Accuracy Needs for Autonomy

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TITAN Overview

Products

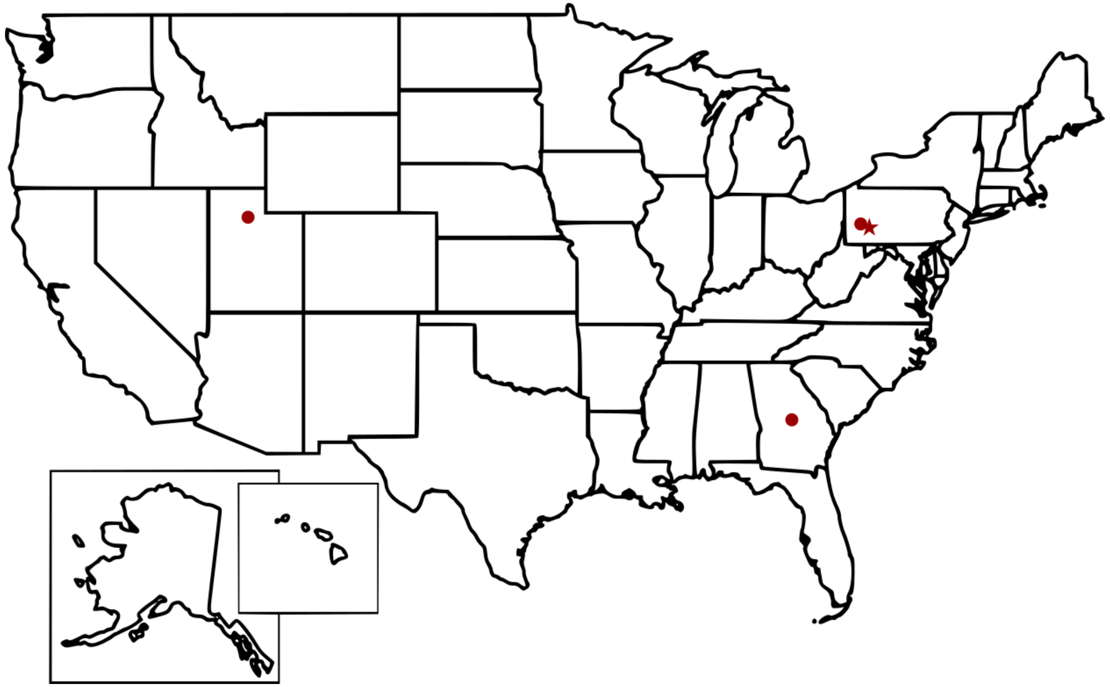
Extra Large to Medium sized robotic systems
Specializing in solving challenging problems
Focused on adaptive processes

Growth

70 + Employees
2024 Fastest growing companies in PGH
2024 Best places to work in PGH
100% Organic Growth, not VC Funded

Facilities

★ Headquarters & Engineering in Pittsburgh, PA
● Integration and Test Facility at PIT Airport
● Southern Support office in Georgia
● Western Support office in Utah



Who we are

Full Vertical Robotics Engineering Team

- Full-Stack expertise in Process Control, Hardware, Electrical, Automation, Safety, Software, and UX/UI
- Experience researching, developing, and building custom production ready automation solutions

Reliable Autonomy that Adapts Like a Skilled Artisan

- Level IV+ Industrial Autonomy
- Efficient automatic tool paths and process control to perform tasks according to configurable process parameters, sensor data, and operator preferences without the need for human review

Unlimited Configurations Including Mobility

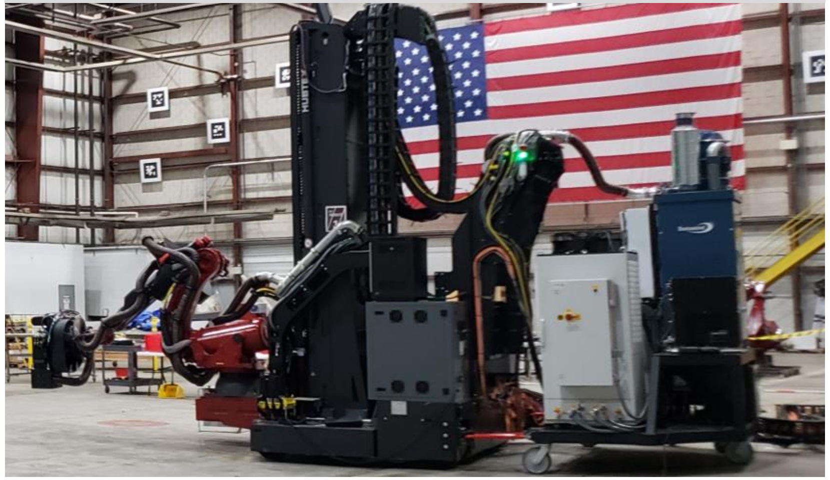
- Autonomous mobile manipulators, gantries, fixed systems, movable workpieces, etc...
- Specify hardware configuration based on customer needs
- Safe, reliable, collision free, navigation in environments with high value workpieces

Precision manufacturing is dominated by manual labor (still!)

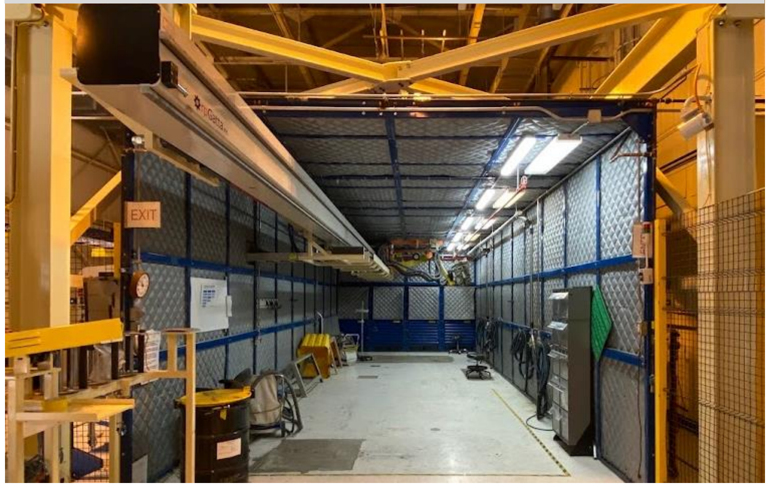
- **Aerospace, Large Vehicle, Semi-Custom Asset, Manufacturing/Remanufacturing are very manual.**
- **Often Dull, Dirty, Dangerous Tasks**
- **Why no automation?**
  - High-Mix
  - Large Scale
  - Variations in each workpiece
  - Workpieces placed in different locations
  - Artisanal, Adaptive, and Selective processes

Deployed Systems

Laser Coating Removal



Sanding

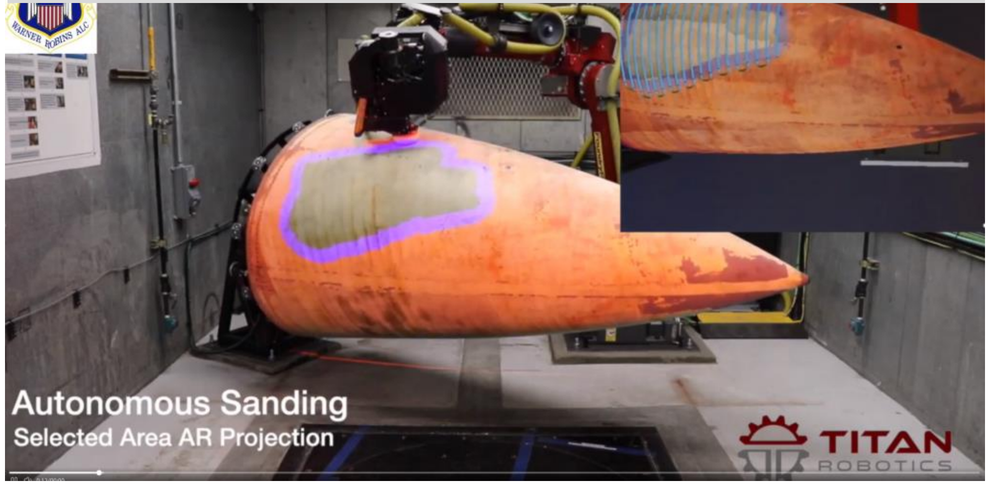


Thermal Spray

Paint

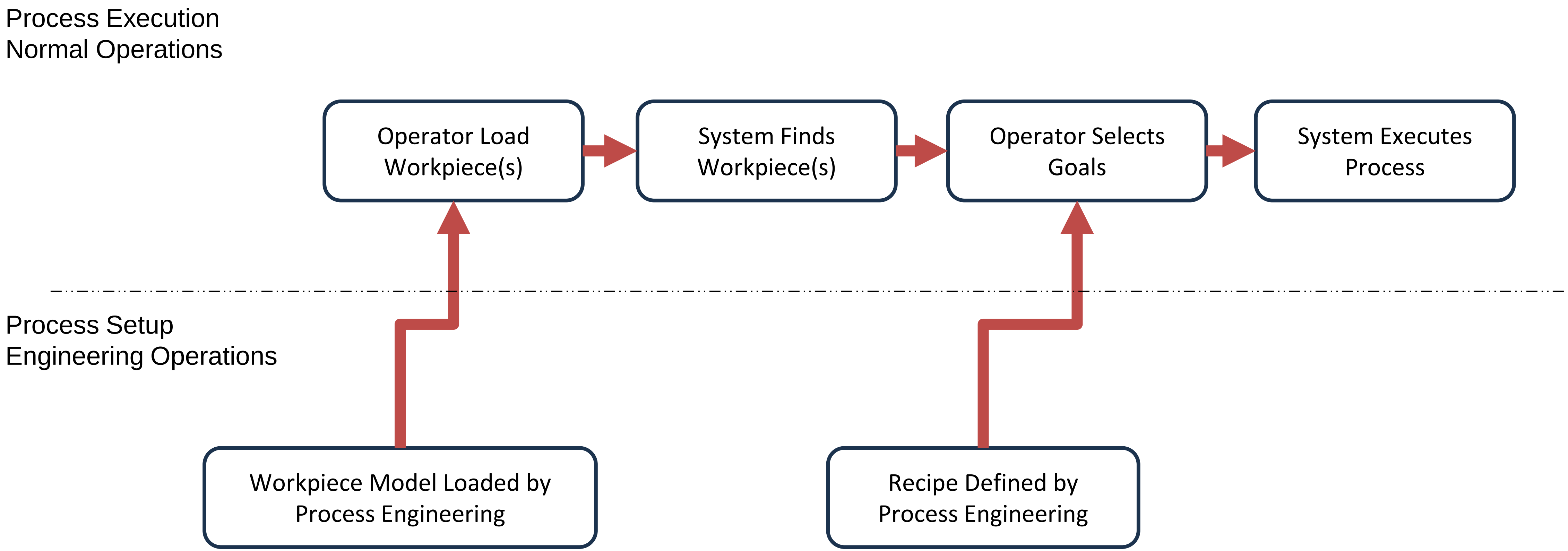
Defastening

Composite Repair



Laser Depaint, Painting, Sanding, Milling, X-ray, NDI, Defastening, Thermal Spray, Metrology, and others.

