IMPROVING QUALITY OF AIRCRAFT STRUCTURAL JOINS VIA ADAPTIVE TOOLING AND A FLEXIBLE HMI

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Adaptive tooling benefits

Adaptive tooling:

- **In conjunction with automated metrology, improves part and join metrics.**
- **In conjunction with a task-based HMI, standardizes assembly process, making it deskilled and automated.**
- **Enables the use of more sophisticated and appropriate join criteria compared to hard tooling.**
- **Enables join optimization which in turn reduces overall assembly error.**

Presentation Agenda

1. What is adaptive tooling?
2. How can we set join criteria?
3. System overview of final assembly line
4. Details of a wing-fuselage join
5. Flexible HMI and system software
6. Conclusion

What is tooling?

“Tooling” is mechanical equipment which holds parts in proper relationship for accurate assembly.

Traditional tooling is “fixed”. Modern tooling is often “flexible” or sometimes “adaptive” or even both.

Fixed (hard) tooling

Fixed tooling or “hard” tooling has fully constrained geometry – with the intention that the resulting assembly is always “exactly” the same.

Adaptive tooling

Adaptive tooling

- Designed to be adjustable on-the-fly.
- Adjusts indices so as to reduce the negative impact of part or subassembly variances.
- Makes it easy to “split the difference” and share out tolerance budgets sensibly.
- Usually achieved through servo control, since the required adjustment changes for each new set of parts.

Why adaptive tooling?

Why adaptive tooling?

- Provides flexibility for OOT part assembly.
- Improves assembly accuracy.
- Can implement a complex and more correct join criteria, e.g. ordinate frame creation including virtual points.

Flexible tooling

Flexible tooling

Designed to accommodate more than a single variation of the part or assembly, **e.g.**:

- left and right wings
- freighter vs passenger
- long range vs short range variants.

- May be achieved by swapping or by adjusting an index.

Establishing join criteria

Fixed tools:

Select most important features and assign to nominal values.

Adaptive tools:

Establish practical, convenient criteria based on key features, perhaps even directly from the drawings.

Or

Best fit critical index points to nominal values.

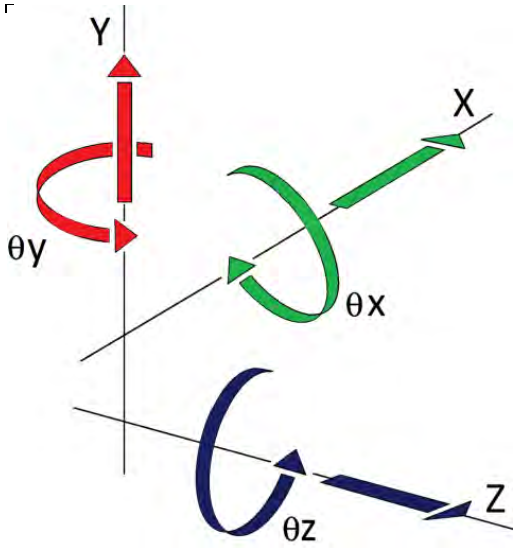
Join criteria option: ordinate frames

- Ordinate frames are a convenient tool for adaptive tooling joins.
- An ordinate frame can be created in each part or assembly to be joined, based on key features of that part.
- Given automated programmatic workflows, an ordinate frame can easily be constructed in real time even from elaborate criteria based on multiple features including virtual features such as midpoints, planes, axes, etc.

What is an ordinate frame?

An ordinate frame is another word for coordinate system.

Each workcenter has a primary coordinate system or ordinate frame. Other ordinate frames may exist in that workcenter. Each offers a mathematical view of the world from a different perspective.



Frame to Frame transformation method

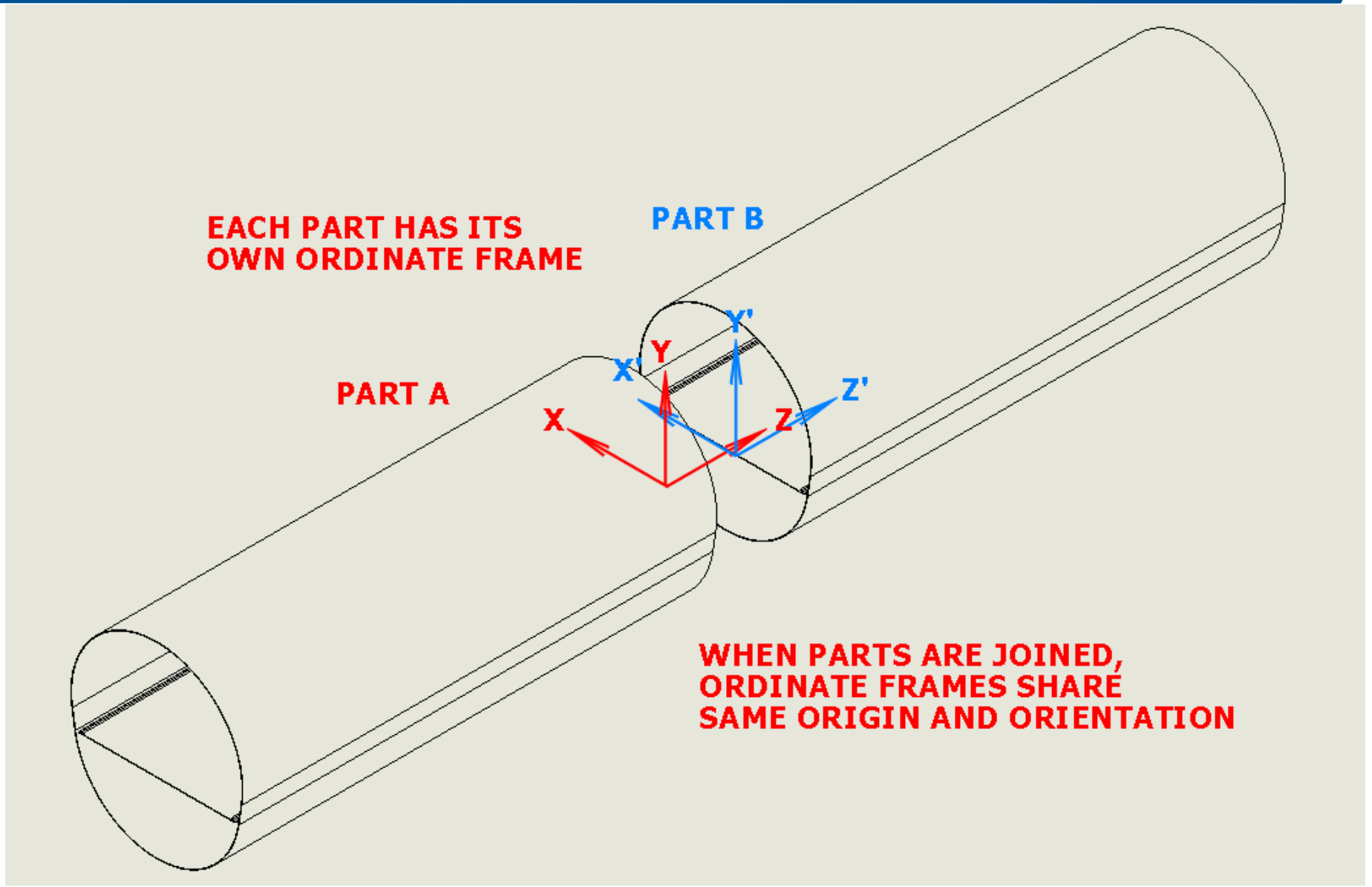
Calculating the transformation matrix for a join:

- Define an ordinate frame on each assembly
- Make frames coincident when fully joined

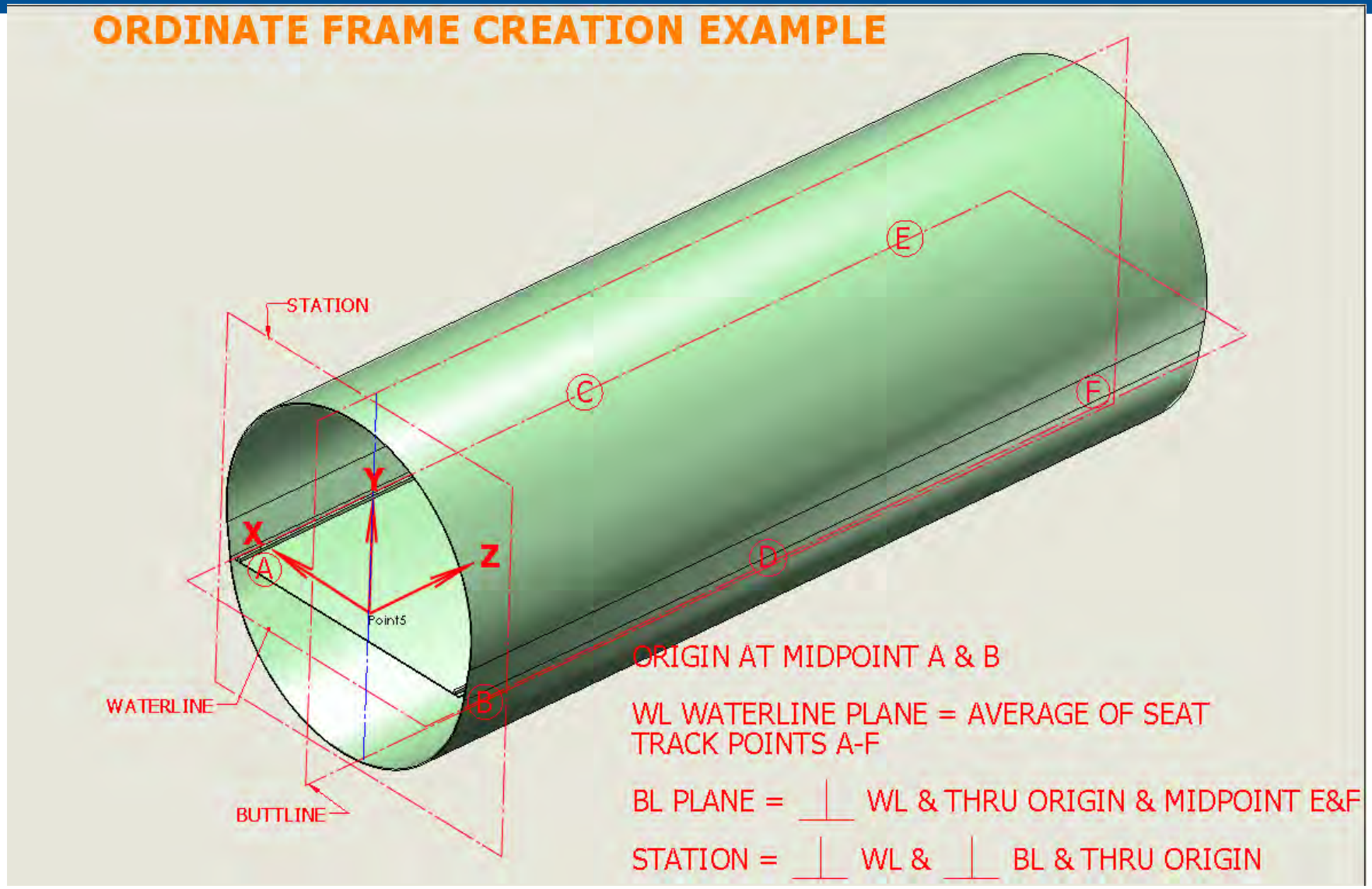
This method enables workflow modularity by supporting separation of the two ordinate frame definitions…

and therefore simplifies any future modifications to the join criteria.

