Behr Systems, Inc.
V-STARS Demonstration

EXECUTIVE SUMMARY

- The work cell was completely inspected in less than one hour from start to finish.
- Coordinate data accuracy was typically better than (0.045, 0.025, 0.045)mm in XYZ.
- Two repeat measurements of the monument points agreed to 0.12mm and 0.21mm respectively.
- System is portable and can be used to complete off site inspection and verification of cells.
- System is capable of working in environments with unstable floors.
- System is flexible enough to work in environments with challenging lines of sight.

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Introduction

The following report is a summary of the V-STARS work carried out at the Behr Systems, Inc. facility in Auburn Hills, Michigan

One measurement was undertaken using the V-STARS metrology system.

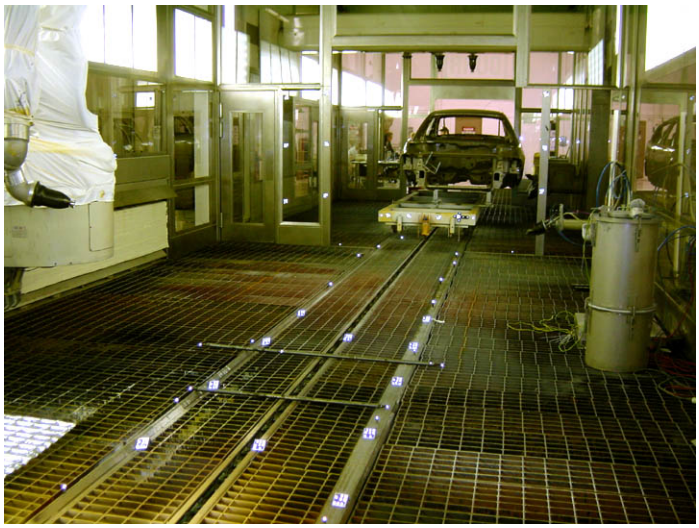
The measurement involved the determination of the location of a number of monument points in a robotic paint cell.
The objective of the measurement is outline below in the requirements section.

V-STARS with INCA camera.

Requirements

Robotic Work Cell

1. Demonstrate camera use and object targeting.
2. Compute location of 12 key mock monument points.
3. Determine location of two mock calibration plates.
4. Track the position of the car skid in the paint cell.
5. Compare data to data derived from the robotic measurement.
6. Repeat measurement to simulate process repeatability.
7. Transform data into Robotic coordinate system.


Robotic Paint Measured

Equipment Used

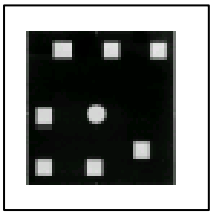
1. V-STARS S6 INCA Camera System

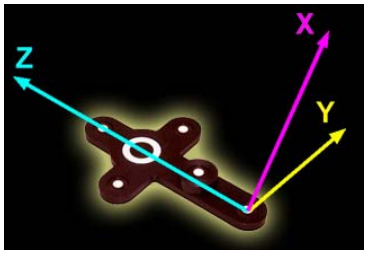
Measurement Procedure

Targeting

In order to meet the measurement objectives outlined earlier it was necessary to target the work cell. In general, targets are placed on points or surfaces that are of interest. For surfaces, strips of retro-reflective tape of variable pitch and dot size are commonly used. They are relatively cheap, disposable and easy to apply. To coordinate tooling datums such as bushed holes or button datums, tooling targets are used. These come in a variety of shank and dot sizes. They are also available in variable orientations.

To automate the measurement process it was necessary to add "coded" targets to the object. These targets are automatically detected and help the software determine the location and orientation of the camera at the time the photograph was taken. They also help tie the entire object into a uniform coordinate system.