System Operation at a Glance



Systems as a Tool

A Titan System is a Tool

What is being automated?	What is the goal?	Where is the application?
A tool that can [industrial process]	based on [input mechanism] on	[desired workpiece] without programming.

[industrial process]	[input mechanism]	[desired workpiece]
Paint	Coating requirements	Aerospace control surfaces
Sand	Visual inspection	Aerospace structures
Grind	Surface geometry	Sheet metal weldments
Media Blast	Operator input	Flat components
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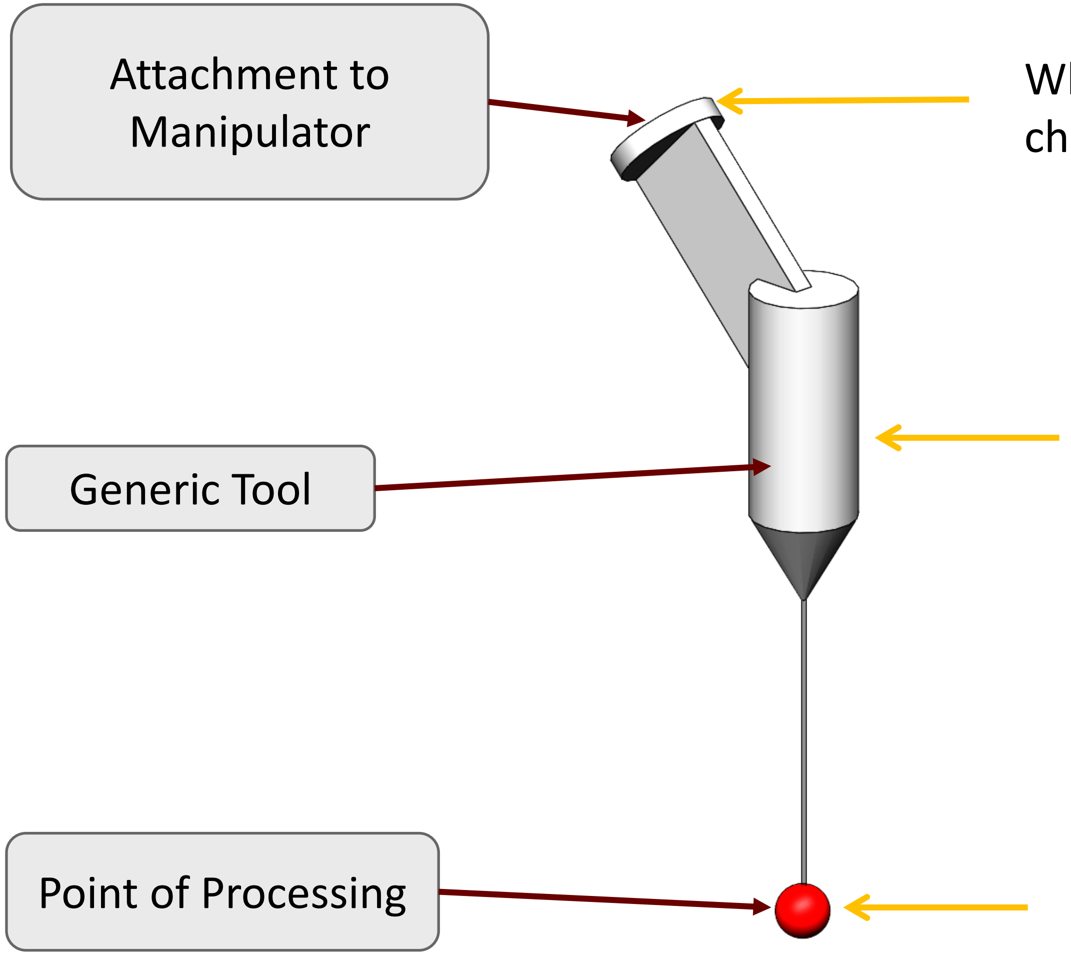
.	.	.
.	.	.

There is always a positional relationship between a tool and a workpiece that matters.

A Generic Tool



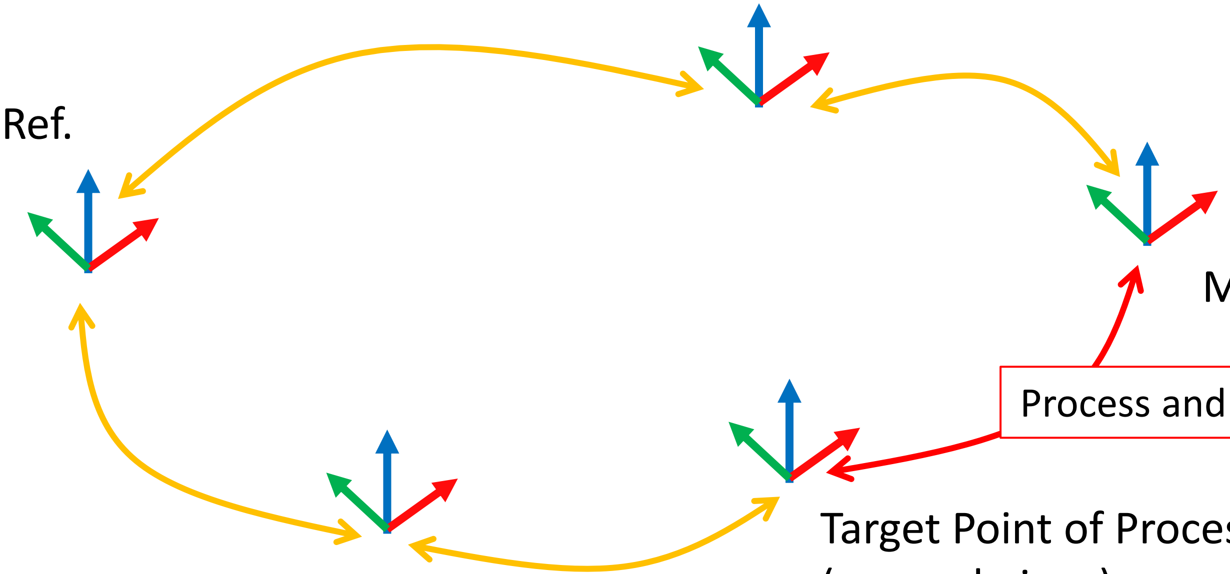
Where the tool attaches to the upstream kinematic chain.

The tool that is sensing something, dispensing something, or touching something.

The point where the tooling is interacting with the workpiece.

Positional Relationships

If a system always works on a workpiece, there is always complete kinematic chain that can be assessed.
Note the world ref. for all systems to provide a common reference.



Pose in Time

- With tighter process precision requirements, there is an increased need to understand the relationship between commanded time and actuation time.

- Accuracy of operations where there is constant motion of the process tooling while executing a process will suffer the most when time is not considered in the accuracy of the system.

- With well characterized hardware, it is possible to compensate for known temporal effects.

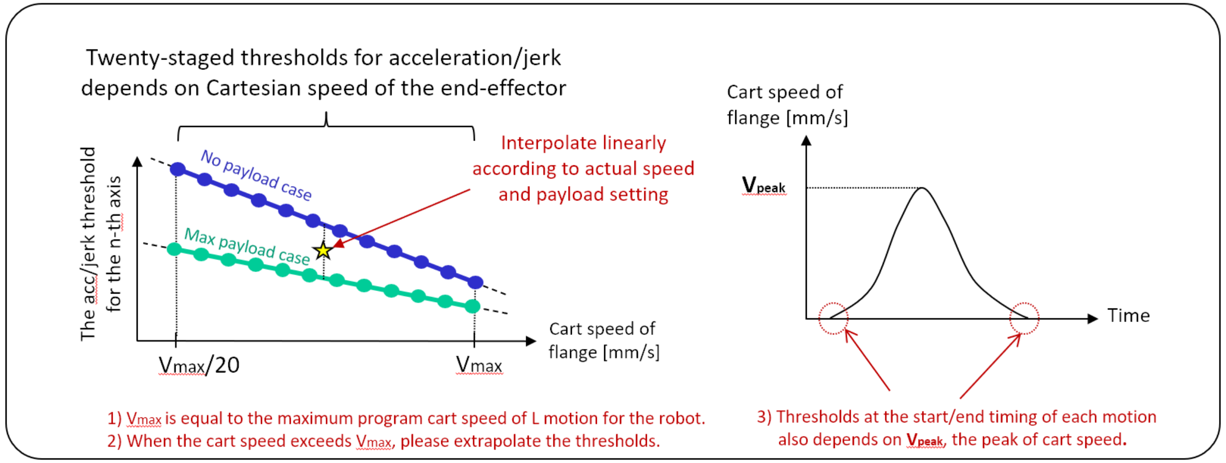
Titan has trajectory planners that adhere to:

- Position Limits
- Velocity Limits
- Acceleration Limits
- Jerk Limits

AND

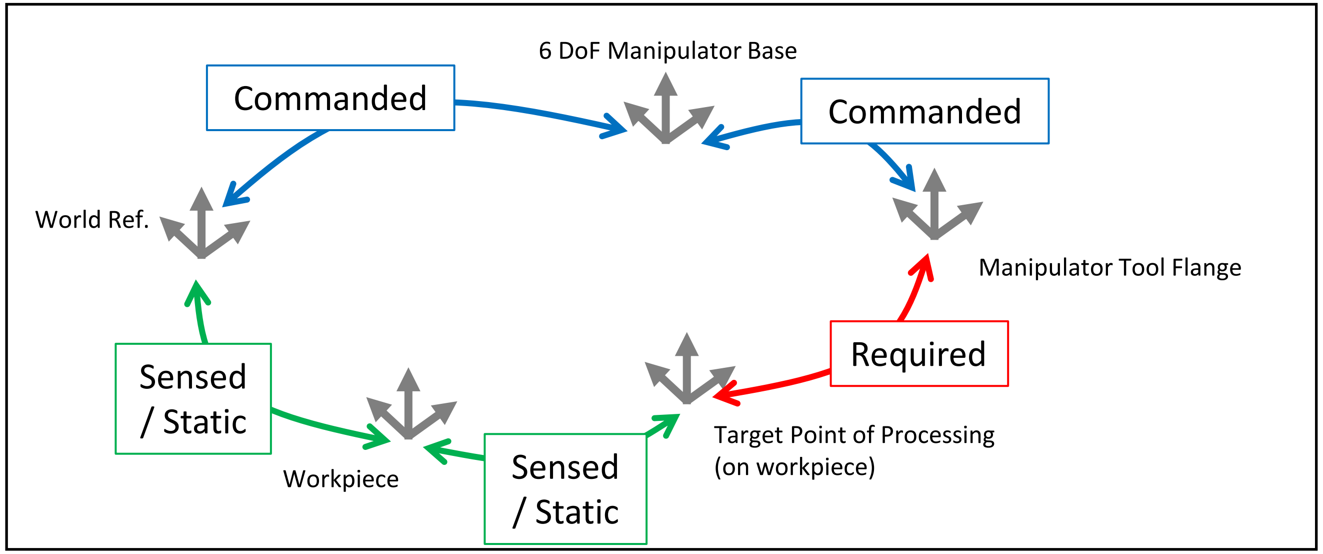
- the ability to spool out trajectories with a temporal shift to compensate for hardware latency.

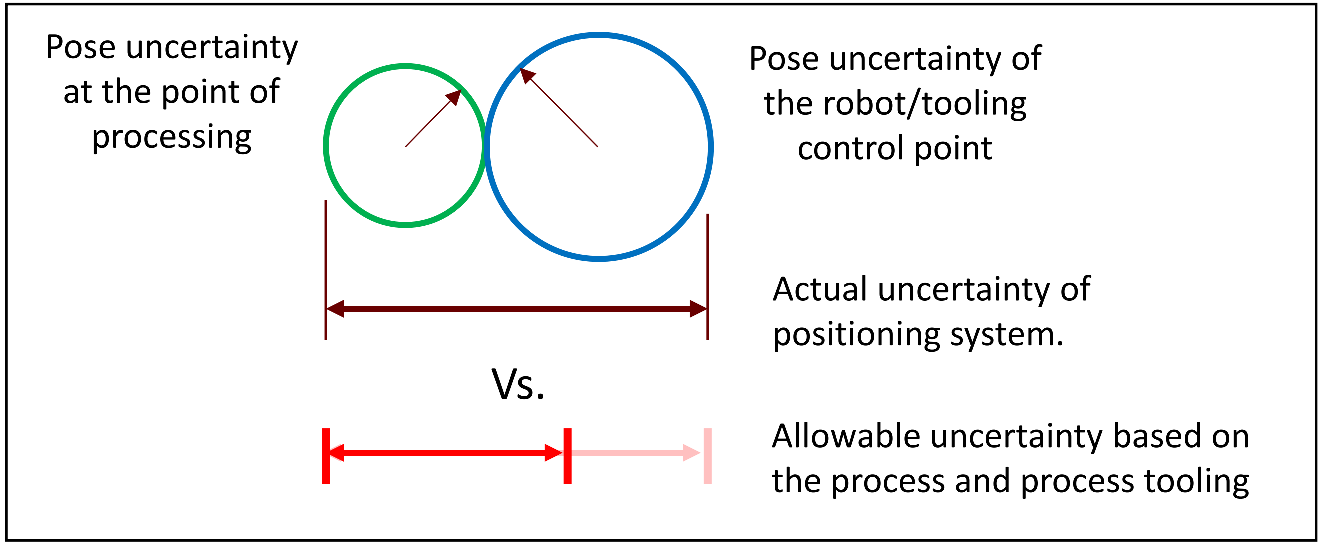
Example Documentation for Manipulator Vendor (FANUC)



Category	Contents of inquiry	Answer example
Tracking performance	How long is the time delay for the robot to actually reach the desired position specified in the command packet?	In the case of an robot with 8ms interval, there is a delay of about 50 ms including communication delay and servo tracking delay. (It becomes about half of that in case of a robot with 4ms interval) There is no way to make this shorter.

The Full Stack Simplified





When designing a system, we are iterating on the choices of Process Tooling, Manipulator Hardware Selection, and Workpiece Localization Approach to create a positioning uncertainty stack such that is less than the allowable uncertainty of the Process and allowed by the capabilities of the Process Tooling.

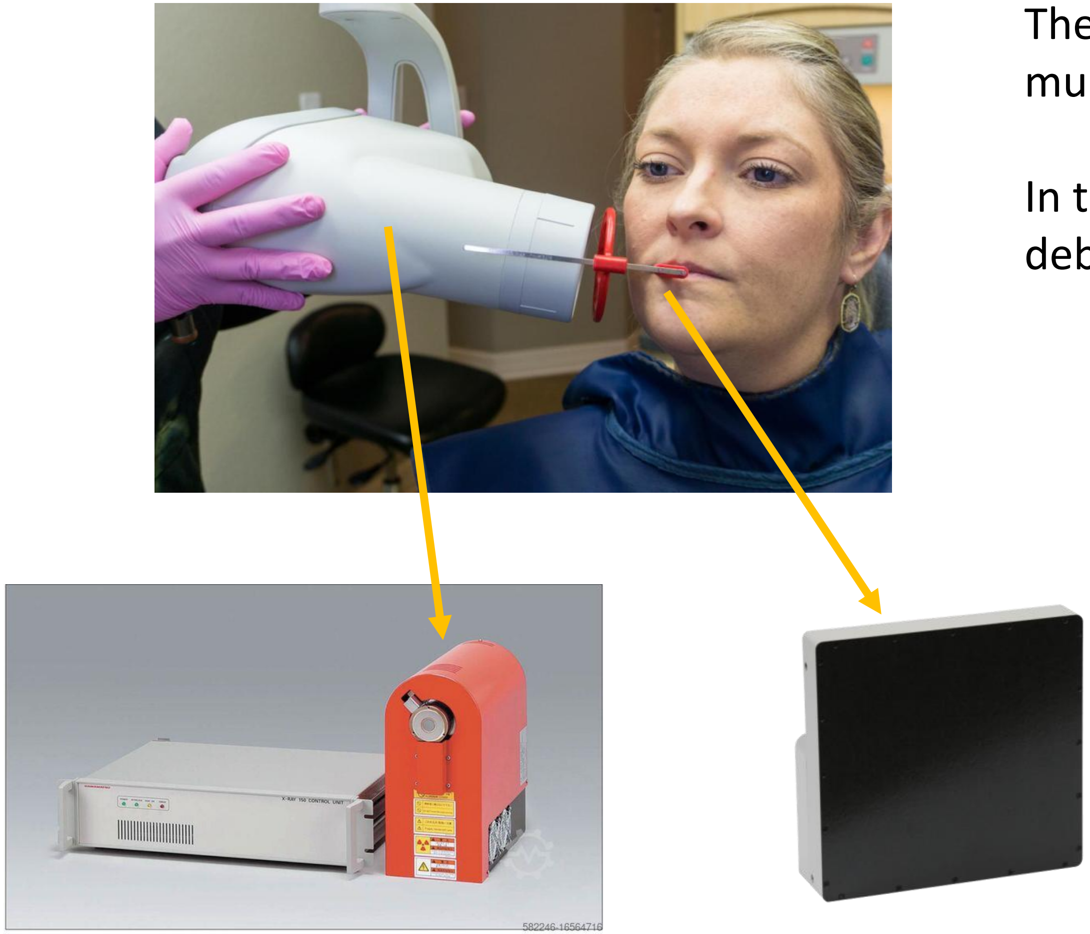
Fundamental Approaches Balanced in Design:

- Reduce positioning uncertainty
- Reduce localization uncertainty
- Increase allowance for tooling positioning accuracy

TITAN ROBOTICS

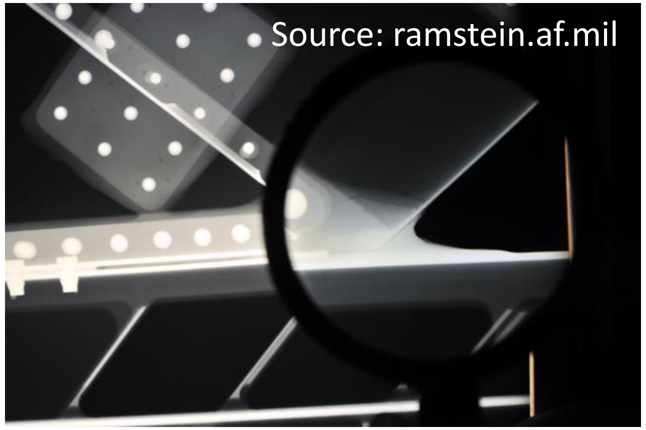
An Example – USAF Digital X-Ray

Example – USAF X-Ray



The USAF uses various types of X-Ray inspection techniques for multiple inspections.

In this example the goal is to use digital x-ray for foreign object and debris (FOD) inspection to find things that should not be there.



Example – USAF X-Ray

Titan Goal:
Add autonomy to an existing digital x-ray hardware system.

