Behr Systems, Inc. V-STARS Demonstration

<section-header>

- 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.

Table of Contents

EXECUTIVE SUMMARY	<u>1</u>
Table of Contents	3
Introduction	4
Requirements	4
Equipment Used	5
Measurement Procedure	5
Targeting	5
Photography	7
Processing	7
Initial Notwork	88 o
Repeat Network 1	
Repeat Network 2	
Numbering Guide	
Alignment	11
Analysis	12
Results	
Skid Tracking Measurement Repeatability	13
Time Summary	15
Concluding Remarks	

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 riaht. 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.

Measure Project Status: Press the Activity:	e begin o	r continue	e buttor	n to scan p	ictures
Pictures Measured: 106 of	107	Nun	nber Le	ft: 1	
Picture	Points	Codes	Bars	RMS	
Frame001.pic	218	10	1	0.38um	
🔣 🔛 Frame002.pic	190	14	1	0.46um	
Frame003.pic	250	15	1	0.42um	
🔣 Frame004.pic	186	12	1	0.36um	
🔣 Frame005.pic	247	17	1	0.37um	
🔣 Frame006.pic	225	16	1	0.37um	
🔣 Frame007.pic	120	10	1	0.35um	
Frame008.pic	162	13	1	0.39um	
Points					
Total: 787	Matched:	. 75	Co	des: 77	Bars: 1
Find new point	s 🗖 :	Solve pic	ture sta	ations 🗖	Attended Mode
Begin	<u>C</u> ontinu	e			Close

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	0.02	1mm
Accuracy RMS X,Y,Z	Х	0.050mm
	Y	0.022mm
	Ζ	0.050mm

Repeat Network 1

No. of photos	81	
No. of points	447	
Number of scale bars	2	
Scale Agreement	0.01	9mm
Accuracy RMS X,Y,Z	Х	0.045mm
	Y	0.019mm
	Ζ	0.043mm

Repeat Network 2

No. of photos	114	
No. of points	447	
Number of scale bars	2	
Scale Agreement	0.02	3mm
Accuracy RMS X,Y,Z	Х	0.041mm
-	Υ	0.023mm
	Ζ	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.

V-STARS - [nk Eile Project	k block front.prj] MMade	Picture	⊻iew <u>T</u> o	ols <u>W</u> ind	low <u>H</u> elp				
	1 2 1 4 4	1- X. .07	10.1	1.1	2.,	8 2 8	R		
M nkk block from	Point Label	×	У	Z	Sigma X	Sigma Y	Signa Z	Offset	Descri
E 🙆 Cameras	AUTOBAR1	0.0002	-0.0000	-0.0002	0.0001	0.0000	0.0000	0.0000	
Pictures	AUTOBAR2	0.0002	-0.0507	0.1139	0.0001	0.0000	0.0000	0.0000	
- R Data	AUTOBAR3	0.0000	0.0000	0.1773	0.0001	0.0000	0.0000	0.0000	
D Y Eleal B	AUTOBAR4	0.0000	0.0507	0.1140	0.0001	0.0000	0.0000	0.0000	
30 Pinor Sc	AUTOBAR5	0.0128	0.0000	0.0569	0.0001	0.0000	0.0000	0.0000	
10 30 Deti	AUTOBAR6	0.0001	0.0001	0.1272	0.0001	0.0000	0.0000	0.0000	
Point	4 BP1	-2.4124	0.0070	9.8901	0.0006	0.0002	0.0002	0.0000	
B- Auto	851	-2.3785	0.7986	-9.7041	2000.0	0.0001	0.0001	0.0000	
🗄 📫 Mea	CODE1	-2.6036	4.2835	4.8204	0.0002	0.0002	0.0001	0.0000	
FI-3D Final B.	CODE2	0.3899	1.9855	-8.4028	2000.0	0.0002	0.0002	0.0000	
+- 3D Sokkia r	CODE5	-1.0329	0.7115	-3.9801	0.0001	0.0001	0.0001	0.0000	
+ 30 Trianau	CODE6	-0.1347	-0.2348	-9.2510	0.0001	0.0001	0.0001	0.0000	
TO VISTAD	CODE7	-2.0924	-0.7831	2.8637	0.0001	0.0000	0.0001	0.0000	
D DD M CTAR	CODE8	-12.2461	6,7397	-1.6260	0.0003	0.0001	0.0001	0.0000	
+	CODE9	-2.7518	4.0206	3.0968	0.0003	0.0003	0.0001	0.0000	
	CODE10	0.3867	1.7759	-6.9284	0.0002	0.0001	0.0001	0.0000	
E 3D V-STAR	CODE11	-1.6466	4.0758	0.2547	0.0001	0.0001	0.0001	0.0000	
🖹 🖉 Scale Bars	CODE13	-2.7290	4.3392	-3.5758	0.0003	0.0002	0.0001	0.0000	
- g/ Recycle Bir	CODE14	-12.2748	6.6771	-3.3706	0.0002	0.0001	0.0001	0.0000	
and the second s	CODE15	-2.4332	3.3067	-0.9534	0.0002	0.0001	0.0001	0.0000	
	CODE17	-2.3241	3.9971	-5.2726	0.0003	0.0002	0.0001	0.0000	
	CODE18	-12.8074	4,2349	0.2771	0.0002	0.0001	0.0001	0.0000	
	CODE19	-13,2119	2,4353	1.4138	0.0001	0.0000	0.0001	0.0000	
	CODE20	-12.2666	6.4742	3.7455	0.0003	0.0001	0.0001	0.0000	
	CODE21	-12.4317	5.0322	1.0635	0.0003	0.0001	0.0001	0.0000	
	CODE22	-12.5722	5.0806	5.0040	0.0002	0.0001	0.0001	0.0000	
	A COD E22	12 5030	5 7640	£ 1016	0.0000	0.0001	0.0001	0.0000	