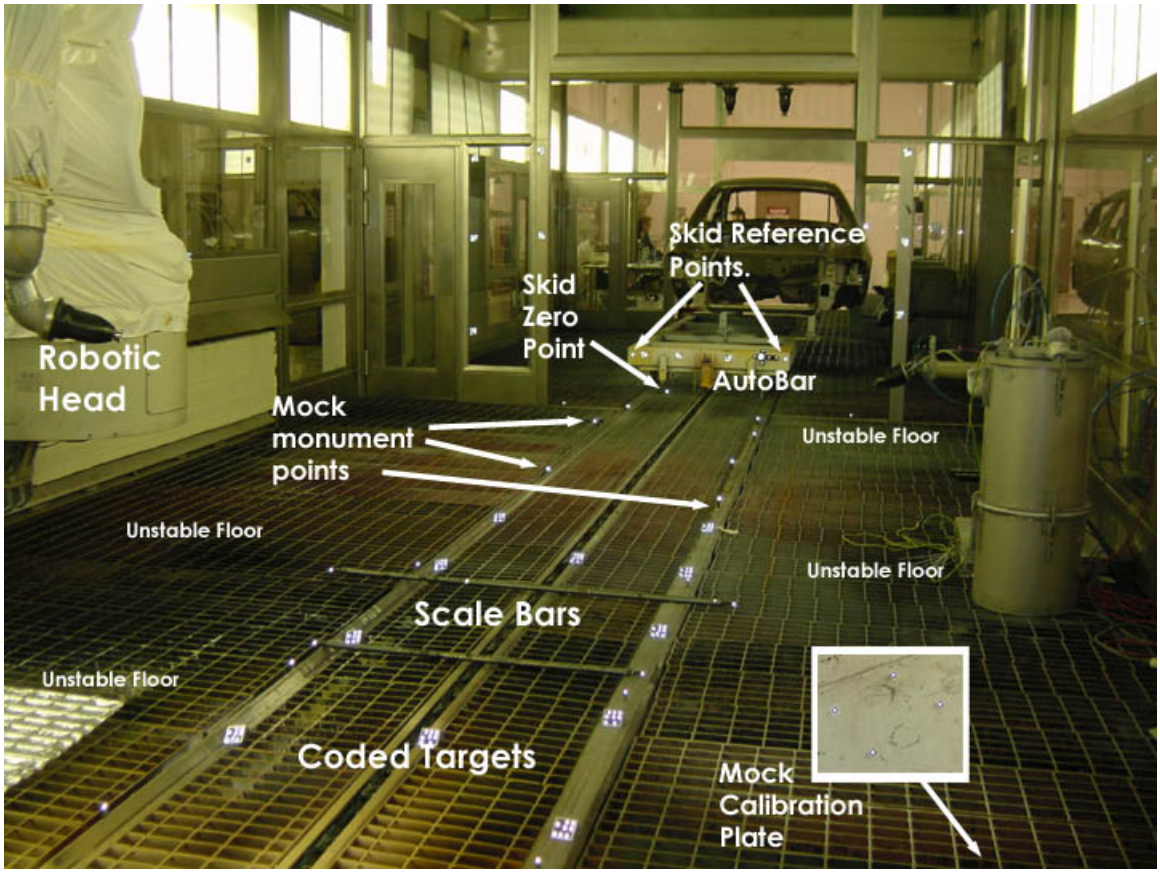
The initial coordinates system and approximate scale is determined via the AutoBar. The AutoBar used by the V-STARS system is a fixture with five targets arranged in the form of a cross. The target's known coordinates are used by the resection procedure to determine the camera's orientation relative to the AutoBar. The AutoBar is securely attached on or near the measured object, preferably in a highly visible location. The AutoBar's default coordinate system has its origin at Target 1 at the bottom of the AutoBar. The positive Z-axis goes through Target 3 at the top of the bar. The positive X-axis is up out of the AutoBar. The diagram on the left shows both the AutoBar and its coordinate system.

To scale a photogrammetric measurement, there must be at least one known distance. Normally this distance comes from a calibrated coded graphite scale bar or invar scale bar (Refer to adjacent image). Typically, multiple scales are used for redundancy. Two scale bars were used to complete each measurement.