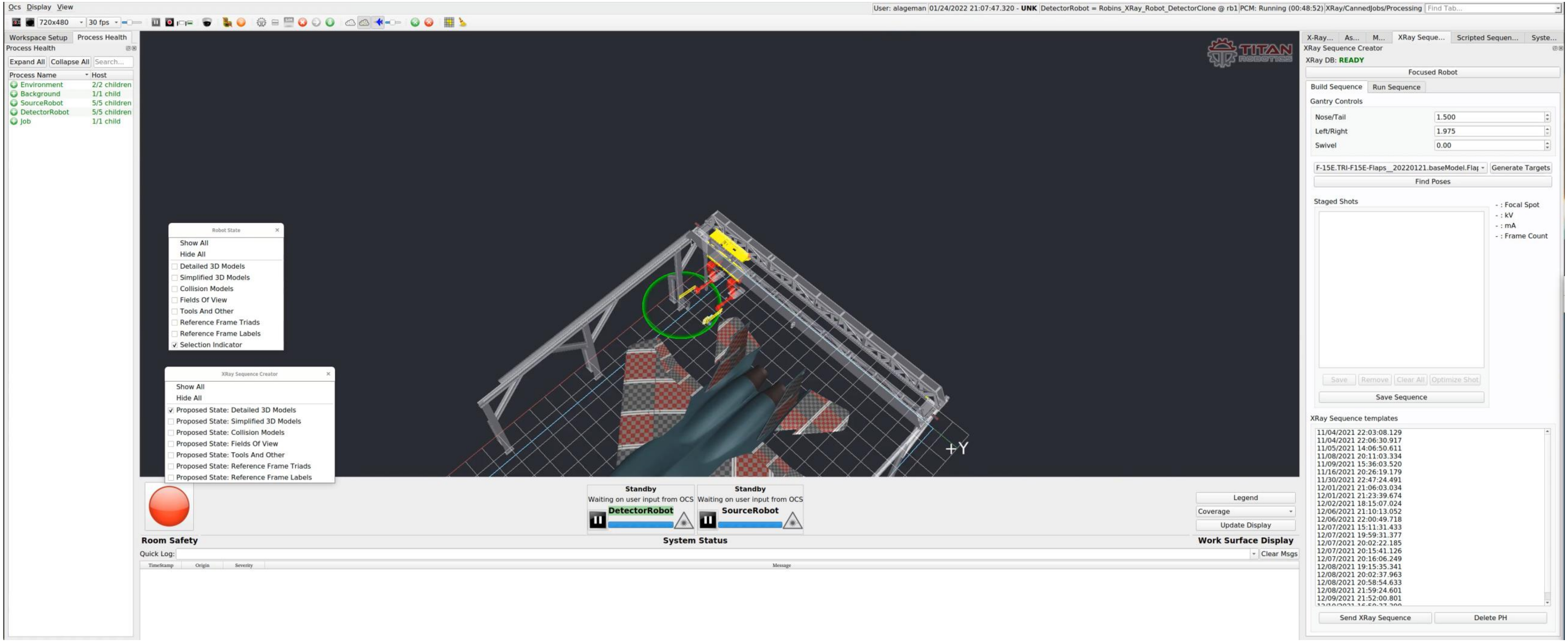
- Autonomously plan shot positions given an inspection area set by the operator
- Autonomously plan and execute robot motions between shots
- Trigger 3rd party x-ray equipment

Wingspan: 42.8 feet (13 meters)
Length: 63.8 feet (19.44 meters)
Height: 18.5 feet (5.6 meters)


Source: USAF Flickr

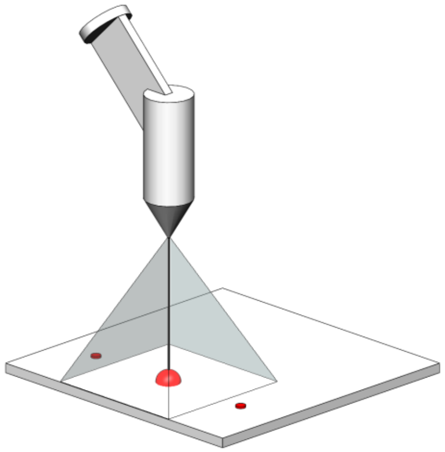

Source: afmc.af.mil

Example – USAF X-Ray



Example – USAF X-Ray

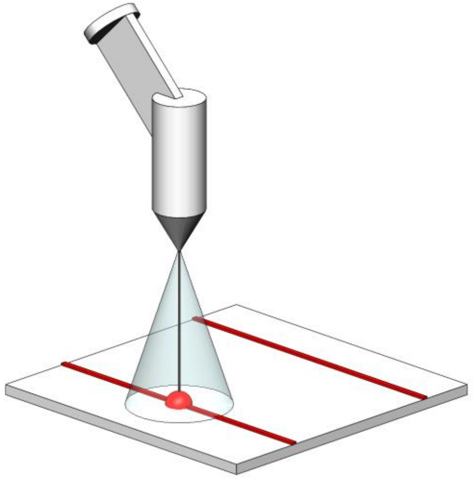
Detector Positioning Requirements



Area Tool
Positioned relative to the workpiece.
Active area 6”x6”

Z-Offset	~2 inches	+/- 0.5 inches
X-Y Position	User Defined (aircraft relative)	+/- 0.5 inches
Z-Orientation	User Defined (shot to shot relative)	< 5 degrees
X-Y Orientation (Z Normalcy)	Z- Normal	< 5 degrees

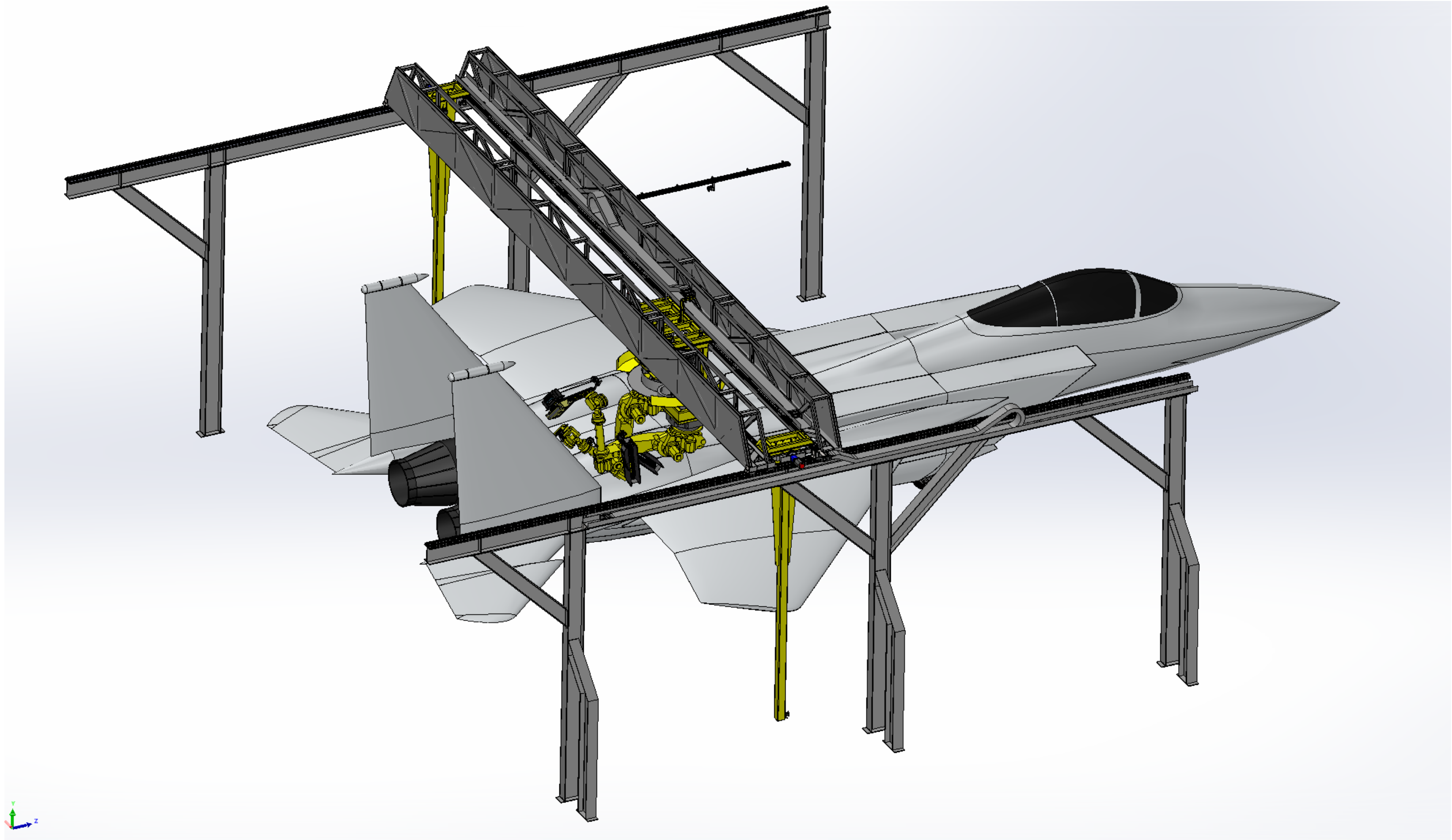
Source Positioning Requirements



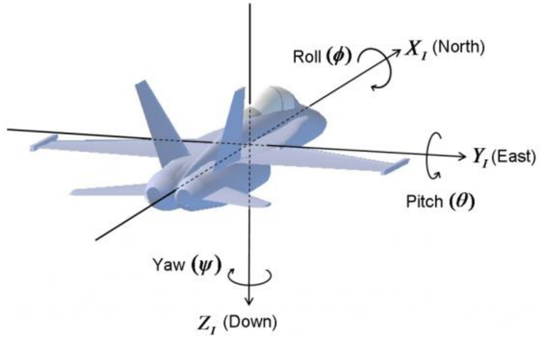
Conical Tool
Positioned relative to the detector.
Derived based on detector hardware properties.