Frame to Frame transformation method



Frame to Frame transformation method



Case study: Business jet FAL (existing variant)

A/C Details

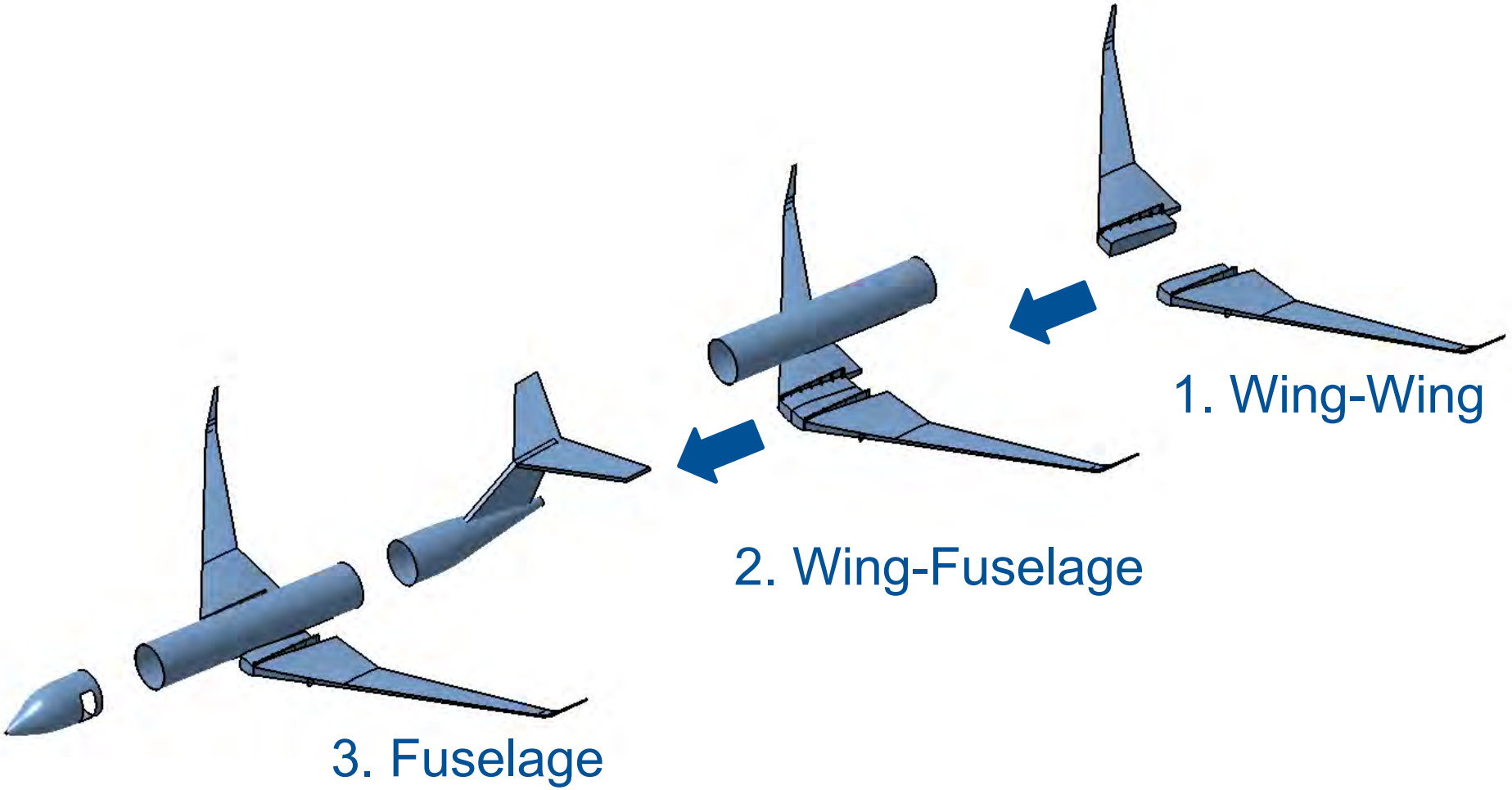
- 105’ length and wingspan
- Arrives at FAL as 2 wing halves and 3 fuselage sections
- Additional assembly requirements include:
  - Flight controls rigging
  - Aircraft leveling

Why new assembly method?

- Improve assembly metrics
- Enable metrics based adaptation
- Reduce error in critical tolerances
- Improve assembly consistency
- Make process methodological
- Reduce assembly time