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	
Таре	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.

	X Alignment Information	×
	Design Measured Residuals Transformation	1
Alignment - Quick Data Set: Position 2 Transformed Wall Points - millimeters Options Bejection: 30 000 Automatic Rejection Design: 11 Weasured: 141: 24 420 Path Vision Points Vision Measured: Field Scale Solution Done RMS of Residuals Solution Done	Label DX DY DZ Total 1 -33.796 106.611 -42.073 119.494 2 -27.803 115.588 -26.207 121.739 3 -24.736 119.080 -17.907 122.933 4 -29.443 104.173 -8.971 108.625 5 -14.655 111.519 -9.925 112.915 6 34.967 75.288 61.639 103.394 Φ 8 1.118 0.327 -2.988 3.207 Φ 9 1.547 -0.407 2.498 3.207 Φ 9 1.547 -0.407 2.498 3.207 Φ 9 1.547 -0.407 2.498 3.207 Φ 1 0.325 0.116 0.593 0.702 Φ 11 0.232 0.391 1.421 1.493 Φ 12 2.076 0.427 1.516 2.606 K	
X: Y: Z: Total 1.276 0.353 1.390 2.390	Rejection: 30.000 Recalc Save	
Begin Undo More Close	OK Cancel	ply

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.

Plane Parameter:	\$	
Name: NewPlan	ne12	
A: -0.0008		
B: -0.0039		
C: 1.0000		
D: 16.3405		
Rejection Limit:	0.0040	
Final RMS:	0.0011	
Points Accepted:	8	
Points Rejected:	0	
Create Templa	ate Officet	
	onsec]	
Label	Residuals 🔺	
💠 CODE118	0.0017	
🔹 💠 NUGGET118	3_1 0.0004	
🔹 💠 NUGGET118	3_9 0.0001	
🔷 NUGGET118	3_14 0.0011 💌	
0	IK Cancel	

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

	Y Alignment Information
	Design Measured Residuals Transformation
	Label DX DY DZ Total
	MON1 -0.201 0.006 -0.009 0.201
	MON3 0.060 -0.046 -0.105 0.129
	MON4 0.006 -0.038 0.121 0.127
	MON5 0.037 0.019 0.015 0.044
	MON6 -0.062 0.056 0.025 0.087
	MON7 0.004 0.012 0.000 0.012
	✿ MON8 -0.067 0.042 -0.040 0.088
nment - Quick	✿ MON9 0.121 0.042 0.036 0.133
ta Sat	✿ MON10 0.004 -0.058 -0.087 0.104
Plons Points Iterations Iterations	♥ MUN11 0.097 -0.035 0.044 0.112
Automatic Bejection	RMS of Residuals
Image: Measured: Measured: Image: Measured:	X: 0.088 Y: 0.039 Z: 0.062 Total: 0.115
Y: Z: Total 0.068 0.039 0.062 0.115	Rejection: 0.357 Recalc Save
Begin Undo More Close	OK Cancel Apply

Second Repeat- Total RMS = 0.215mm

	X Alignment Information
	Design Measured Residuals Transformation
Alignment - Quick	Label DX DY DZ Total
Options Points Rejection: 0.653 If Automatic Rejection Messured: If Hold Scale PMS of Residuals X: Y: X: Y: V: Y: 0.181 0.083 0.078 0.214	RMS of Residuals X: 0.181 Y: 0.083 Z: 0.078 Total: 0.214 Rejection: 0.653 Recalc Save

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.