Z-Offset	~50 inches (from detector)	+/- 2 inches
X-Y Position	User Defined (detector center relative)	+/- 2 inches
Z-Orientation	N/A	N/A
X-Y Orientation (Z Normalcy)	Z- Normal (to detector face nominal)	< 2 degrees

Example – USAF X-Ray

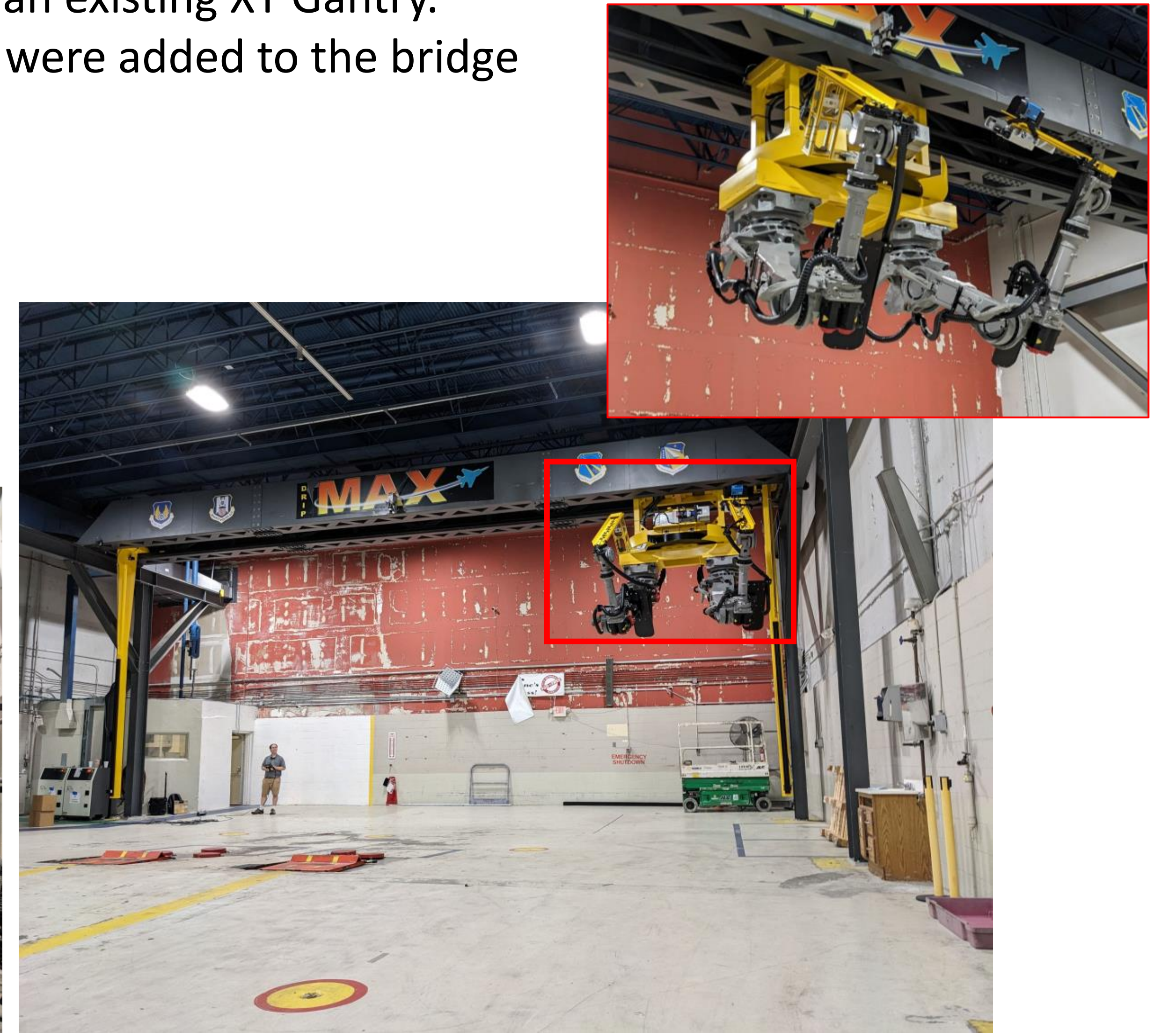


Allowable Aircraft Positioning Relative to a Nominal Pose in World Frame	
X Position	+/- 12 inches
Y Position	+/- 12 inches
Z Position	+/- 6 inches
Roll	+/- 1.2 degrees
Pitch	+/- 2 degrees
Yaw	+/- 2 degrees



Example – USAF X-Ray

- Major mechanical modifications were made to an existing XY Gantry.
- Industrial manipulators and a rotary positioner were added to the bridge carriage.

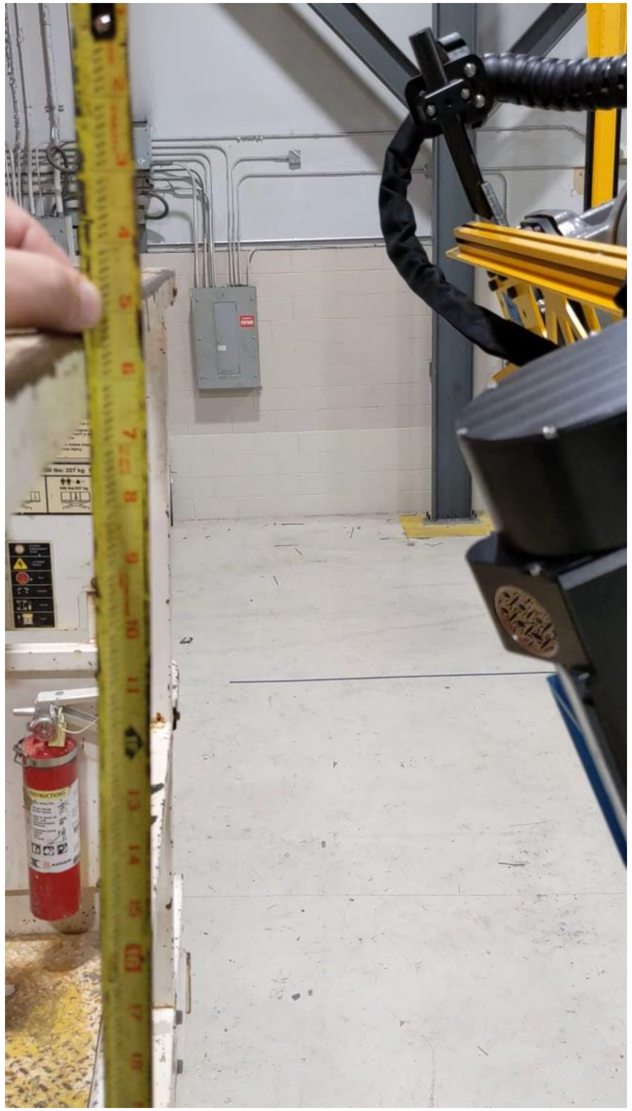


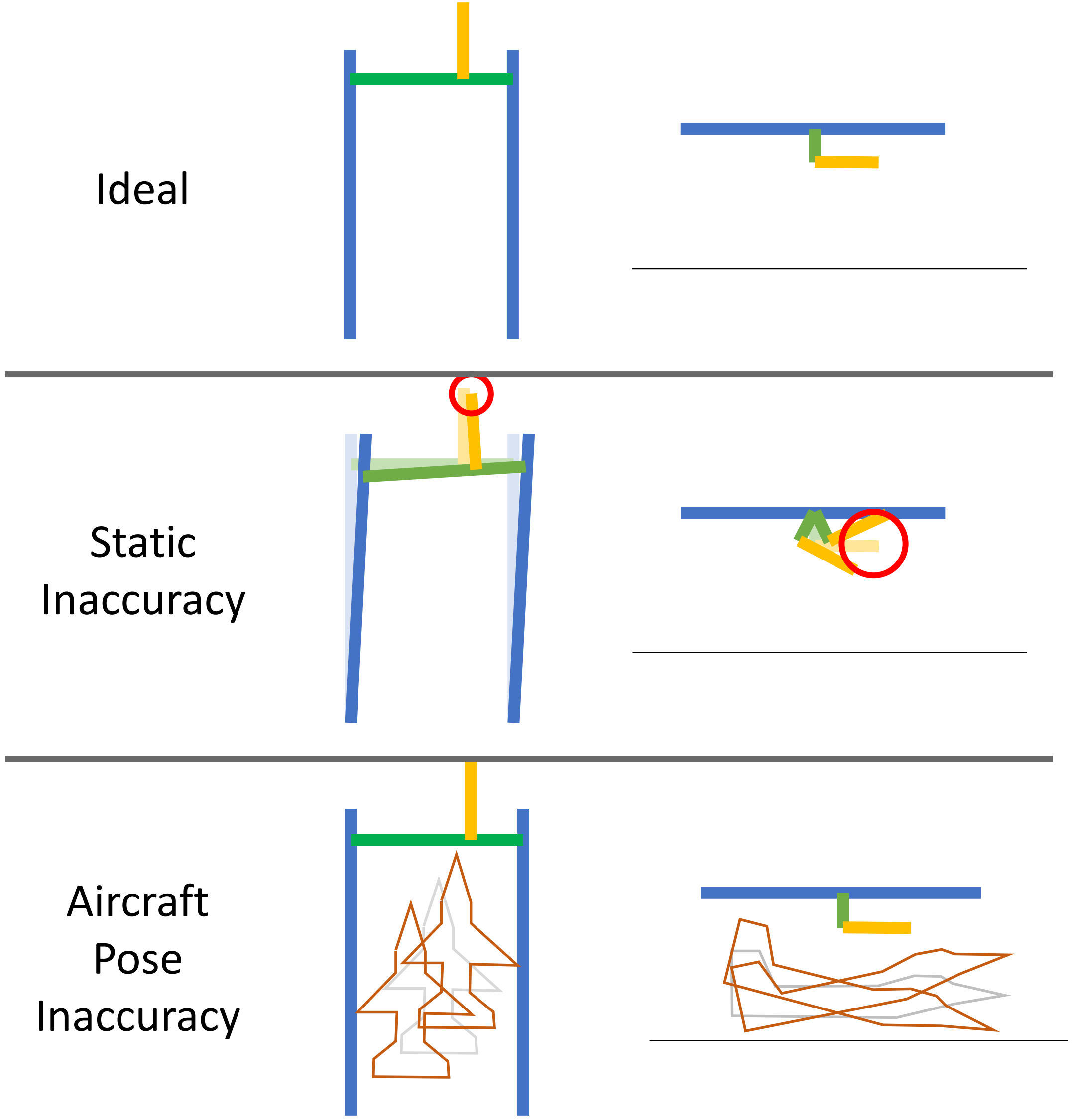
Example – USAF X-Ray

REALITY HIT

- The gantry was not designed for this application. It is way too inaccurate.
- As-built is far from CAD.