FAL Overview

FAL Overview



Material handling - wing

Wing halves are loaded into the workcenter via crane

“Iron wing” for testing

Wing halves are joined

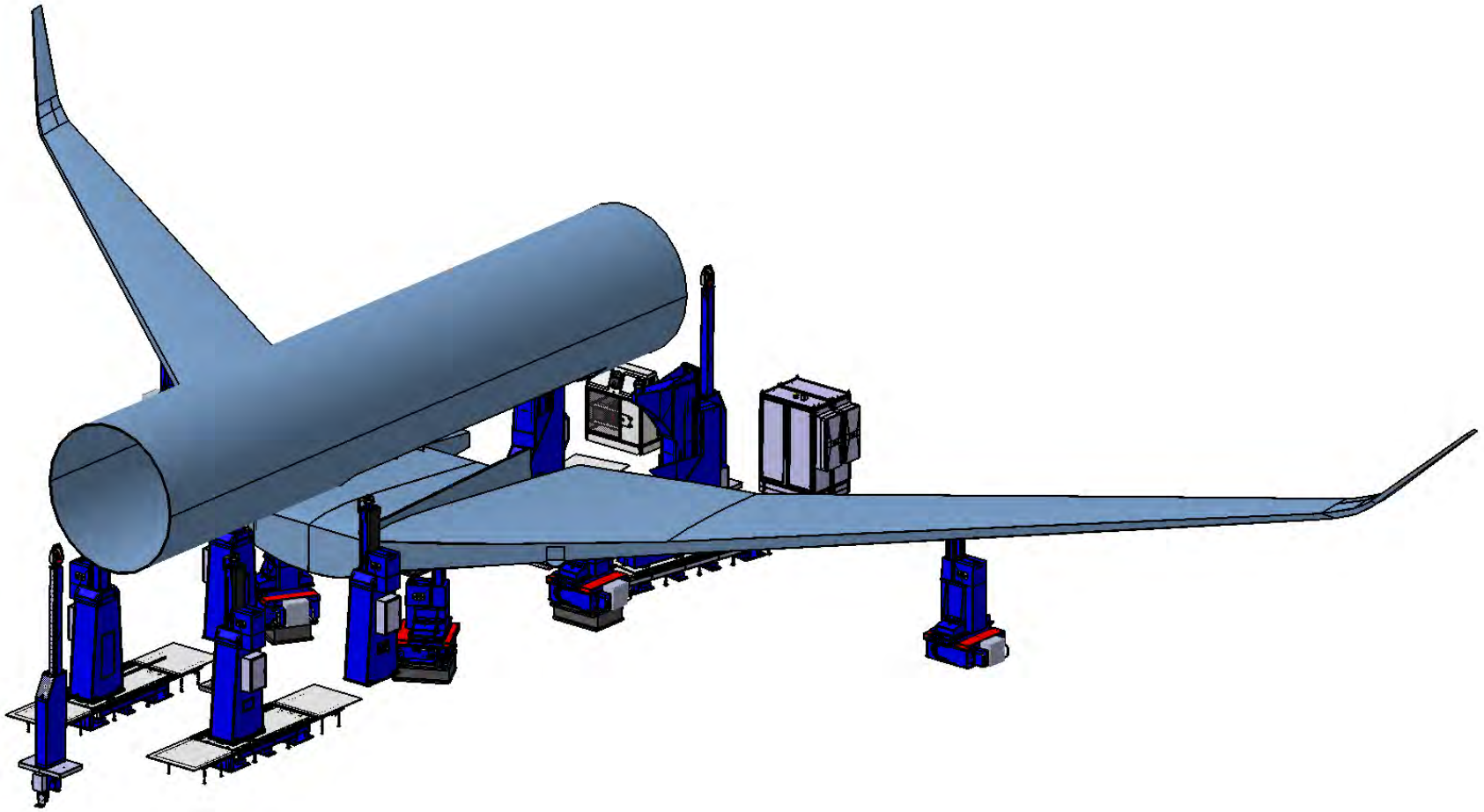
Material handling

Joined wing is carried by ATLAS to next workcenter

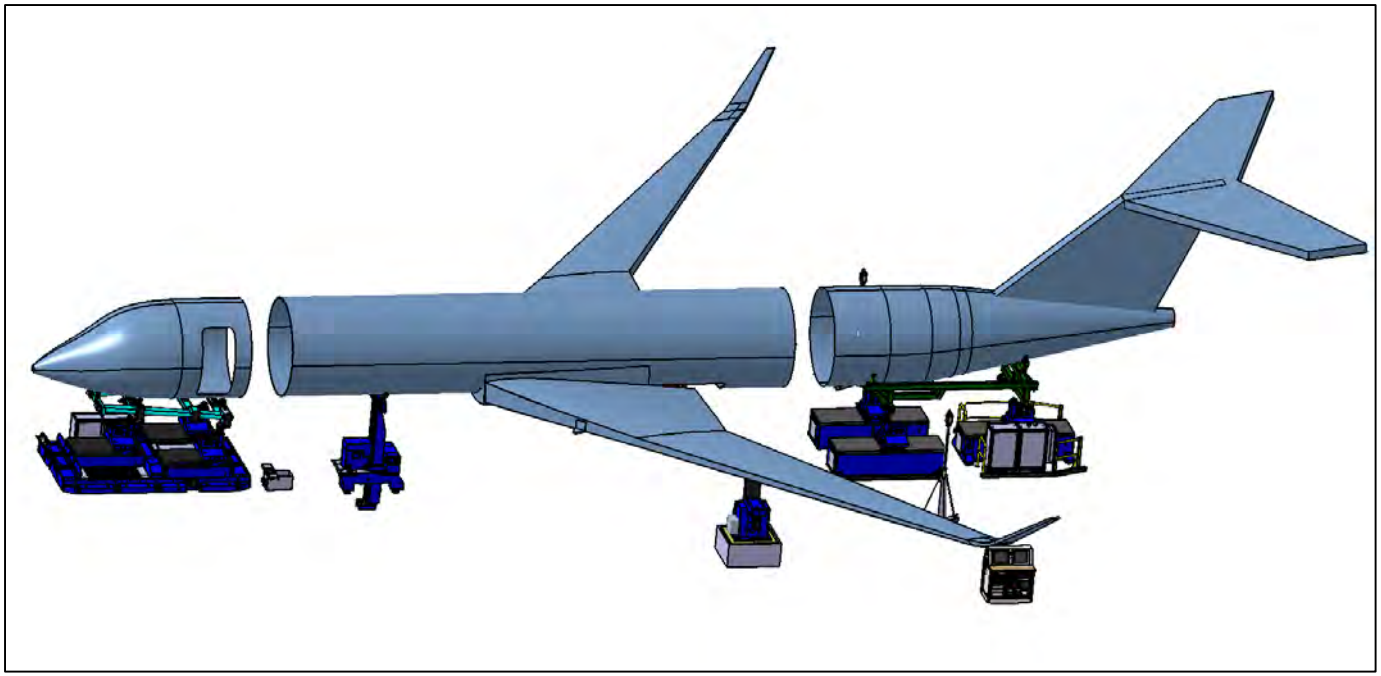
Line move example

Center fuselage is loaded via crane

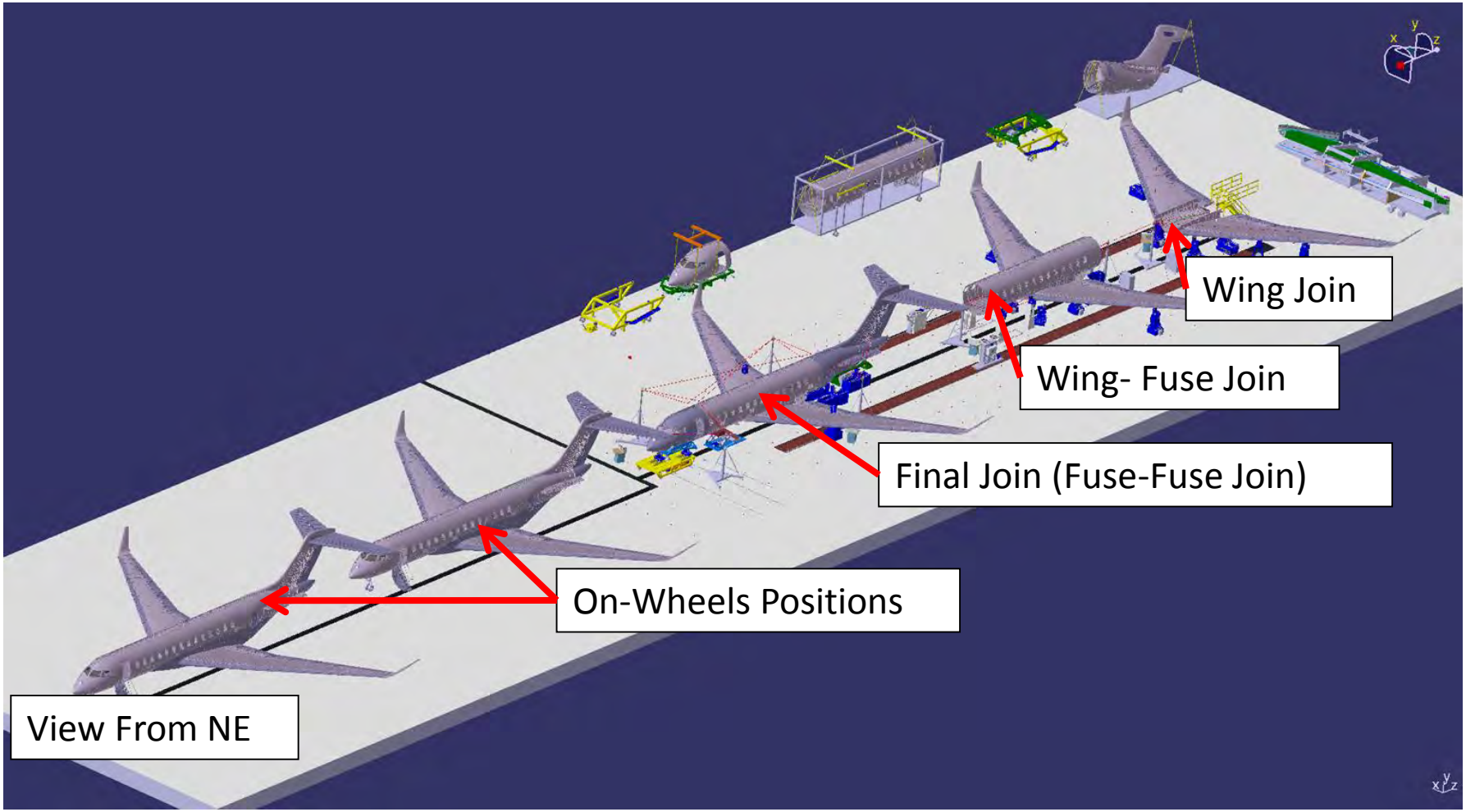
Wing-Center fuselage join completed



Forward & Aft fuselage joins completed



FAL


Wing Join
Wing- Fuse Join
Final Join (Fuse-Fuse Join)
On-Wheels Positions
View From NE

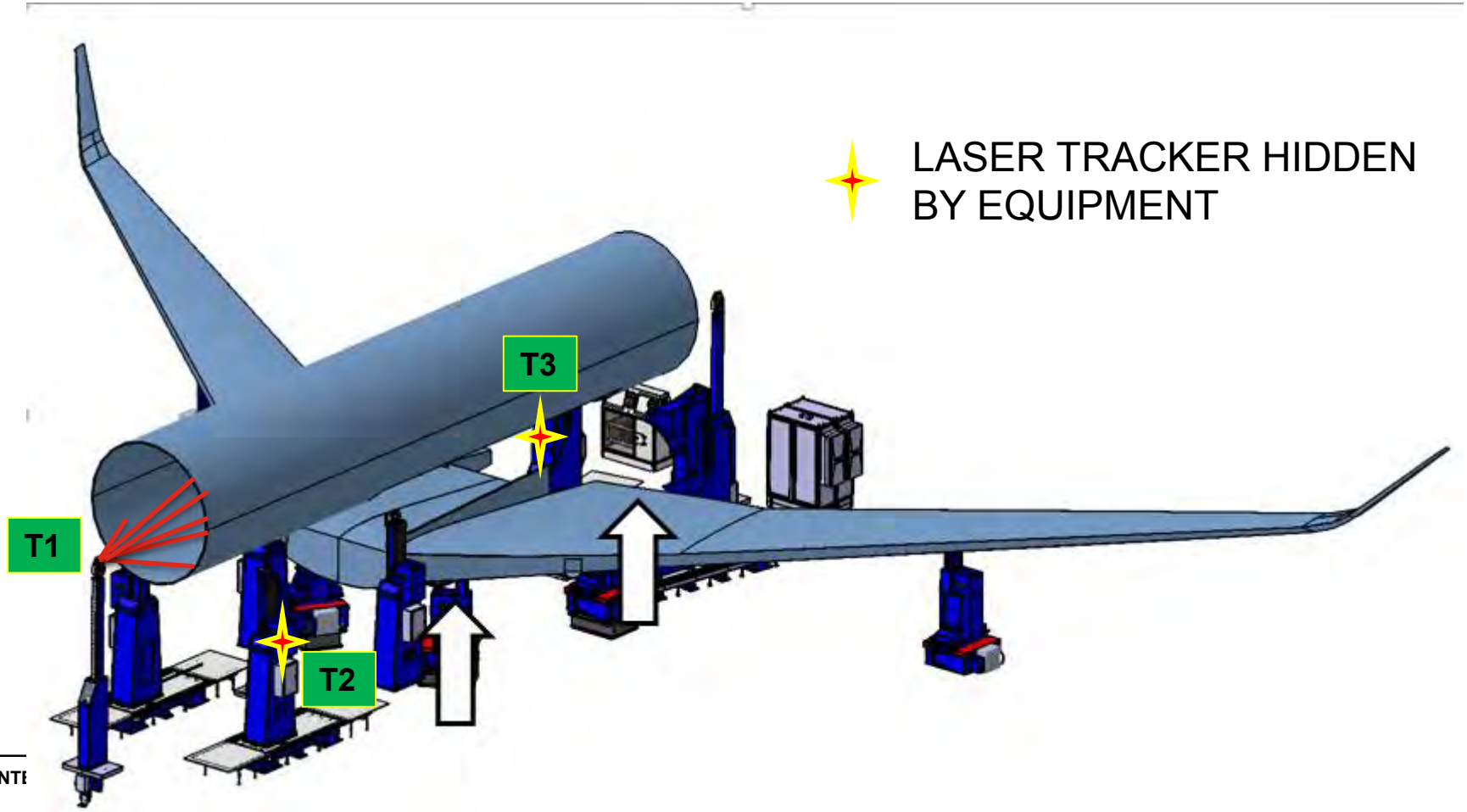
Join Details

For brevity, consider just the wing-fuselage join.

Wing-fuselage join details

Two trackers measure wing and exterior fuselage.

One tracker measures center fuselage.



Wing-Fuselage join process

1. Measure common points (in foundation) with 3 laser trackers; orient trackers.
2. Use tracker T1 to measure seat track beams at 8 points
3. Create ordinate frame for center fuselage – origin at midpoint of tension fittings.
4. Measure interface points on front and rear spar with trackers 2 and 3
5. Create ordinate frame for wing – origin at midpoint of tension fittings.
6. Calculate transformation required to make ordinate frames coincident and share same orientation.
7. Pass transformation to PLC and execute.

