Developments in Non-Contact Measurement Using Videogrammetry

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ABSTRACT
Over the past five years videogrammetry has emerged as a very popular measurement tool for industry. This acceptance is not unexpected given the immense potential of the technology. One factor that has limited the acceptance of photogrammetry is the requirement to target and/or touch points of interest. This paper examines a new, non-contact targeting technique that removes this burden in particular applications. The new technique is especially suited to surface measurement and non-contact metrology in general. This paper describes the principles involved, and some typical sample applications.

INTRODUCTION
Developments in Videogrammetry software and hardware over recent years have dramatically improved the convenience and reach of the technology. (Ganci and Handley 1998) Due to advancements in digital image processing software, coded targets and auto-correlating methods, a large number of photogrammetric measurement tasks can now be fully automated. (Fraser 1997a;b) As soon as digital images are acquired, a "one button click" is often all that is needed to provide 3D-coordinates of measurement points without any further operator involvement. Hardware development has come in the form of the "intelligent camera". The intelligent camera contains an integrated computer and processes the image immediately after it is taken. One such camera, INCA, is shown in FIGURE 1. With INCA, the operator receives feedback about the measurement when it is needed most – during image acquisition. These improvements have made videogrammetry a powerful and popular measurement tool. One limiting factor, which affected the acceptance of photogrammetry in general, is the need for point-of-interest-targeting. The need to target and/or physically touch the object is sometimes a burdensome requirement. Most users appreciate the speed of the technology at acquisition time but find the setup phase, that is, targeting, tedious and time consuming. If thousands of targets are required, target cost can also be an issue. The time to apply the targets and the actual target cost can occasionally make the measurement unattractive.


FIGURE 1 – INCA Camera

With this in mind, the focus of recent developments has been to remove the necessity to target the measured object. This paper examines a new non-contact targeting technique that uses a high power stroboscopic projector to project dots or "targets" onto the object. The new target system, called PRO-SPOT, is a target projector available from Geodetic Services Inc. (Geodetic Services, Inc., 2000) Refer to FIGURE 2. The target projection system is particularly well suited to surface measurement and non-contact metrology in general. This paper describes the principles involved and some of the features of a targetless system. The performance of the new system will also be examined through reference to a number of example measurement applications.

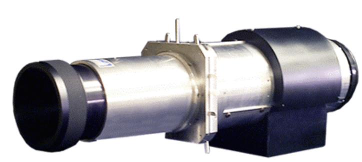


FIGURE 2 – Target Projector

BACKGROUND

The principle of the projection system is relatively straightforward. It works much like an ordinary slide projector. A light source illuminates a target slide. This illuminated pattern passes through a series of lenses that magnify the slide and project it onto the object. As with a slide projector, it is necessary to focus the lens so that the target slide is in focus on the object surface.

The actual construction of the projector is complicated by the need to accurately control the whole process. By far, the greatest concern is the stability of the dot pattern. Instability of the pattern is tantamount to moving the physical target point during the measurement.

FIGURE 3 shows the dots from the projector on a surface. They are of high-contrast and quality. They mimic conventional retro-reflective targets, but have no inherent target thickness. The size of the projected dots grows as the projector gets further from the object, and hence the dot is always the right size for a good measurement.

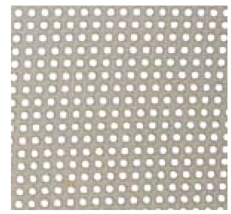


FIGURE 3 – Projected Dots

Like conventional targets, the projected dots must be bright and of high contrast for a good measurement. Generally, the projector is set far enough back to cover the object with the dot pattern. The strobe intensity is then adjusted so the dots are measurable. If the entire object cannot be measured in a single set up, then multiple setups that collectively cover the entire object can be used.

The area that can be measured in a single setup of the projector depends on several factors such as

a) the color of the surface,
b) its finish and
c) its curvature

FIGURE 4 can be used to determine the approximate area that can be measured in a single setup.

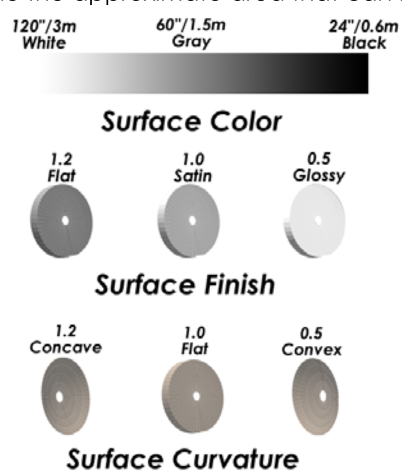


FIGURE 4 – The three factors that control projection use

Size (diameter in inches/meters) = Color x Finish x Curvature

For example, take the case of a white, concave object with a satin finish

Size (diameter) = White x Satin x Concave
Size (diameter) = 120"/3.0m x 1.0 x 1.2 = 144"/3.6M

The guide above can be used as a rough indication. In practice, one may need to take some test shots to determine how far back the projector can be set.