Estimated Static Tool Position Uncertainty:
~6 inches w/o dynamics





Example – USAF X-Ray

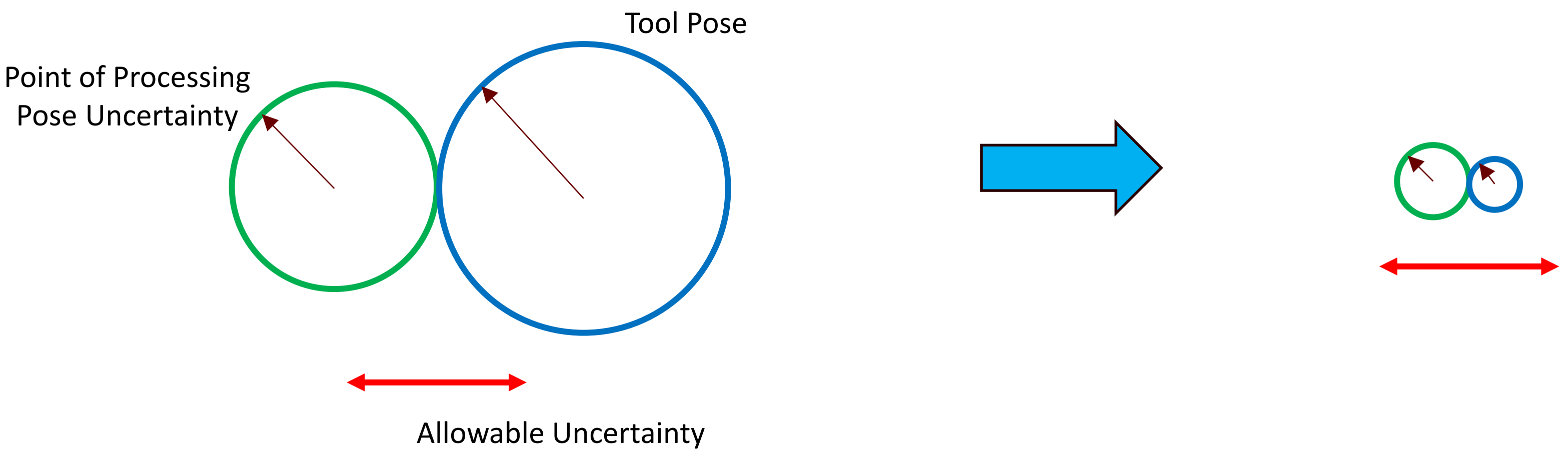
NOW WHAT

- How will we get more accuracy out of the gantry?
- How will we sense the pose of the workpiece?
- How will we manage the dynamics of the system?

THE PLAN

1. Create a better model of the positioner
   - ~~Ideal~~
   - Bent – static calibrated
   - Bendy – dynamic model
2. Choose a good Workpiece Localization Sensing Strategy
3. Adjust Process or Process Tooling as Necessary

GOAL



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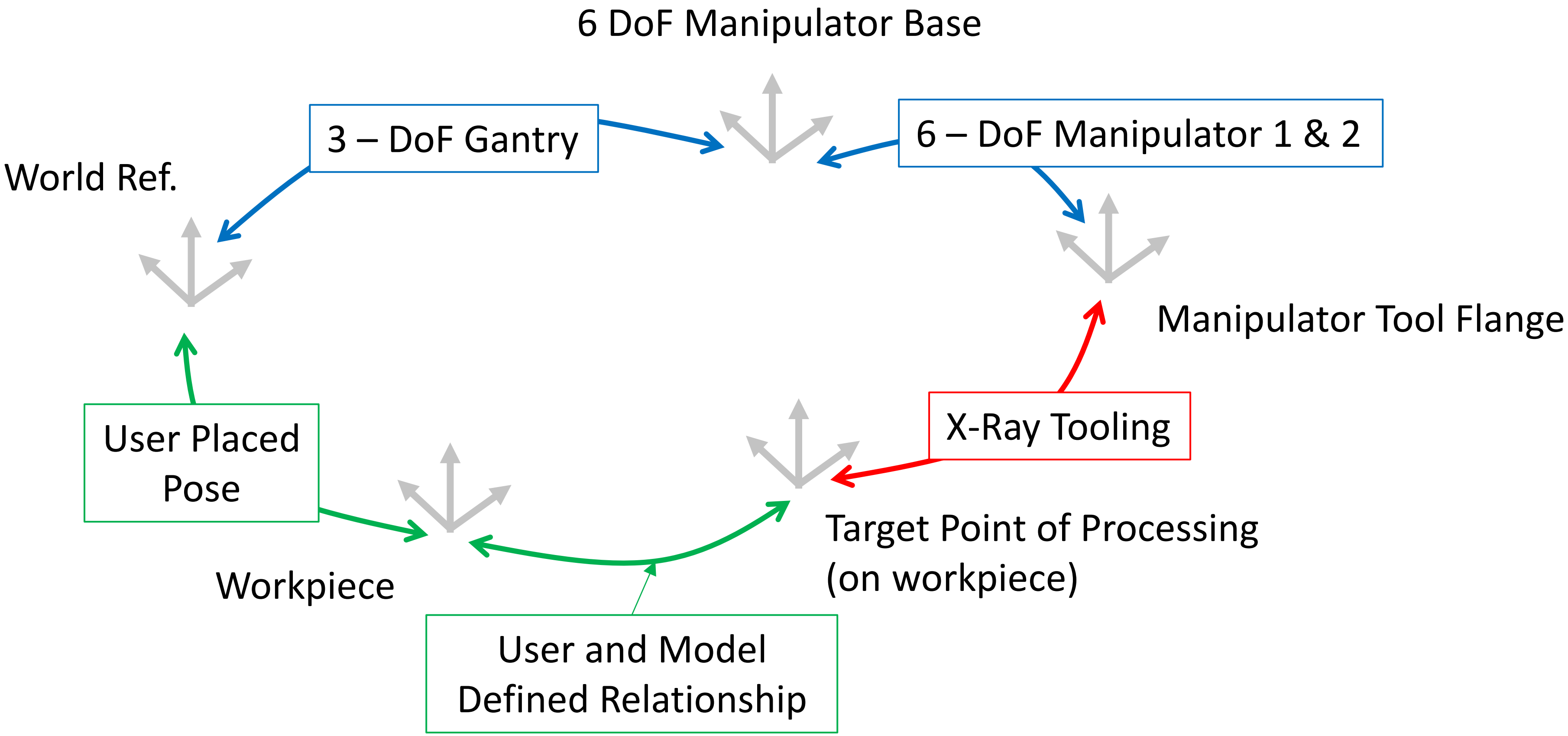
Example – USAF X-Ray

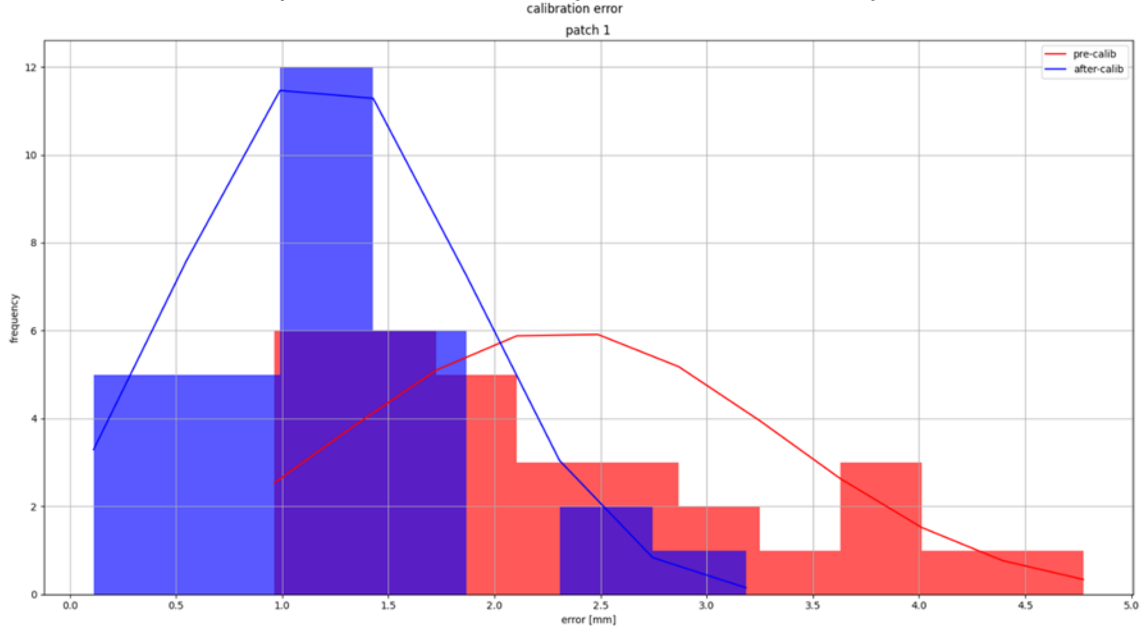
The choice on how to close a control loops with sensing must based on process requirements and the accuracy capabilities of both the manipulator AND the sensing in an autonomous system.



Detector 6-DoF Robot Calibration

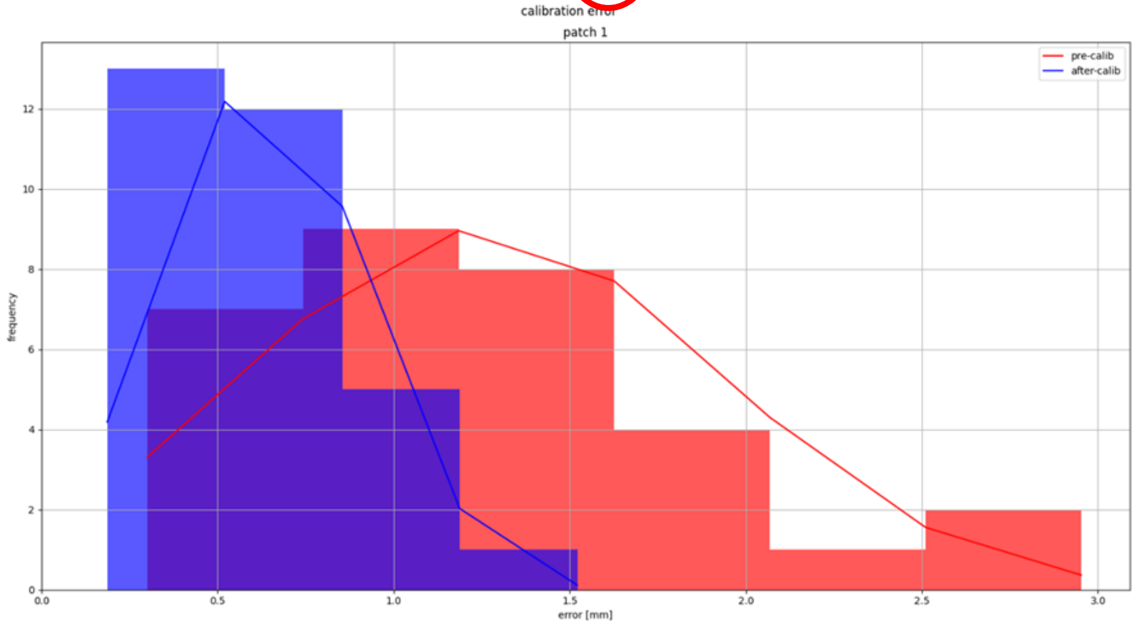
1) Mastering Only

	Before Calibration Error [mm]	After Calibration Error [mm]	Error Reduction [%]
L2 Average Error	2.5	1.4	45.8
Maximum Error	4.8	3.2	33.3