Wing raised to meet center fuselage

Wing moved to within 0.100” of contact, then moved to contact until load is seen on positioners.

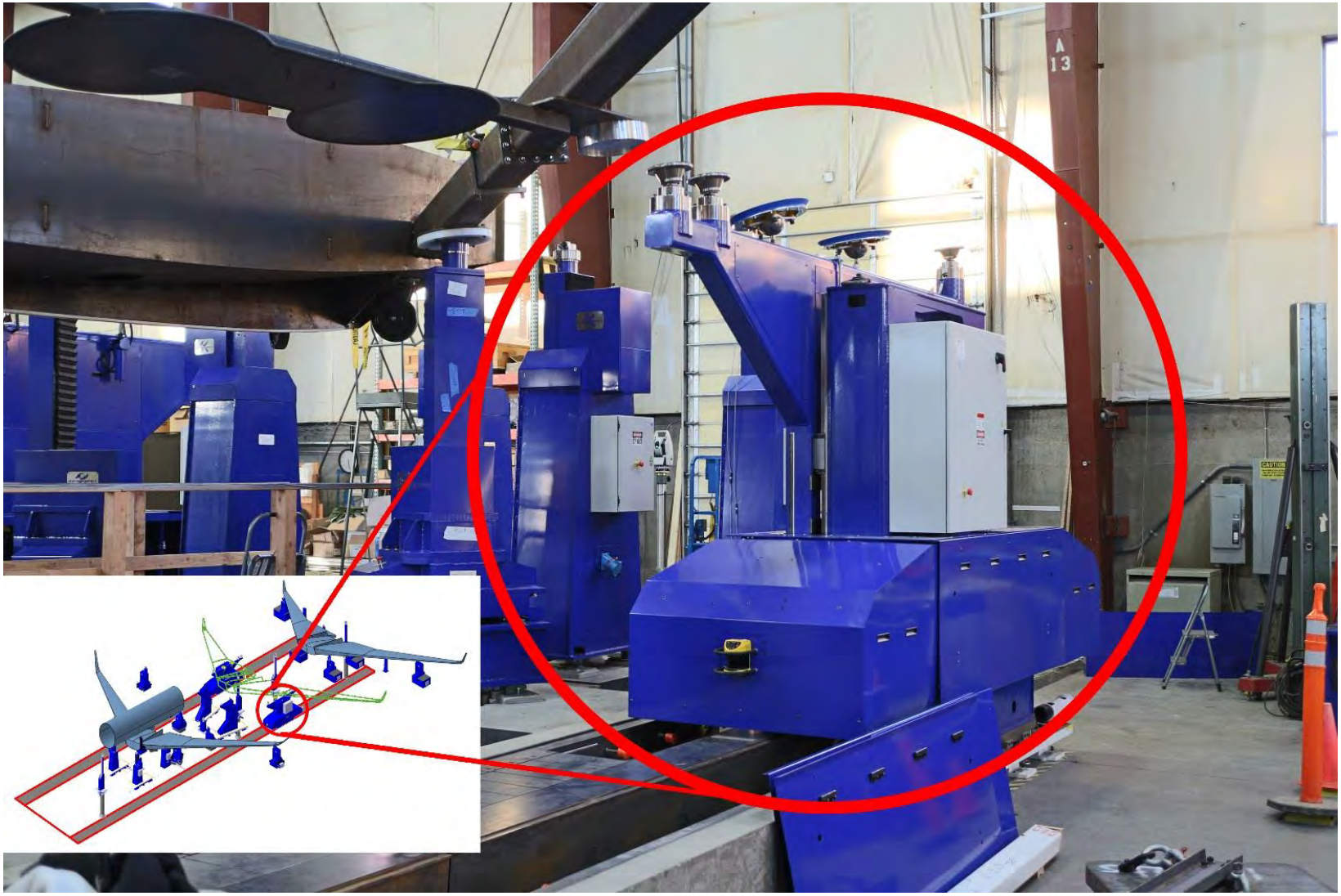
Leveling & Flight controls rigging

The task based HMI proved to be convenient for laser tracker based aircraft leveling operations as well as laser tracker based flight controls rigging validation.

Required Equipment for Adaptive tooling implementation

- **Hardware**
  - **material handling**
  - **tooling**
  - **instrumentation**
- **Software**
  - **Metrology HMI (PC)**
  - **Metrology Workflow (PC)**
  - **PLC HMI**

ATLAS & Crane material handling



Instrumentation

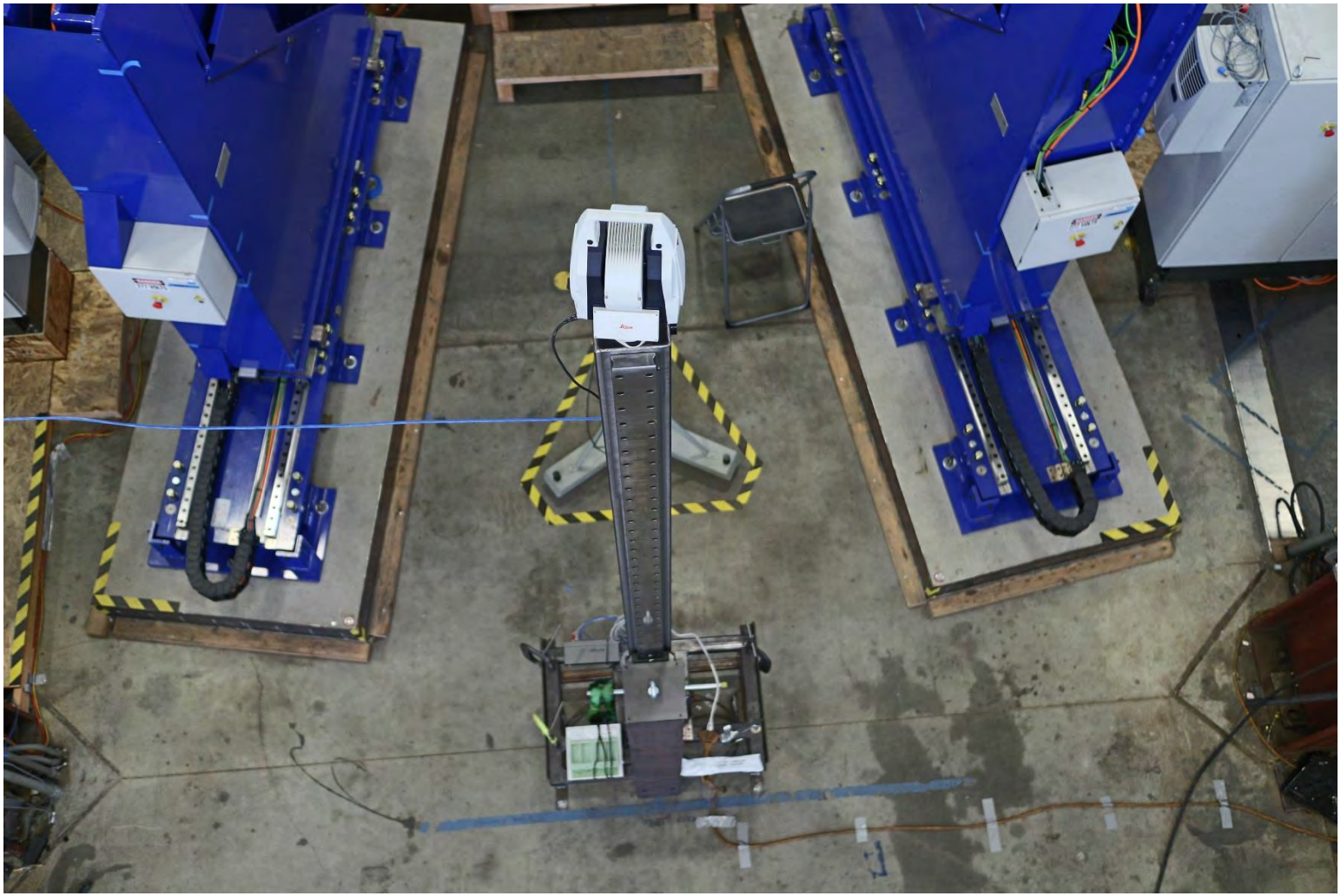
FARO Vantage for dynamic measurements (required for flight controls rigging)

Leica AT401/402 for all join applications

Targeting

Both conventional targeting and specialized targets required…vector bars shown.

Popping posts for 8-12’ of height



Positioner Hardware

Mobile Robot

Software Details

Software

FAL Software

- PLC HMI
- PC HMI
  - Workflow scripts
  - Spatial Analyzer (off-the-shelf)

What does the PC HMI do?

What does the PC HMI do?