Invar Scale Bar Kit

Scale bars made up of the same material as the Fixture are also popular as they have the same thermal expansion properties.

Some of the typical targeting features are shown in the image below: -



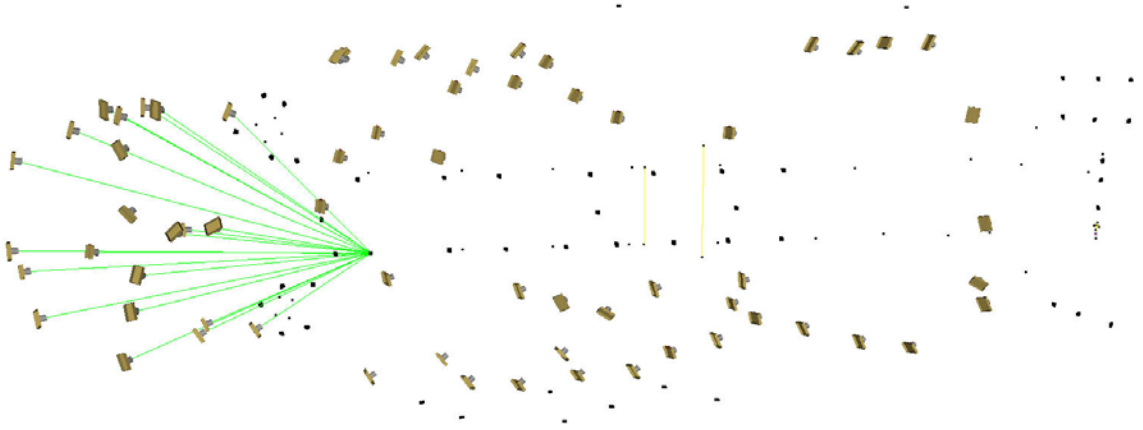
Targeting Used

1. AutoBar for initial coordinate system.
2. Coded targets to tie photography together.
3. Scale bars to scale the network.
4. Individual target to define zero point on skid.
5. Individual targets to define skid reference points.
6. Tooling targets to define mock “monument” points.
7. Back to back targets to strengthen the network.

Photography

The photography is carried out once the object targeting is completed. Put simply, the aim of the photography is to record each of the targeted points in as many images as possible from as wide a range of angles as possible. To improve the accuracy of the measurement, generally photos are taken both close to the ground and from an elevated position. The number of photos taken depends on the complexity of the measurement and accuracy requirements. In this measurement, the photography was straightforward. The only complication was trying to shoot the walls as well as the floor.

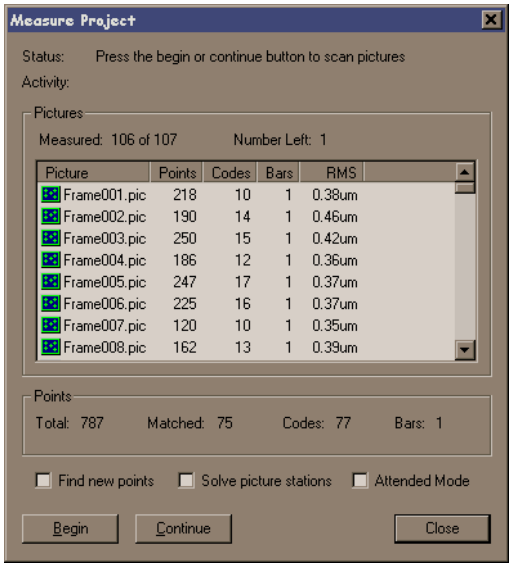
The geometry used to create the initial network for the measurement is illustrated in the image below. Also shown is an example of the rays of intersection to a point.



Processing

Once the photography has been completed the images are transferred to the system laptop. The images are stored on an IBM MicroDrive hard drive and V-STARS accesses these images directly from the drive.

