none	F11	11/18/2016	93	1128.422	110.984	-10.844	1128.437	110.913	-10.848	-0.015	0.071	0.004	0.071	-			1126.997	78.048	-41.929
none	F12	11/18/2016	60	1201.167	115.903	-11.480	1201.190	115.903	-11.483	-0.023	0.001	0.002	0.002	-			1199.503	83.512	-42.693
none	F13	11/17/2016	9	1291.883	122.231	-13.082	1291.894	122.291	-13.084	-0.012	-0.060	0.002	0.060	-			1290.181	90.344	-43.342
none	F14	11/17/2016	80	1373.569	126.481	-13.989	1373.566	126.481	-13.992	0.003	0.000	0.003	0.003	-			1371.088	96.073	-44.396
none	R01	11/17/2016	29	1460.159	130.677	-16.070	1460.164	130.677	-16.071	-0.005	0.001	0.001	0.001	-			1457.617	101.262	-45.437
none	R02	11/27/2016	84	292.092	300.362	-45.251	292.392	300.363	-45.255	-0.300	-0.001	0.003	-	0.300			296.075	318.612	-85.085
none	R03	11/28/2016	30	399.110	295.041	-36.719	399.340	295.041	-36.721	-0.230	0.000	0.002	0.002	-			402.653	319.552	-84.042
none	R04	11/11/2016	45	491.910	298.530	-27.887	491.928	298.528	-27.888	-0.018	0.001	0.001	0.002	-			495.400	316.475	-84.055
none	R05	1/15/2017	81	584.540	330.819	-52.455	584.797	330.844	-52.455	-0.256	-0.025	0.000	-	-			582.705	322.537	-58.050
none	R06	11/14/2016	50	601.706	262.511	-20.876	601.742	262.494	-20.878	-0.036	0.018	0.002	0.018	-	0.002		616.585	286.858	-64.231
none	R07	11/14/2016	62	716.807	246.510	-12.862	716.805	246.510	-12.863	0.002	0.000	0.001	0.001	-	0.001		728.371	272.826	-58.004
none	R08	11/14/2016	96	821.230	233.060	-3.637	821.255	233.061	-3.638	-0.025	-0.001	0.001	0.002	-			824.760	263.322	-39.337
none	R09	11/14/2016	53	940.674	220.165	-2.958	940.671	220.166	-2.960	0.003	-0.001	0.001	0.002	-			944.161	250.721	-40.967
none	R10	11/14/2016	68	2076.481	205.141	-4.900	2076.489	205.141	-4.902	-0.008	0.000	0.001	0.001	-			1079.977	236.178	-45.960
none	R11	11/15/2016	22	2214.034	193.123	-8.142	2214.042	193.124	-8.145	-0.008	0.000	0.002	0.002	-			1217.548	223.231	-46.693
none	R12	11/16/2016	98	2308.718	188.286	-12.871	2308.716	188.285	-12.873	0.002	0.000	0.002	0.002	-			1312.236	217.874	-55.473
none	R13	11/17/2016	25	2396.008	185.335	-14.229	2395.999	185.336	-14.230	0.009	-0.001	0.001	0.002	-			1399.514	214.217	-48.970
none	R14	11/17/2016	49	2468.037	183.448	-16.194	2468.027	183.448	-16.196	0.010	0.000	0.001	0.001	-			1471.565	210.640	-48.943
													0.000						

Close_Cell | Schedule_Status | Toolpoint_Inspection | CP37_Check | Internal_InspectionReports | CNC_StatusReport | Action_Items | Summary | Raw_Data | Nominal_Tolerances

input, meaning the user does not need to remember to execute any reporting or data storage actions. But simple data storage can be taken to another level - to include data protection.

Protecting Data

A frequent requirement of metrology data and files is that they are protected against loss, accidental changes or even deliberate tampering. A strong data archival and protection scheme may be necessary for such cases. Fortunately, these can be easy to implement in the context of a programmatic workflow.

In our case study example, the team was already using SourceGear Vault for software revision control, so it was a natural candidate for archiving data and report outputs from automated metrology workflows. A WAN hotspot enabled internet communication and direct access to a designated Vault repository. Some minor software additions enabled the workflows to copy their output folders directly into the appropriate repository. The workflows establish the folder paths and filenames, so the data always goes to the correct location, and "fat finger" errors are eliminated. No files are ever forgotten. Vault applies revision control rules to all files, so once written into the repository the raw data is preserved.

Exploiting Consistent File Naming Schemes

The benefits of automatic data archival extend beyond the elimination of a number of major data handling concerns. For example, automated rational naming of all data files enables the further development of automated data analyses and reporting. In the case study example, the team was able to automatically consolidate 108 reports into a single master report for each fixture. This replaced a tedious, error-prone, manual copy and paste process in Excel and saved many engineering hours.

Future Efforts

It is usually easy to see where improvements can be made, and in the case where long and complex workflows are being executed some good candidates revolve around process validation. One essential validation tool is the ability to run the workflow in simulation mode. "Sim" mode enables the simulation of both the laser tracker measurements and interaction with the CNC. The value of running in sim mode can be maximized by several actions: A) Using only realistic values for the simulation and B) Incorporating the use of a "reference solution".

Realistic Values for Sim Mode

As may be expected, running in sim mode is a bit different from running real equipment. In particular, trackers are assigned arbitrary locations and orientations (depending on the software in use). Most operations work perfectly in sim mode with the tracker in any location, however it can make certain kinds of measurement problems obscure or be more difficult to unravel. A best practice for sim mode is to assign realistic locations for the laser tracker; then subsequent visualization makes more sense. This more realistic simulation is not strictly necessary but it is certainly beneficial and worth the extra effort.

Incorporating a Reference Solution

Another key validation for a typical workflow will include verifying that the workflow algorithm correctly executes the intended process. For example, suppose the requirement is to join two objects together based on a well-defined set of criteria. A first level of validation is to develop a "reference solution" - a valid model and valid solution for that join. This can be developed via pure math, through the use of software or via CAD construction or some combination of these. The same inputs can then be applied to the workflow and the outputs compared to see if the workflow is correct.

A second level of validation development is to implement the reference solution and validation scheme into the workflow such that it can run automatically anytime the developer feels the need. This integrated solution would be very useful for identifying the very subtle errors that can often occur in complex metrology processes.

Automated Data Retrieval and Storage

The implementation of automated data retrieval and storage are not groundbreaking. However, the strong benefits of this practice motivate us to explore implementation even on manual metrology jobs. We look forward to experimenting with some ideas on this front.

Apply Best Practices Rigorously

Finally, we have a growing list of "best practices." Listing them is easier than implementing, but one goal is to truly be rigorous about applying our identified best practices, and thereafter reap the benefits.

Conclusion

As we have shown, there are very strong arguments for automation of metrology processes. Those who implement such automation can expect to see benefits including de-skilled operations, reduced training, setup times and data analysis, strongly configured input data, real time error checking, consistent automated reporting as well as automatically archived data. Such benefits are too significant to ignore and make automated metrology a best practice wherever metrology is called for in production processes.

For Further Information

Rob Flynn, Electroimpact
4413 Chennault Beach Road
Mukilteo, WA 98275
(425) 609-4900
robf@electroimpact.com

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