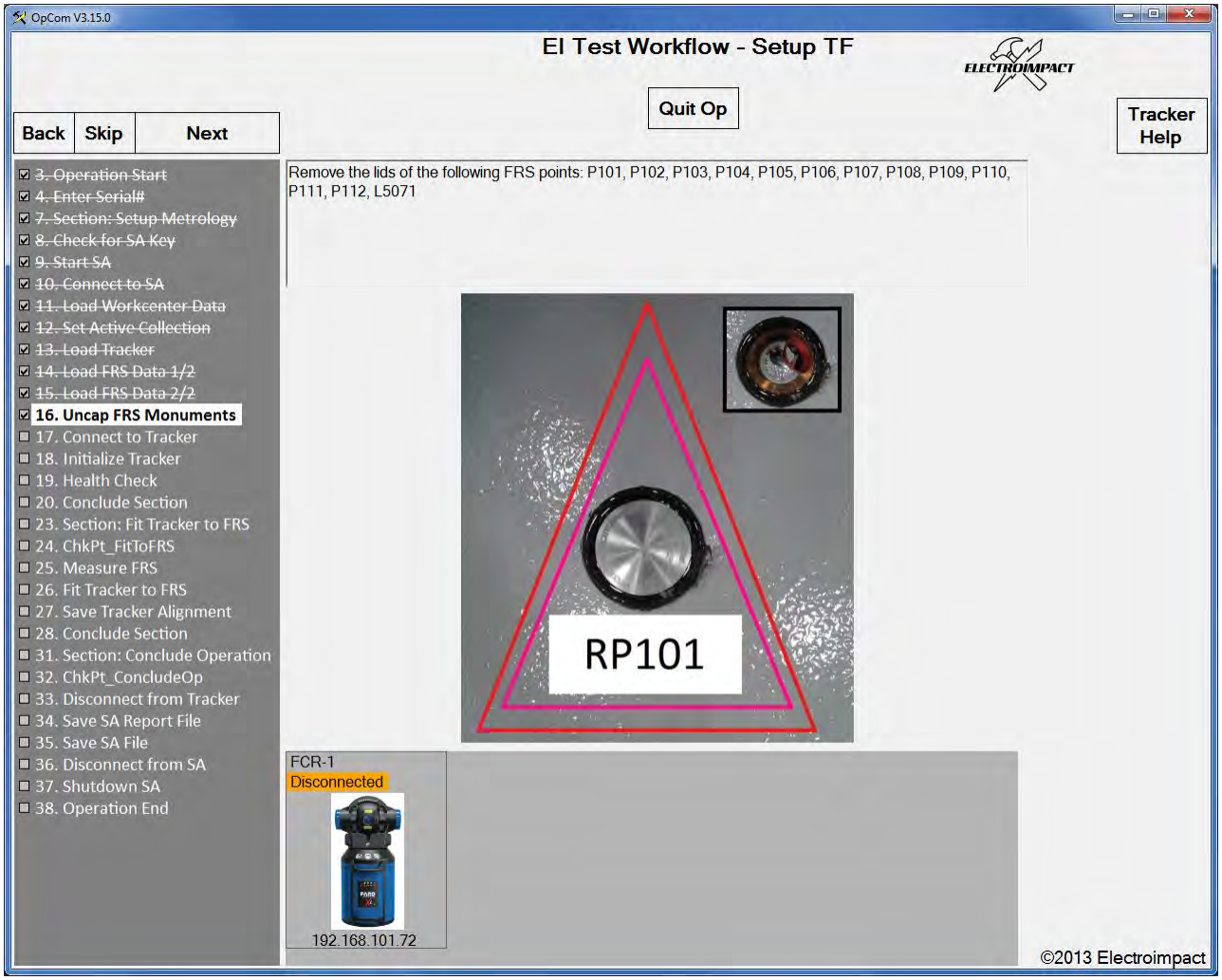
- Shows operator manual instructions
- Communicates with cell laser tracker
- Communicates with cell PLC
- Controls join process
- Issues reports

Why a custom HMI?

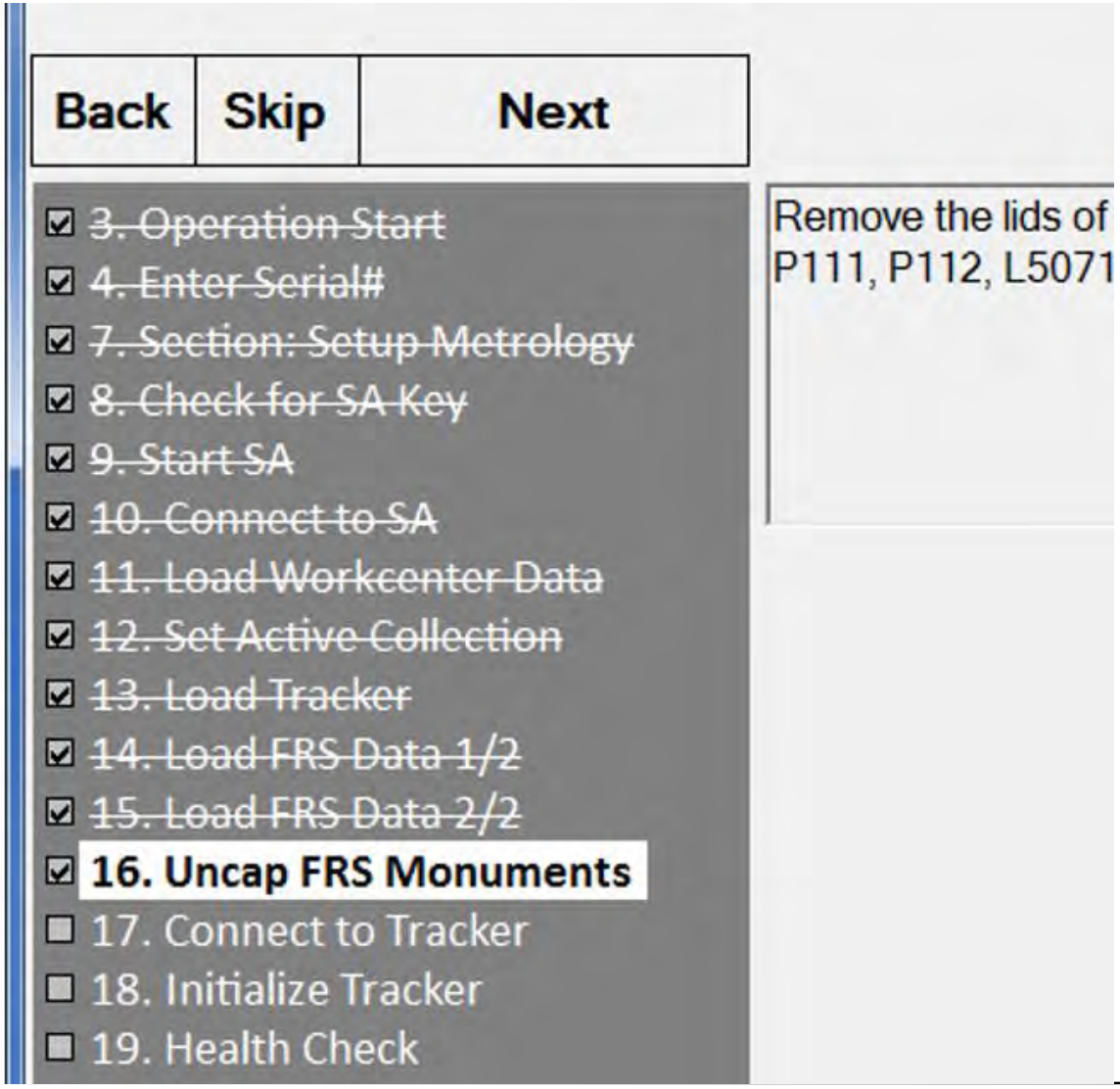
1. Lower operator training requirements
2. Increase process repeatability
3. Customize automation and user instructions uniquely per-join
4. Coordinate entire join process
5. Use to automatically generate assembly reports