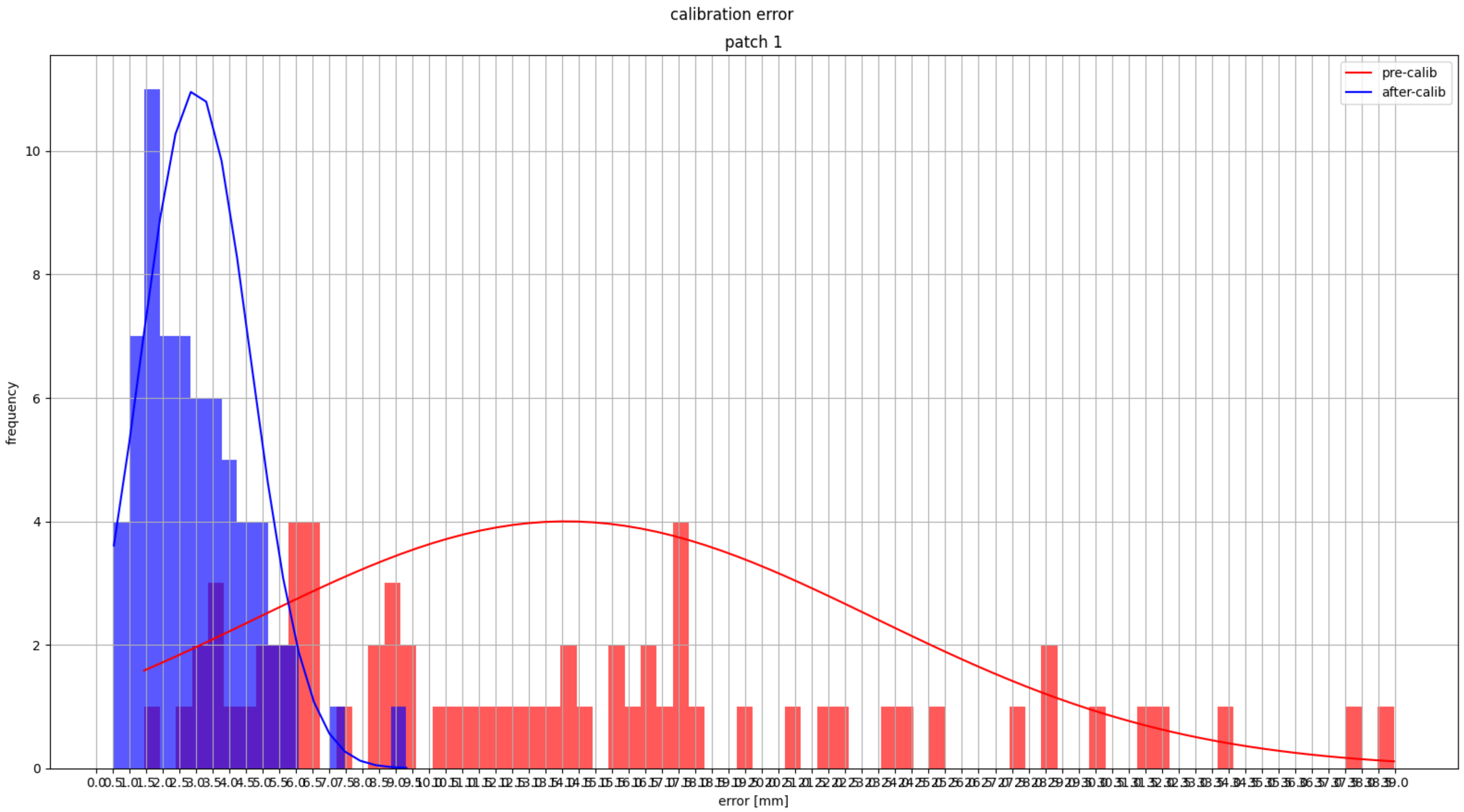
2) With Links Calibration

	Before Calibration Error [mm]	After Calibration Error [mm]	Error Reduction [%]
L2 Average Error	1.4	0.7	51.4
Maximum Error	3.0	1.5	48.5

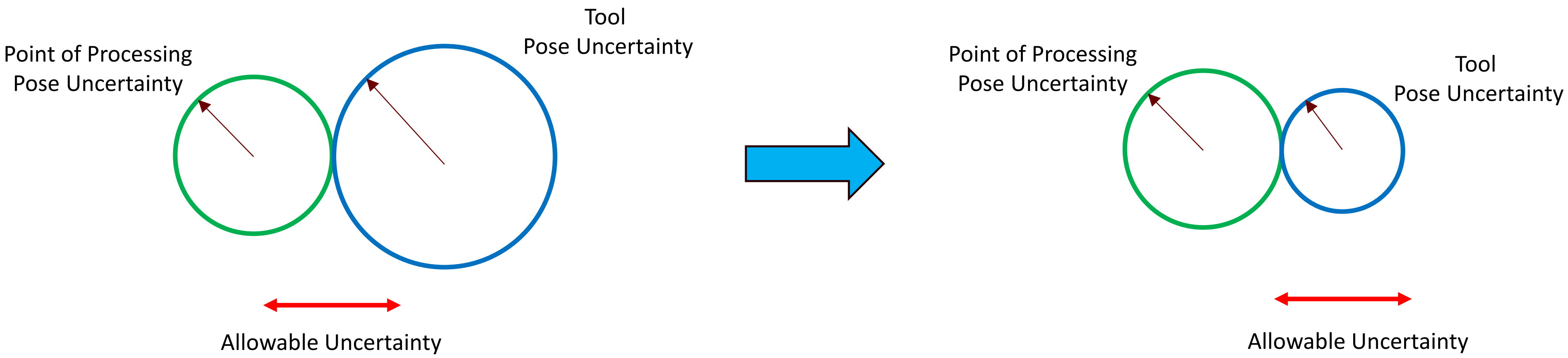


X-Y Gantry Calibration

	Before Calibration Error [mm]	After Calibration Error [mm]	Error Reduction [%]
L2 Average Error	16.9	3.4	79.6
Maximum Error	39.0	9.3	76.1



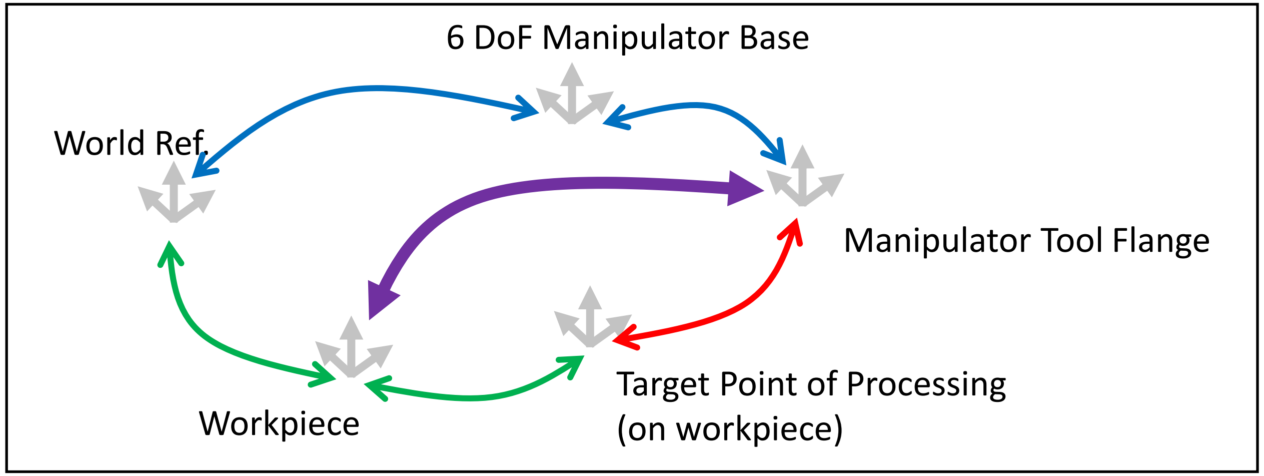
Example – USAF X-Ray



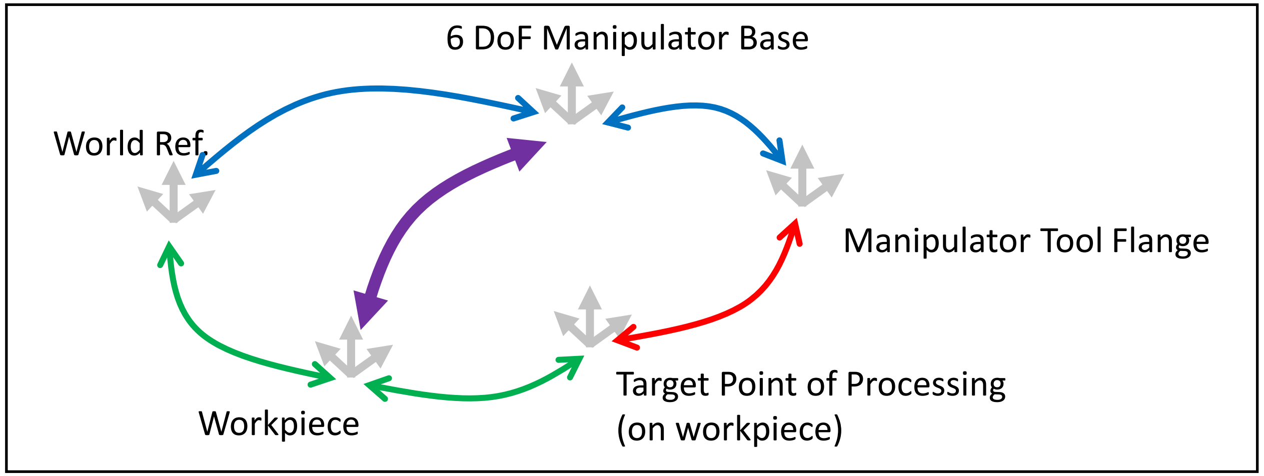
Example – USAF X-Ray

Where localization sensors are positioned in the kinematic chain and how they are used is important to consider.