MEASUREMENT PROCEDURE

In a typical application, the system would be setup and used as shown in FIGURE 5. The projector is placed so that its dots cover the area of interest on the object. Then, the single-camera is used to take pictures from two or more different locations around the object.

Each time a picture is taken, the projector also projects the pattern of high-contrast dots onto the object. After all pictures are taken, they are automatically processed to yield the 3-dimensional coordinates of each dot. The measurements from different camera stations are tied together using reference targets placed around the object. The coordinates of these points are determined as a by-product of the measurement. In this mode of operation, the dot pattern and the object must be stable for the duration of the photography.

FIGURE 5 – Typical single camera set-up

An extension of the single camera method is the two camera, real-time approach. In a typical application, the system would be setup as shown in FIGURE 6. The two cameras are located in front of and to the left and right of the object. The projector is located between them. When a measurement is needed, the projector flashes the point pattern onto the surface. The two cameras image the projected dots simultaneously. During the imaging, the location of the cameras is determined by the reference targets placed around the object. Unlike in the single-camera setup, the coordinates of the reference targets must be pre-determined. This information is then used to triangulate the 3-dimensional coordinates of each dot. In the real-time approach, the dot pattern must only be stable for the duration of the projector flash. This approach is particularly useful for measurement of dynamic objects undergoing movement or deformation, and for measurement in unstable environments. Although the FIGURE 6 shows the object mounted vertically, it could also be mounted horizontally with the cameras and projector positioned above it.

FIGURE 6 – Typical two camera setup

The primary difference between the two configurations is that the two camera system can acquire images instantaneously. This means the object, cameras and projector do not have to be rigidly mounted or stable. This can simplify mounting and measurement in many cases. This approach can be especially useful in high-speed production measurements. Examples include measurement of car body surfaces on a production line, or measuring stamped parts as they are produced.

The single-camera approach takes multiple pictures, so acquisition time is not instantaneous. Therefore, the projector and object must be stable during the time it takes to acquire all pictures. However, in many cases, the acquisition time is extremely fast so stability is only required for a short period.

PROJECTION SYSTEM FEATURES:

The two configurations have many common features, but some distinct differences. These are summarized in TABLE 1.

	One 	**Two** 
True Non-contact Measurement	Since nothing touches the surface, it is not deformed or moved. This makes PRO-SPOT ideal for applications that require the measurement of delicate objects and objects that move when touched. PRO-SPOT is also well suited to objects that are too hot to touch. Another advantage is the time and money saved on target application.	
High Accuracy	1 part in 100,000 of the object diameter or 0.010mm (0.0004") per meter of object diameter. The single camera system produces higher accuracies by virtue of the fact that more pictures are taken.	1 part in 40,000 of the object diameter or 0.025mm (0.001") per meter of object diameter.
No target thickness	Since the target is projected onto the surface there is no target thickness or probe offset to consider.	
Fast Acquisition	Although not instantaneous since multiple pictures must be taken from different locations, acquisition is still very fast. In most single setup situations, acquisition time is just a matter of minutes.	Imaging time is practically instantaneous because of the flash illumination. Therefore, this mode is ideal for measuring dynamic objects. Furthermore, this means the object does not have to be rigidly mounted (into a holding fixture for example). It can simply be hung in place or laid on the floor.
Fast measurement	The time to calculate the measured 3-D coordinates of the projected points will depend on the number of points and the processor used. The single camera takes longer in most cases because it also determines the location of the reference targets used to tie the measurement together. Still, most measurements are done in less than a minute.	With two cameras, a thousand points or less can be measured in less than ten seconds using a standard 266Mhz Pentium notebook computer.
Fast cycle time	Cycle time can be very fast because the object can be removed immediately after the pictures are taken. While those images are processed, the next object can be put in place.	