Almost all of the measurement process is automated. The images are processed and the coordinates extracted by the "AutoMeasure" command. A typical AutoMeasure dialog box is shown on the right. The AutoMeasure command will open each of the images, determine the camera location, find new target points and finally adjust all the measurements in the "Bundle Adjustment". At the conclusion, the user is left with the XYZ coordinates for all the target points in the network. The AutoMeasure procedure is very powerful as it allows the user to continue working while it processes the data. It also means that relatively unskilled workers can be used to process the data.



Typical AutoMeasure Dialog

The AutoMeasure routine will assign random labels to the points it finds. These labels start with the key word "Target" followed by a number. If specific labeling is required the random labels can be easily changed to labels defined by the user. This is possible in both the picture view and the graphical 3D view. In this measurement the labels were changed to simplify analysis.

Measurement Statistics

Initial Network

No. of photos	67	
No. of points	430	
Number of scale bars	2	
Scale Agreement	0.021mm	
Accuracy RMS X,Y,Z	X	0.050mm
	Y	0.022mm
	Z	0.050mm

Repeat Network 1

No. of photos	81	
No. of points	447	
Number of scale bars	2	
Scale Agreement	0.019mm	
Accuracy RMS X,Y,Z	X	0.045mm
	Y	0.019mm
	Z	0.043mm

Repeat Network 2

No. of photos	114	
No. of points	447	
Number of scale bars	2	
Scale Agreement	0.023mm	
Accuracy RMS X,Y,Z	X	0.041mm
	Y	0.023mm
	Z	0.033mm

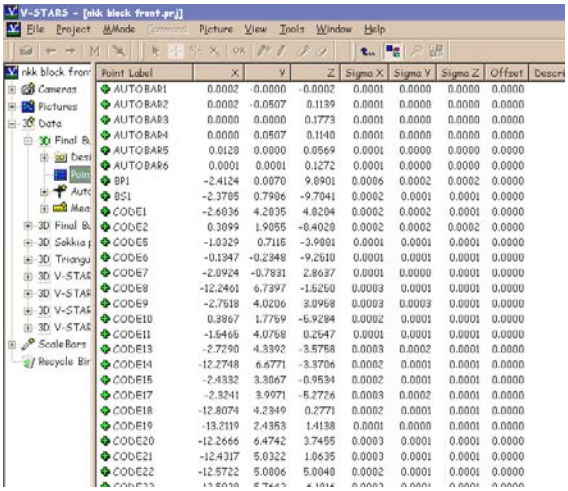
Note that images were added to the first and second repeat network. This was done to accommodate requests for additional point data on the wall of the cell.

Seen below is a typical measurement image.

The green crosses represent points that have been located in this particular image. Note that the image appears a little dark and difficult to see. This is intentional as the best photogrammetric measurements are made on images that have dark backgrounds and bright targets. One of these targets is shown in the zoom window in the corner. If the scale bar is visible then a yellow line will be drawn between the two ends.