HMI as seen in work cell

HMI Screenshot



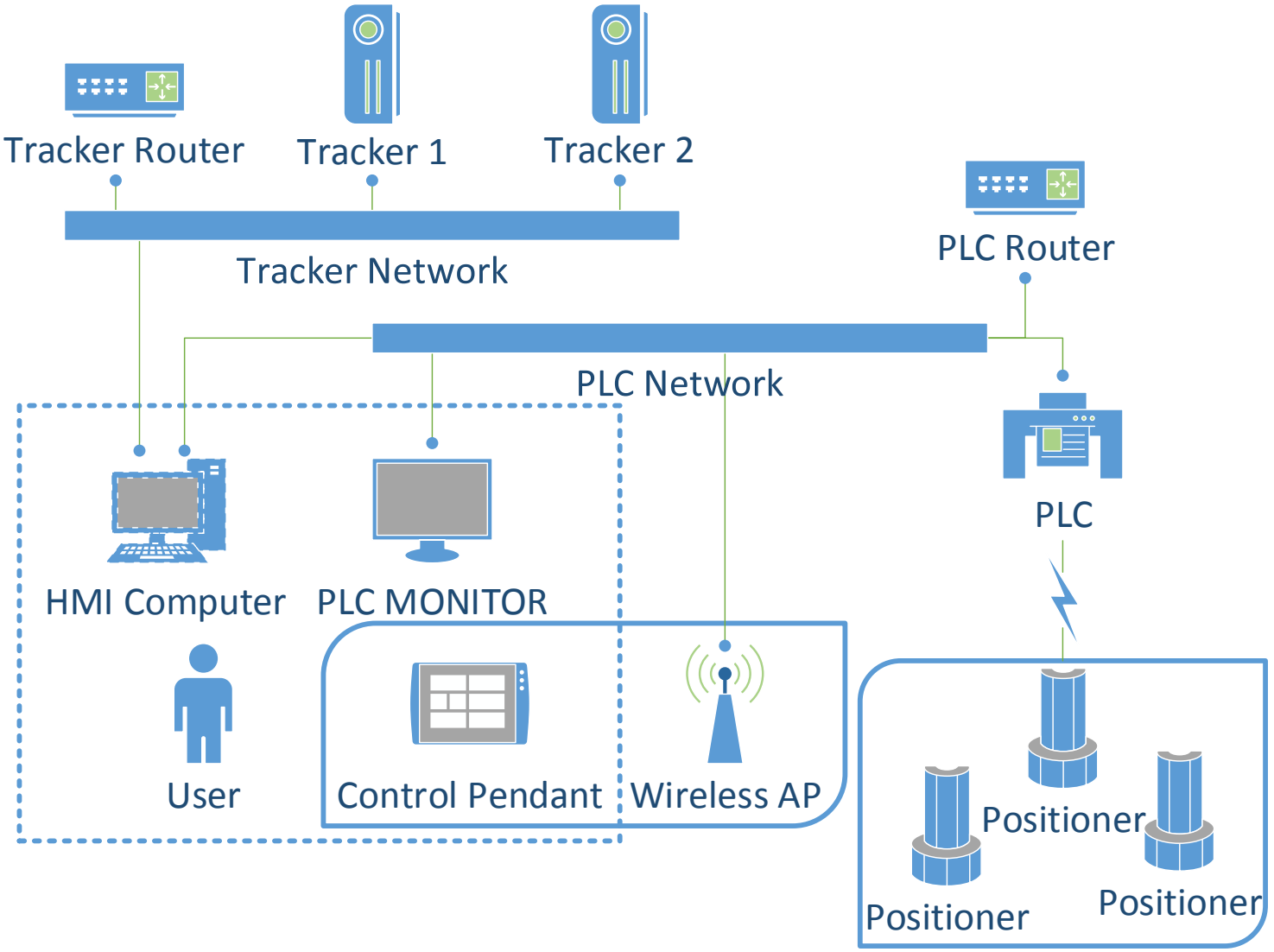
HMI details…checking off tasks



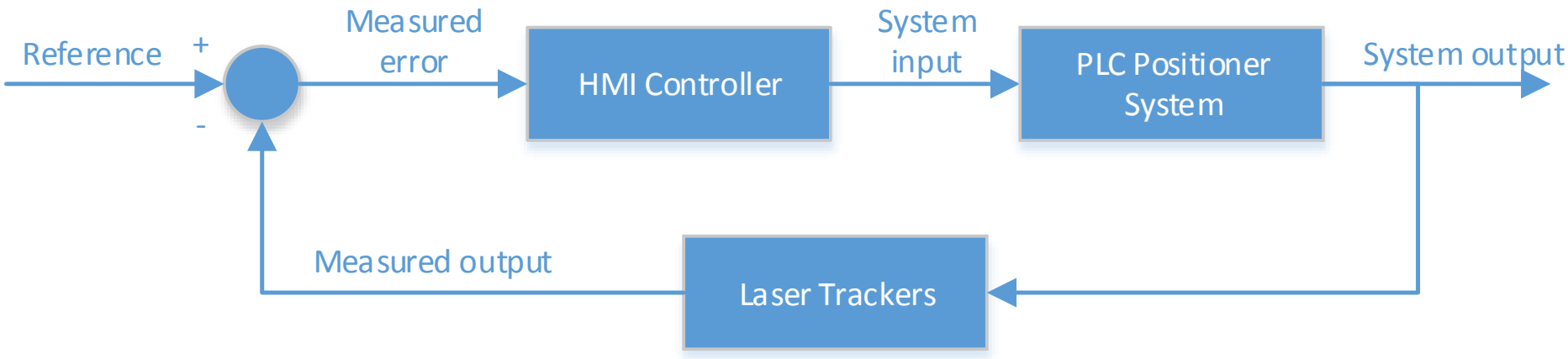
HMI Key Features

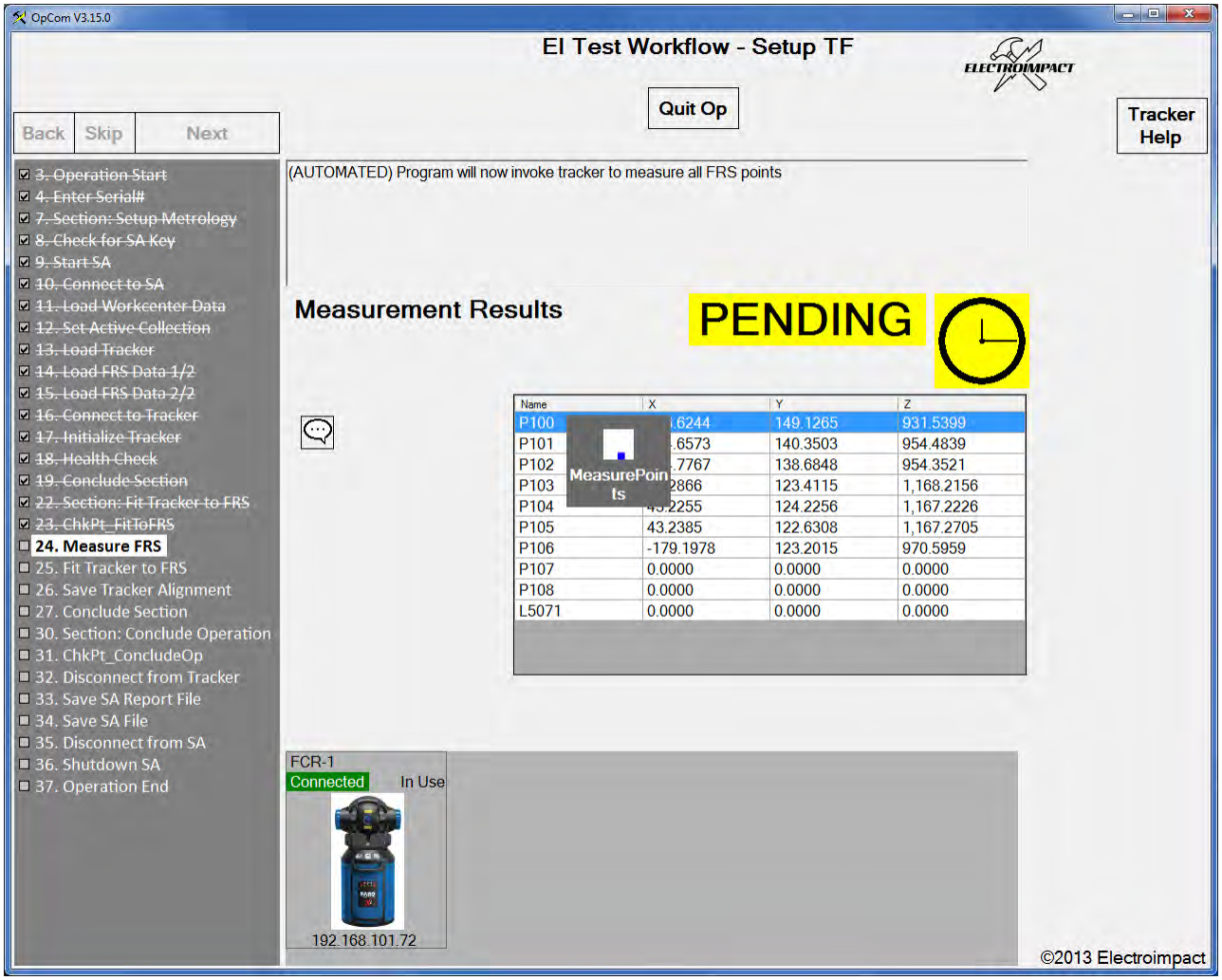
- The HMI controls laser trackers through a software interface to a dedicated metrology program called “Spatial Analyzer”
- The HMI allows non-metrologists to perform quality joins with laser trackers