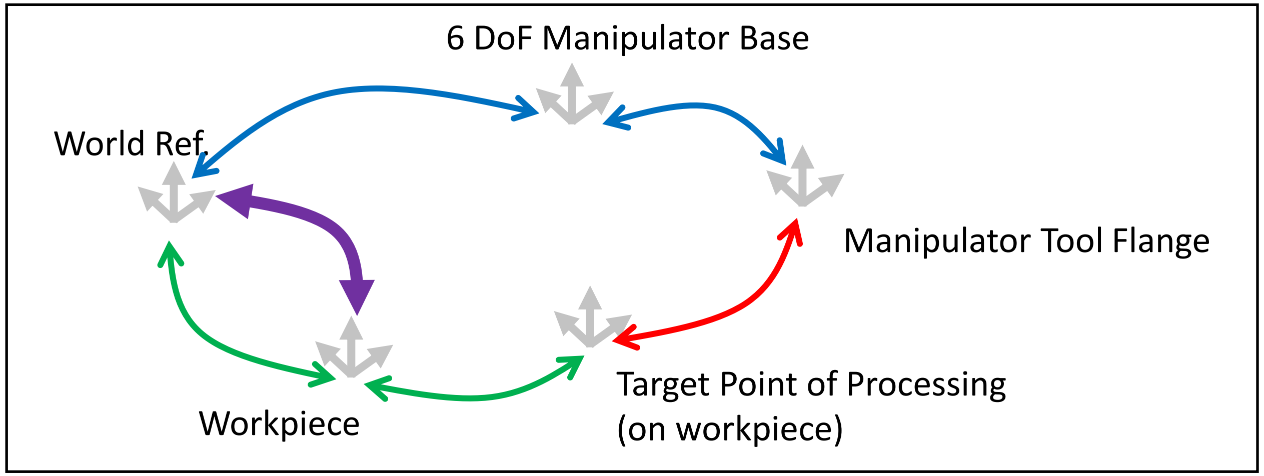
Manipulator mounted sensors



Gantry mounted sensors



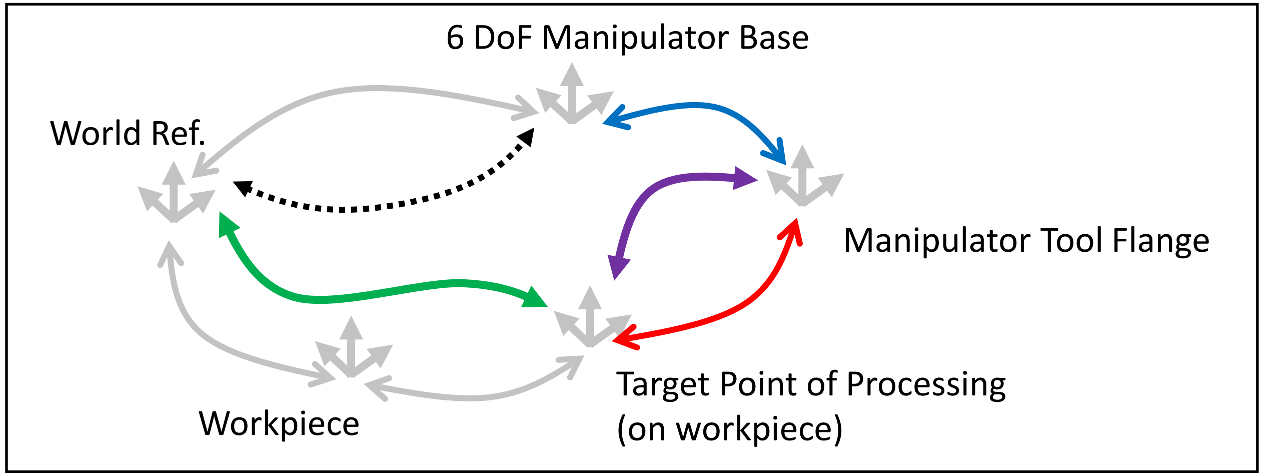
World mounted sensors

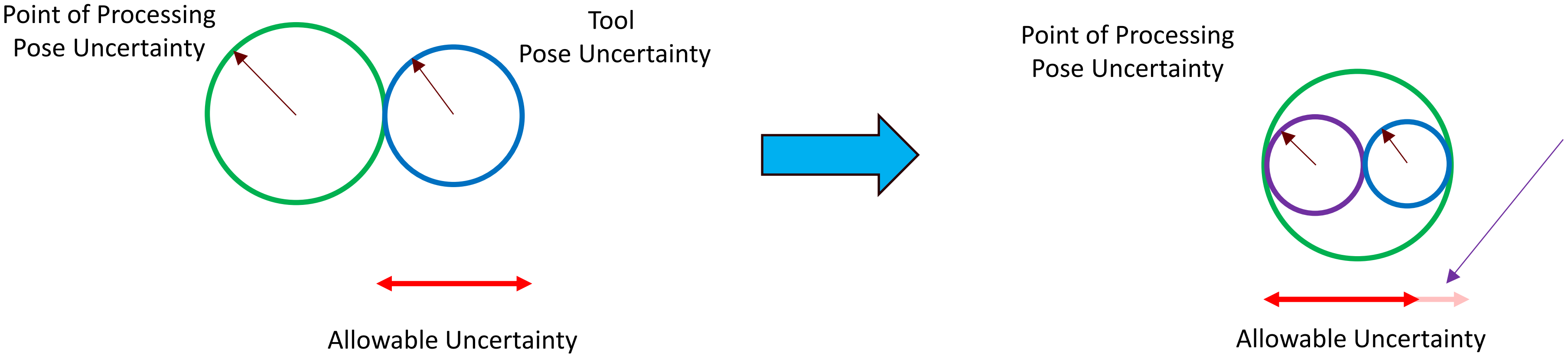


Example – USAF X-Ray

Titan Just-in-Time Localizaiton™

US Patent: 9796089B2





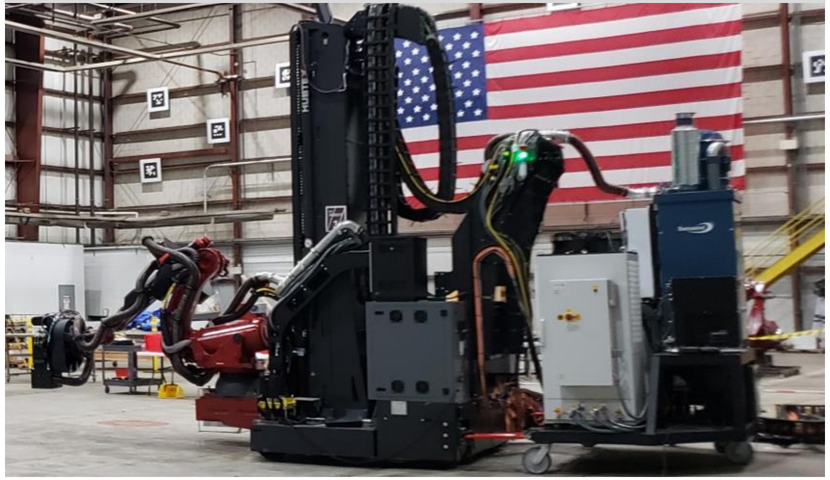
Can we open the allowable uncertainty with a process or process tooling change?

TITAN ROBOTICS

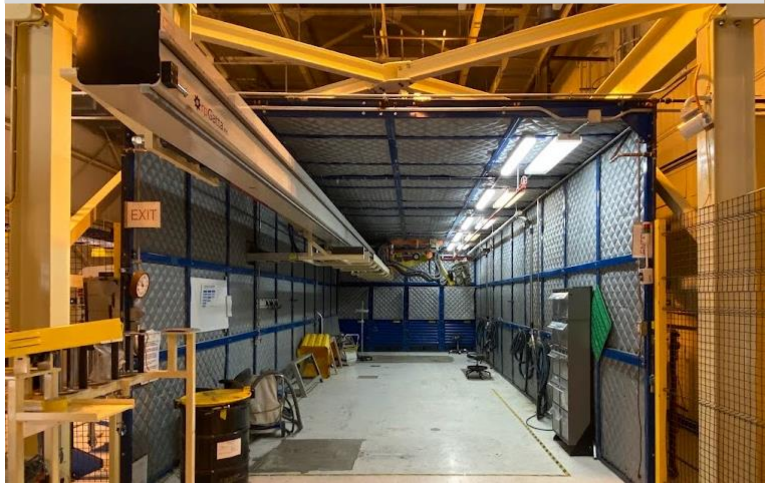
Wrapup

Deployed Systems

Laser Coating Removal



Sanding



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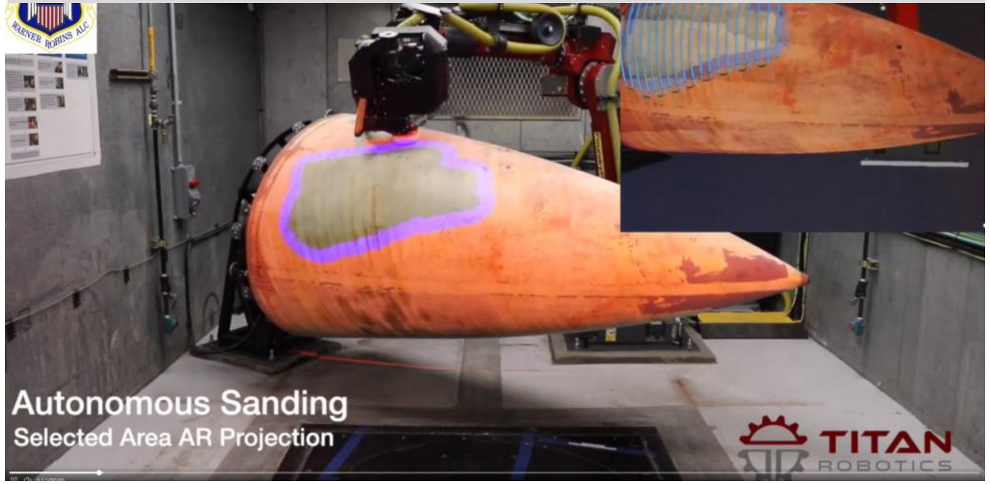

Laser Depaint, Painting, Sanding, Milling, X-ray, NDI, Defastening, Thermal Spray, Metrology, and others.

Final Thoughts

The team at Titan is continually making Make Vs. Buy decisions.

Having <u>trustable</u> spec. sheets with documentation on the accuracy of equipment is vital to making efficient design decisions, reducing time and effort of testing, characterization of components, and reducing overall risk to system performance.