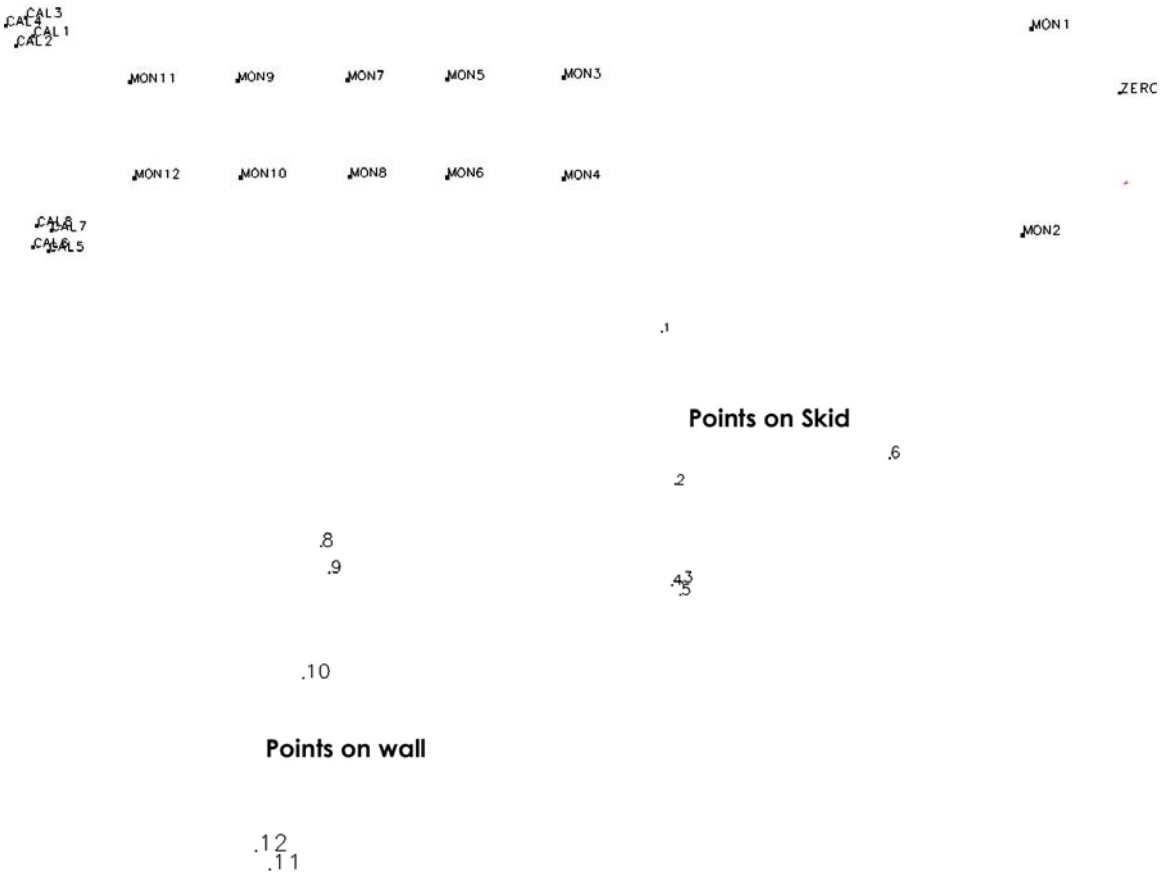
At the conclusion of the AutoMeasure the 3D data is written to a file. A typical point listing from the 3D file is shown in the adjacent image.

This point data can be analyzed within the V-STARS' SOLIDS module, easily exported to almost any CAD platform or other analysis program.



Numbering Guide

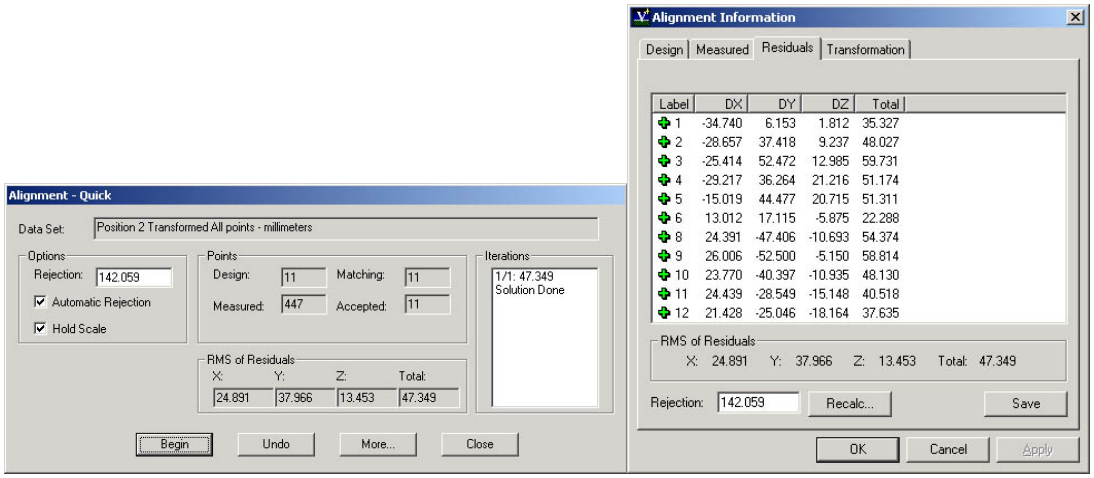
The mock monument points were called MON1 to MON12. The alignment points for the robot were labeled from 1 to 12. The zero point on the skid was called "ZERO". Points on the mock calibration plates were called CAL1 to CAL8. The numbering scheme is shown in the images below.