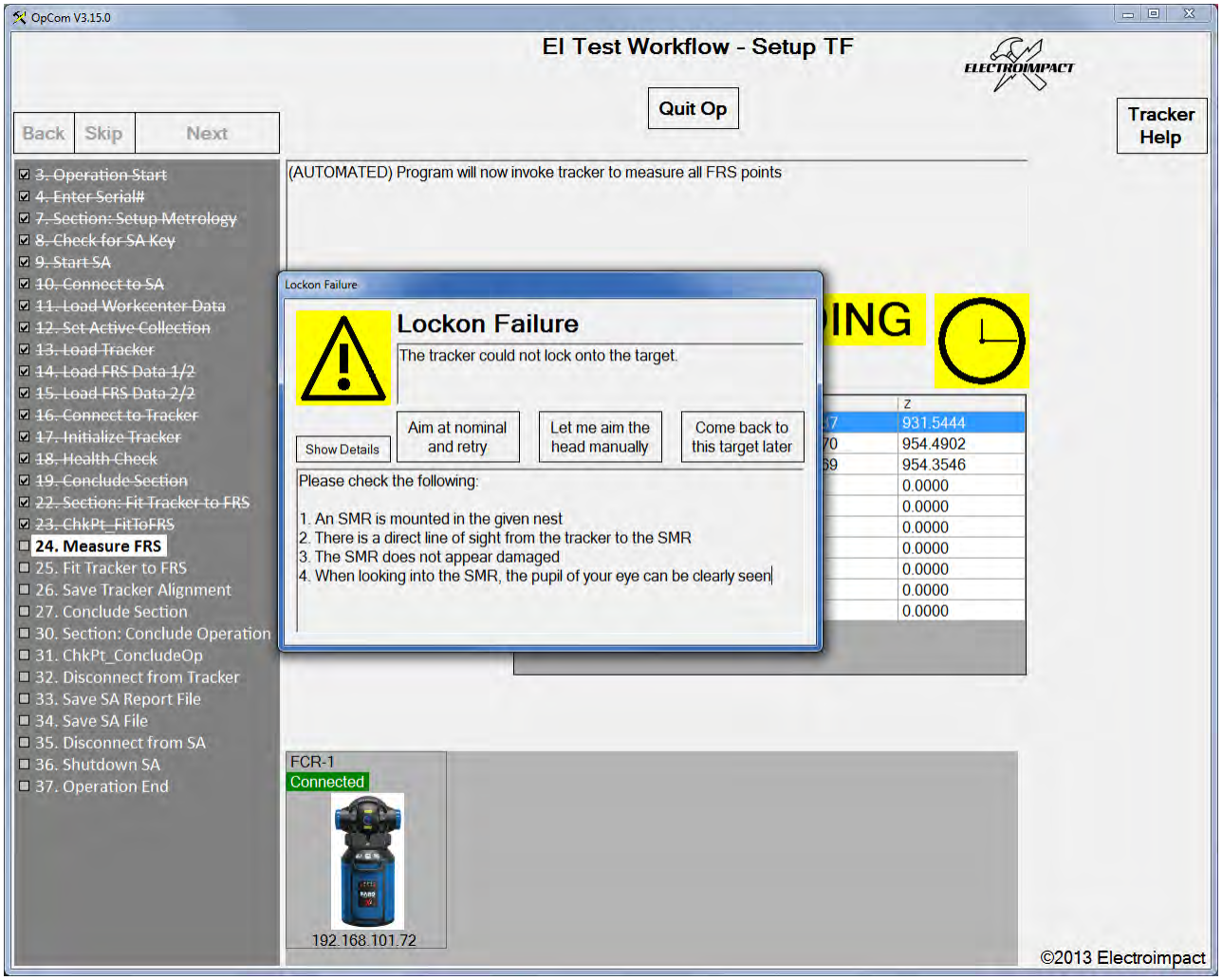
Workcenter Network Diagram



Workcenter Control Loop




OpCom V3.15.0
EI Test Workflow - Setup TF
ELECTROIMPACT
Quit Op
Tracker Help
Back
Skip
Next
(AUTOMATED) Program will now invoke tracker to measure all FRS points
Measurement Results
PENDING
MeasurePoints
Name X Y Z
P100 .6244 149.1265 931.5399
P101 .6573 140.3503 954.4839
P102 .7767 138.6848 954.3521
P103 .2866 123.4115 1,168.2156
P104 .2255 124.2256 1,167.2226
P105 43.2385 122.6308 1,167.2705
P106 -179.1978 123.2015 970.5959
P107 0.0000 0.0000 0.0000
P108 0.0000 0.0000 0.0000
L5071 0.0000 0.0000 0.0000
3. Operation Start
4. Enter Serial#
7. Section: Setup Metrology
8. Check for SA Key
9. Start SA
10. Connect to SA
11. Load Workcenter Data
12. Set Active Collection
13. Load Tracker
14. Load FRS Data 1/2
15. Load FRS Data 2/2
16. Connect to Tracker
17. Initialize Tracker
18. Health Check
19. Conclude Section
22. Section: Fit Tracker to FRS
23. ChkPt_FitToFRS
24. Measure FRS
25. Fit Tracker to FRS
26. Save Tracker Alignment
27. Conclude Section
30. Section: Conclude Operation
31. ChkPt_ConcludeOp
32. Disconnect from Tracker
33. Save SA Report File
34. Save SA File
35. Disconnect from SA
36. Shutdown SA
37. Operation End
FCR-1
Connected
In Use
192.168.101.72
©2013 Electroimpact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ELECTROIMPACT
Quit Op
Tracker Help
Back
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Next
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23. ChkPt_FitToFRS
24. Measure FRS
25. Fit Tracker to FRS
26. Save Tracker Alignment
27. Conclude Section
30. Section: Conclude Operation
31. ChkPt_ConcludeOp
32. Disconnect from Tracker
33. Save SA Report File
34. Save SA File
35. Disconnect from SA
36. Shutdown SA
37. Operation End
Lockon Failure
Lockon Failure
The tracker could not lock onto the target.
Show Details
Aim at nominal and retry
Let me aim the head manually
Come back to this target later
Please check the following:
1. An SMR is mounted in the given nest
2. There is a direct line of sight from the tracker to the SMR
3. The SMR does not appear damaged
4. When looking into the SMR, the pupil of your eye can be clearly seen
ING
Z
931.5444
954.4902
954.3546
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
FCR-1
Connected
192.168.101.72
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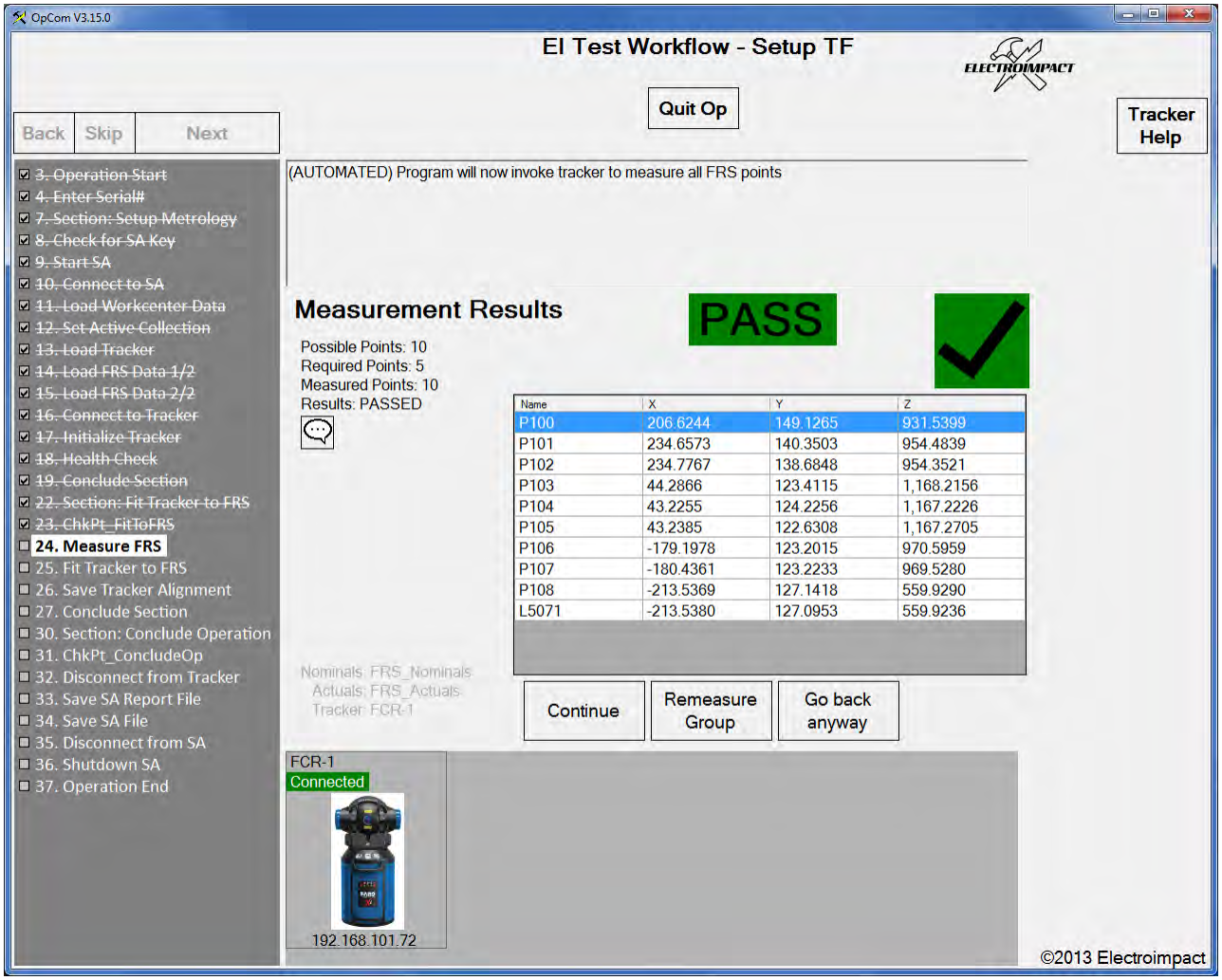
OpCom V3.15.0
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24. Measure FRS
25. Fit Tracker to FRS
26. Save Tracker Alignment
27. Conclude Section
30. Section: Conclude Operation
31. ChkPt_ConcludeOp
32. Disconnect from Tracker
33. Save SA Report File
34. Save SA File
35. Disconnect from SA
36. Shutdown SA
37. Operation End
Measurement Results
PASS
Possible Points: 10
Required Points: 5
Measured Points: 10
Results: PASSED
Name X Y Z
P100 206.6244 149.1265 931.5399
P101 234.6573 140.3503 954.4839
P102 234.7767 138.6848 954.3521
P103 44.2866 123.4115 1,168.2156
P104 43.2255 124.2256 1,167.2226
P105 43.2385 122.6308 1,167.2705
P106 -179.1978 123.2015 970.5959
P107 -180.4361 123.2233 969.5280
P108 -213.5369 127.1418 559.9290
L5071 -213.5380 127.0953 559.9236
Nominals: FRS_Nominals
Actuals: FRS_Actuals
Tracker: FCR-1
Continue
Remeasure Group
Go back anyway
FCR-1
Connected
192.168.101.72
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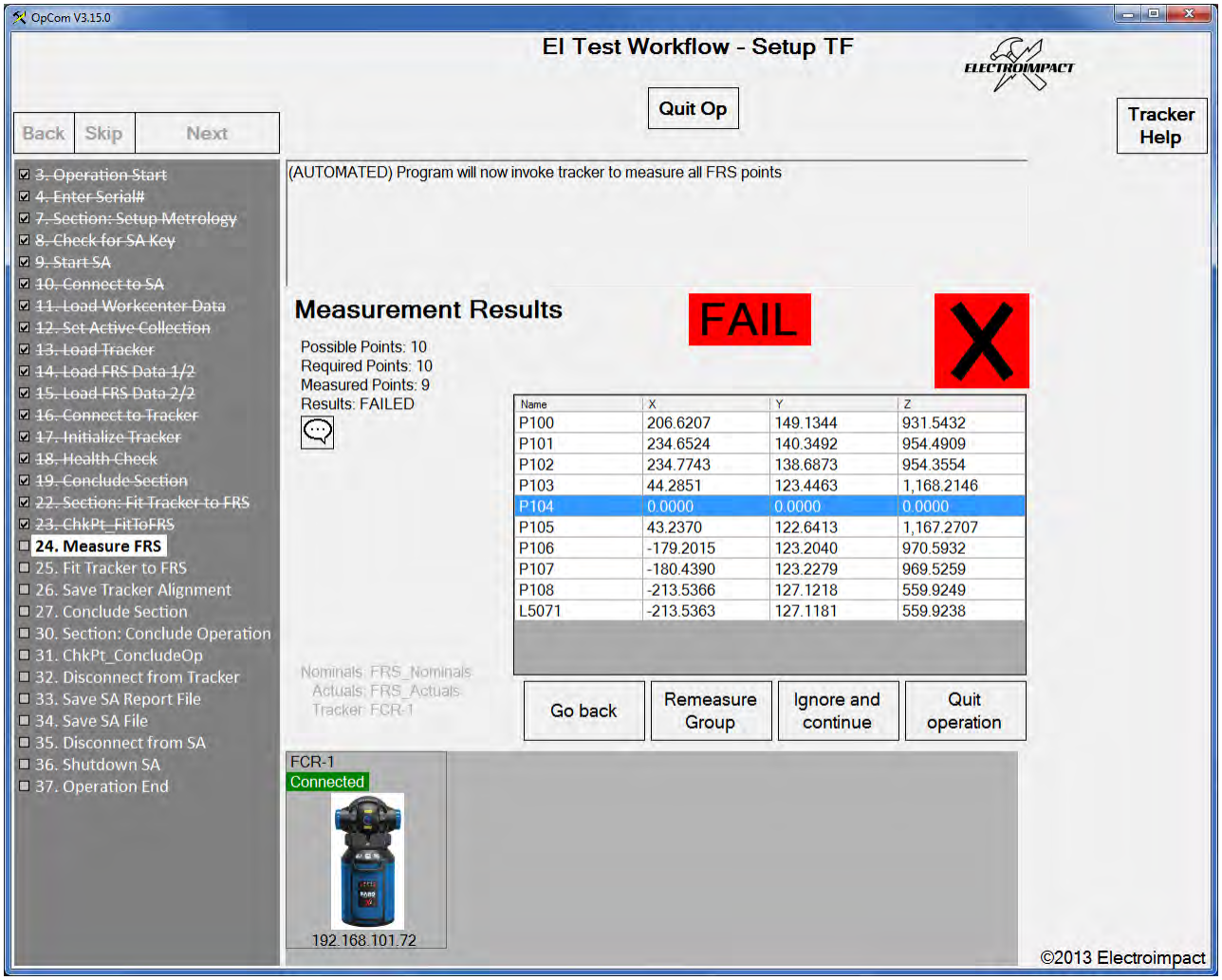
OpCom V3.15.0
EI Test Workflow - Setup TF
ELECTROIMPACT
Quit Op
Tracker Help
Back
Skip
Next
(AUTOMATED) Program will now invoke tracker to measure all FRS points
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23. ChkPt_FitToFRS
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25. Fit Tracker to FRS
26. Save Tracker Alignment
27. Conclude Section
30. Section: Conclude Operation
31. ChkPt_ConcludeOp
32. Disconnect from Tracker
33. Save SA Report File
34. Save SA File
35. Disconnect from SA
36. Shutdown SA
37. Operation End
Measurement Results
FAIL
Possible Points: 10
Required Points: 10
Measured Points: 9
Results: FAILED
Name X Y Z
P100 206.6207 149.1344 931.5432
P101 234.6524 140.3492 954.4909
P102 234.7743 138.6873 954.3554
P103 44.2851 123.4463 1,168.2146
P104 0.0000 0.0000 0.0000
P105 43.2370 122.6413 1,167.2707
P106 -179.2015 123.2040 970.5932
P107 -180.4390 123.2279 969.5259
P108 -213.5366 127.1218 559.9249
L5071 -213.5363 127.1181 559.9238
Nominals: FRS_Nominals
Actuals: FRS_Actuals
Tracker: FCR-1
Go back
Remeasure Group
Ignore and continue
Quit operation
FCR-1
Connected
192.168.101.72
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HMI Key Features