Alignment

Typically one of the last tasks is alignment into the coordinate system of the object being measured. There are two basic types of alignment. The first is a simple Axis or 3-2-1 alignment. This alignment is based on three points – an origin, an axis point and a third point to define the plane in which the axis lies. The second type of alignment uses point correspondence from a known alignment (such as the CAD model) to transform the data into that coordinate system. This is a "best-fit" solution and is preferred as it involves greater redundancy.

For this measurement, the cell was aligned to the Robotic Coordinate System. Examination of this alignment revealed some alarming discrepancies.
The images below show the results of the alignment based on all 11 points.



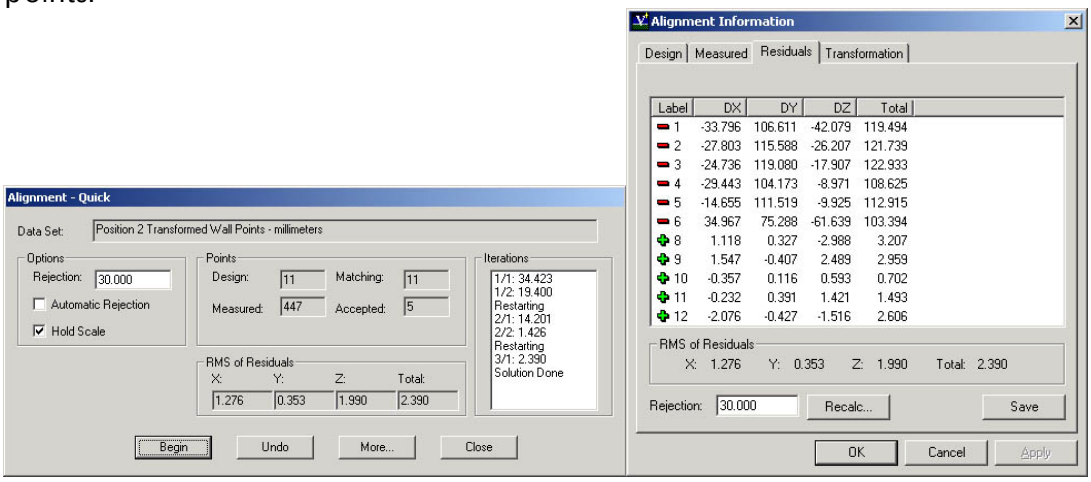
Closer investigation revealed that the robot derived coordinates were as much as 66mm out on the distance between points 6 and 8. The distance was independently checked using a tape measure. The results are tabulated below:

	Distance(mm)	**Delta**
V-STARS	3479.04	
Tape	3479.80	0.76
Robot	3545.10	-66.06

It is clear from these results that there is problem with the robot derived coordinates.

Based on this analysis it was decided to complete the alignment using only the points on the wall. These were more accurate as the robot measured all these points from the same approach angle.

The images below show the results of the alignment based on the five wall points.



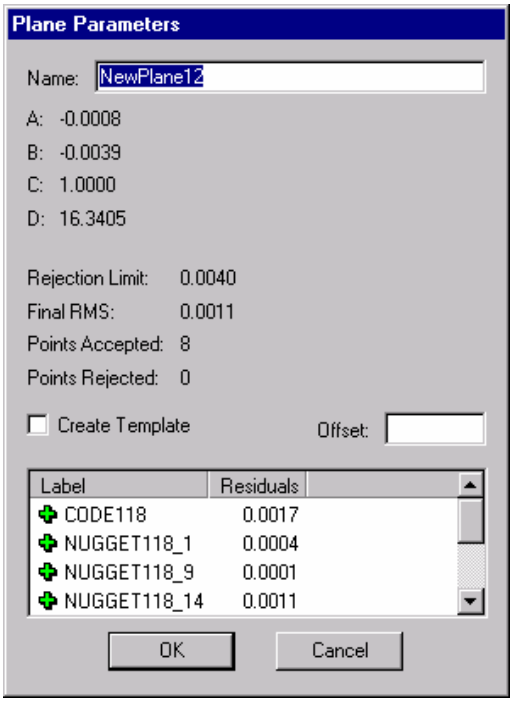
The 2.3mm total error is more in keeping in what was expected when transforming the robot derived data.

Analysis

SOLIDS is the geometric analysis module of V-STARS. For example, consider a simple function like determining the distance between two points. Computing the point-to-point distance is as simple as highlighting the two points and pressing "d". The result appears on the screen and is written to the 3D file.

Calculation of the Best-fit plane is also very simple. The plane points are highlighted and the "P" key is pressed. The plane dialog is shown in the adjacent image. The dialog gives you a few options and reports the results of the operation.

Similarly, best-fit lines, circles, cylinders, spheres, parabolas, etc. can also be calculated. SOLIDS also has the ability to measure between objects. For example, by selecting a point and a plane the normal distance can be computed. This makes SOLIDS a very useful analysis tool.

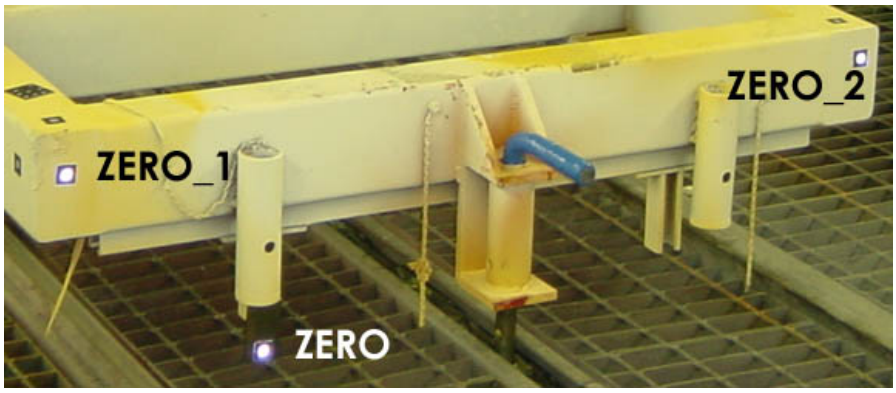


Typical Plane Dialog

Results

Skid Tracking

The results of the measurement from the first, second and third measurements were used to track how far the skid was moved from its original zero position. Three points on the front of the skid were used to determine the relative distance between the two positions. The skid was moved between the two measurements to simulate actual use.



The results(mm) are tabulated below.

Point	First Repeat	Second Repeat	Difference
ZERO	5251.44	5264.23	-12.79
ZERO_1	5253.04	5265.40	-12.36
ZERO_2	5249.08	5261.99	-12.91

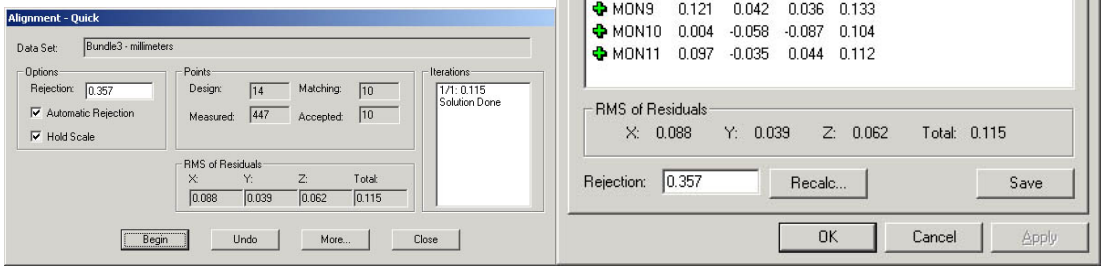
Based on these results it would be reasonable to conclude that:

1. The skid is crabbing down the rails. If the skid was tracking correctly all the distances would be equal. Further investigation revealed that the back wheel was not locked down correctly.
2. The amount of crabbing seems to be consistent. The relative differences are very similar between all three points between the two measurements.

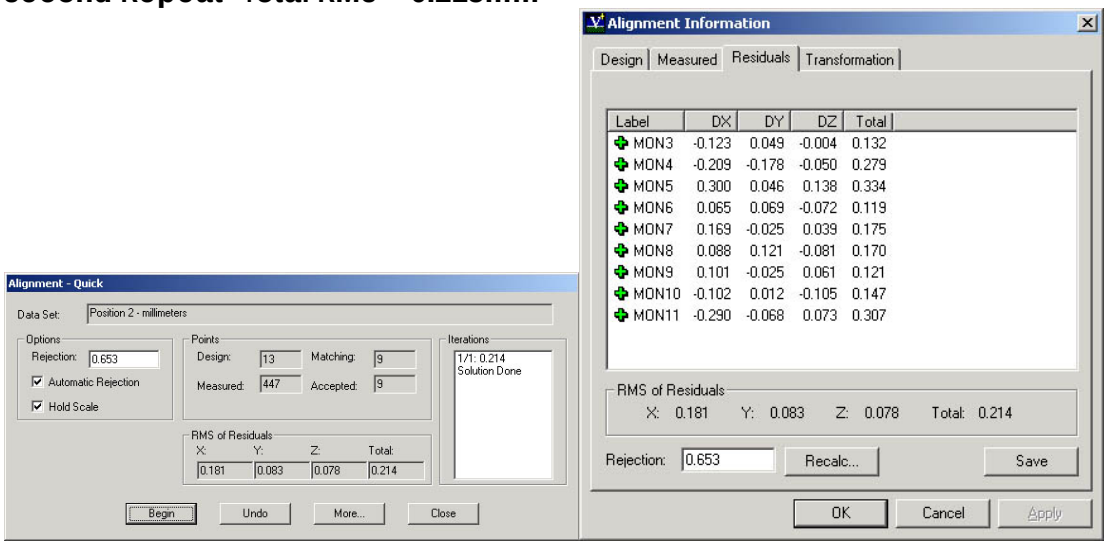
Measurement Repeatability

The monument points were measured three times. The first measurement was called the base measurement. The two subsequent measurements were compared to this. The results are tabulated below:

First Repeat- Total RMS = 0.115mm



Second Repeat- Total RMS = 0.215mm



The following is noted:

1. The first repeat measurement shows a high of agreement to the first base network. Two of the monument points were disturbed between the two networks and were removed.
2. The second repeat measurement still shows a high level of agreement, but is not as good as the first. The second measurement was conducted about two hours after the first and hence there is a chance that the points were influenced by temperature or even settling of the bush into the glue.

Time Summary

Control Targeting	10 minutes
Initial Photography	5 minutes
Initial Processing	5 minutes
Repeat 1 Photography	5 minutes
Repeat 1Processing	5 minutes
Repeat 2 Photography	5 minutes
Repeat 2 Processing	5 minutes
Analysis	20 minutes
Total	**60 minutes**

Concluding Remarks

The measurement undertaken has shown that V-STARS with the INCA S6 system can be a very powerful measurement tool. The results of the measurement undertaken were very accurate and more importantly were produced quickly.

GSI would like to thank Behr Systems, Inc. for welcoming us into their Auburn Hills facility. We will be happy to discuss the results of this report or any other aspect of the technology presented.