- The task-based HMI provides virtual “handrails”: enforced rules which protect the process from operator errors
- HMI can detect tracker errors and prompt user to reattempt, fix, or seek help
- Critical mileposts in the workflows have “checkpoints” that operators can fall back to

HMI Key Features

The HMI supports automated reporting

- Reports are generated as Excel and pdf documents
- Report formatting is through Excel-based macros
- Generated reports can be used to quickly resolve tolerance discrepancies

HMI-Generated Report

Workcenter:	**EI-Testing**		**Report summary:**
Joined component:	**Main_Landing_Gear**		**The results below indicate whether the individual checks passed or failed for each tolerance given.**
Serial Number:	**1005**		
Sub assembly serial numbers:	**Unset**		

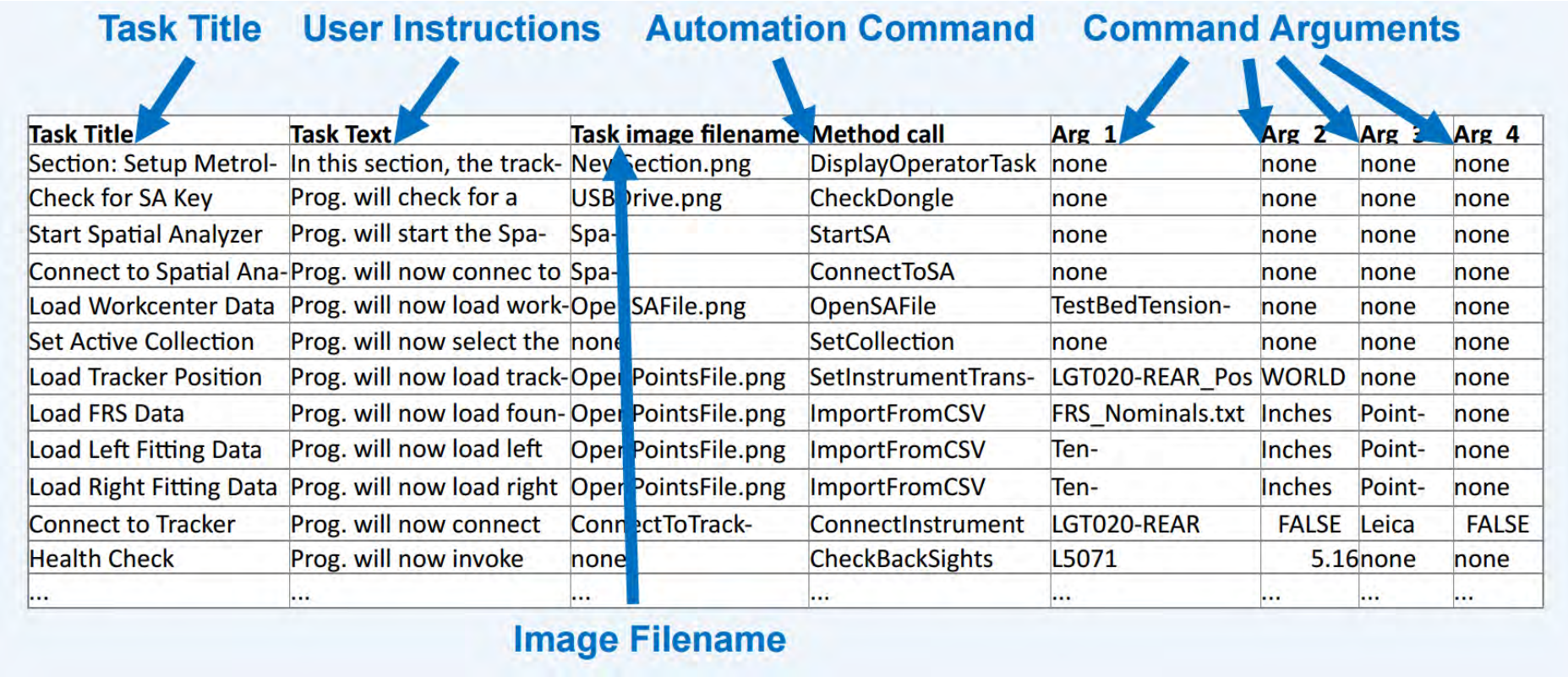
			2	3	4	5	6	7		Report Date: 22/09/2015 15:16:23		2	3	4	
Coll ID	**GROUP**	**POINT**	**X_NOM**	**Y_NOM**	**Z_NOM**	**X_TOL**	**Y_TOL**	**Z_TOL**	**Mag Tol**	**FULL POINT NAME**	**Point**	**ActX**	**ActY**	**ActZ**	**dX**
MacroTest	TestReport	P101	44.930805	73.598139	698.97295	0	0	0	0	MacroTests_TestReportANominals_P1	P101	45.339	73.587	699.112	0.408
MacroTest	TestReport	P102	36.605446	73.671111	693.68061	0	0	0	0	MacroTests_TestReportANominals_P1	P102	36.482	73.666	693.473	-0.123
MacroTest	TestReport	P103	34.897979	73.750257	696.3885	0	0	0	0	MacroTests_TestReportANominals_P1	P103	34.603	73.754	696.427	-0.295
MacroTest	TestReport	P104	43.220337	73.678573	701.67009	0	0	0	0	MacroTests_TestReportANominals_P1	P104	43.458	73.675	702.066	0.238
MacroTest	TestReport	P105	42.790735	73.654305	699.45246	0	0	0	0	MacroTests_TestReportANominals_P1	P105	42.826	73.656	699.590	0.036
MacroTest	TestReport	P101	44.930805	73.598139	698.97295	0	0	0	0	MacroTests_TestReportANominals_P1	P101	45.339	73.587	699.112	0.408
MacroTest	TestReport	P102	36.605446	73.671111	693.68061	0	0	0	0	MacroTests_TestReportANominals_P1	P102	36.482	73.666	693.473	-0.123
MacroTest	TestReport	P103	34.897979	73.750257	696.3885	0	0	0	0	MacroTests_TestReportANominals_P1	P103	34.603	73.754	696.427	-0.295
MacroTest	TestReport	P104	43.220337	73.678573	701.67009	0	0	0	0	MacroTests_TestReportANominals_P1	P104	43.458	73.675	702.066	0.238
MacroTest	TestReport	P105	42.790735	73.654305	699.45246	0	0	0	0	MacroTests_TestReportANominals_P1	P105	42.826	73.656	699.590	0.036
0	0	0	0	0	0	0	0	0	0	0_0_0	0	#N/A	#N/A	#N/A	#N/A
0	0	0	0	0	0	0	0	0	0	0_0_0	0	#N/A	#N/A	#N/A	#N/A
0	0	0	0	0	0	0	0	0	0	0_0_0	0	#N/A	#N/A	#N/A	#N/A
0	0	0	0	0	0	0	0	0	0	0_0_0	0	#N/A	#N/A	#N/A	#N/A

HMI Key Features

Highly customizable join methodology

- Instructions written in Excel spreadsheet
- Each row represents 1 task to perform
- Supports customer-driven process revs
- Easily changeable graphics and user instructions

Workflow Example



Task Title	Task Text	Task image filename	Method call	Arg_1	Arg_2	Arg_3	Arg_4
Section: Setup Metrol-	In this section, the track-	New Section.png	DisplayOperatorTask	none	none	none	none
Check for SA Key	Prog. will check for a	USB Drive.png	CheckDongle	none	none	none	none
Start Spatial Analyzer	Prog. will start the Spa-	Spa-	StartSA	none	none	none	none
Connect to Spatial Ana-	Prog. will now connec to	Spa-	ConnectToSA	none	none	none	none
Load Workcenter Data	Prog. will now load work-	Ope SAFile.png	OpenSAFile	TestBedTension-	none	none	none
Set Active Collection	Prog. will now select the	none	SetCollection	none	none	none	none
Load Tracker Position	Prog. will now load track-	Oper PointsFile.png	SetInstrumentTrans-	LGT020-REAR_Pos	WORLD	none	none
Load FRS Data	Prog. will now load foun-	Oper PointsFile.png	ImportFromCSV	FRS_Nominals.txt	Inches	Point-	none
Load Left Fitting Data	Prog. will now load left	Oper PointsFile.png	ImportFromCSV	Ten-	Inches	Point-	none
Load Right Fitting Data	Prog. will now load right	Oper PointsFile.png	ImportFromCSV	Ten-	Inches	Point-	none
Connect to Tracker	Prog. will now connect	Conn ctToTrack-	ConnectInstrument	LGT020-REAR	FALSE	Leica	FALSE
Health Check	Prog. will now invoke	none	CheckBackSights	L5071	5.16	none	none
...	...	...	...	...	...	...	...

HMI Recap

HMI Strengths

1. Lowers operator training requirements
2. Coordinates entire join process
3. Can be used to automatically generate assembly reports
4. Customizable automation and user instructions
5. Increases process repeatability

Conclusion: Adaptive tooling benefits

Adaptive tooling:

- **In conjunction with automated metrology, improves part and join metrics.**
- **In conjunction with a task-based HMI, standardizes assembly process, making it deskilled and automated.**
- **Enables the use of more sophisticated and appropriate join criteria over hard tooling.**
- **Enables join optimization which in turn reduces overall assembly error.**

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