TABLE 1 – Projection System Features

<table>
<tr><th></th><th>One </th><th>Two </th></tr>
<tr><td>Versatile</td><td colspan="2">The method is extremely versatile in both its use and application. Since the dots are just substitutes for retro-reflective targets, all the applications where retro-targets are used are possible candidates for measurement with PRO-SPOT.</td></tr>
<tr><td>Portable</td><td colspan="2">Since the system is portable, objects can be measured in place, and the system can be easily transported anywhere in the world.</td></tr>
<tr><td>Ease of setup</td><td colspan="2">Setup takes just a few minutes, and there is no warm-up time for the camera(s) or projector. Also, the camera(s) and projector require no time for pre-calibration.</td></tr>
<tr><td>Camera and projector positioning</td><td colspan="2">The cameras and projector do not have to be precisely located relative to each other or the object. Camera locations are not critical; the cameras just need to be located far enough back to see the entire measurement area. The projector location is more critical because the projected targets must fit on the surface and be in focus. The projector setup is usually quick and easy by virtue of the projector’s built-in modeling light and simple focusing.</td></tr>
<tr><td>Variable object sizes</td><td colspan="2">The projector can measure objects or sections of objects up to six meters in diameter. As already noted, the actual maximum size of the measuring area is dependent on the reflectance and curvature of the object. Different sized objects will require a different setup of the cameras and projector, but changing setups is quick and easy.</td></tr>
<tr><td>Variable Point Densities</td><td colspan="2">The point density can be changed easily by changing the slide in the projector to one with the desired point density. The effective point density can also be doubled or even tripled by "jogging" the projector into a slightly different position  </td></tr>
<tr><td>Variable point shapes</td><td colspan="2">The pattern of points can also be changed easily. The standard pattern is circular. This pattern can be changed to any rectangular pattern using the built-in beam shaper. In addition, custom slides with practically any density or distribution of points are available.</td></tr>
<tr><td>Rugged</td><td colspan="2">None of the system components is sensitive to extreme heat or environmental conditions. The cameras and projector can operate from $0^{o}C$ to $+35^{o}C$. Also, the system can operate in standard industrial lighting conditions.</td></tr>
<tr><td>CAD friendly</td><td colspan="2">The regular grid pattern of the data makes it easy to generate Splines and reverse engineer surfaces.</td></tr>
</table>

TABLE 1 (continued) – Projection System Features

CASE STUDIES - Overview
To better illustrate the projector and its capabilities, three case studies were undertaken. The studies are described in TABLE 2:

Case Study	*Object*	*Objectives*
Case 1 Projected versus conventional targeting.	 Antenna	1. To measure surface points using both the projector and traditional targets. 2. To compute the best-fit parabolic surface.
Case 2 Antenna repeat measurement	 Antenna	1. To repeat the measurement of a large antenna ten times. 2. To complete the measurement using both a single and dual camera system.
Case 3 Multiple measurement sets	 Car Door	1. To measure surface points in sub-sections 2. To join sections together to form one model

TABLE 2 – Case Studies Overview

CASE 1 – Antenna Measurement
The first case study involved the measurement of a relatively simple object, namely a 1.2 meter diameter antenna. To compare and contrast the differences between conventional measurement and measurement using PRO-SPOT, the antenna was measured using both stick-on targets and projected dots.

Initially, five reference targets, one AutoBar and 12 rows of strip targeting (283 antenna points in all) were added to the antenna. For convenience the reference targets and AutoBar were attached to the antenna. In an actual measurement, they would be placed on the fixture used to hold the antenna. In this case, the antenna was merely propped up against a table for measurement.

The antenna and target configuration are shown in FIGURE 7. The object was photographed and eight images were collected. Four stations were used and the camera was rolled through 90 degrees at each of these stations. Once the measurement was completed, the targets were removed and the antenna measurement repeated using the projection system. The antenna with projected targets is shown in FIGURE 8. Once again, the same basic four-station network was used.

The basic network used is shown in FIGURE 9 and 10, respectively. Five single dot targets were added in the projector to assist with the orientation of the 3D model.

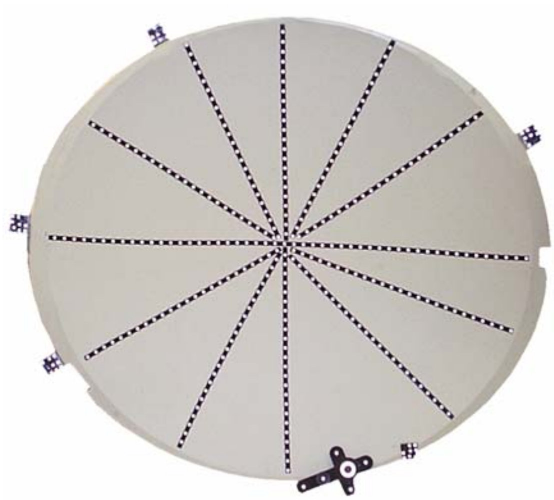


FIGURE 7 – Antenna showing distribution of retro-reflective targets

FIGURE 8 – Antenna showing projected targets.

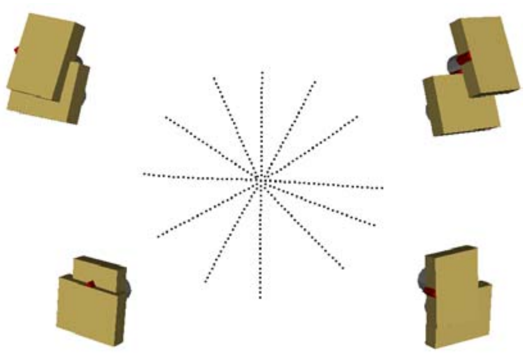


FIGURE 9 – Network and point cloud for retro-reflective case

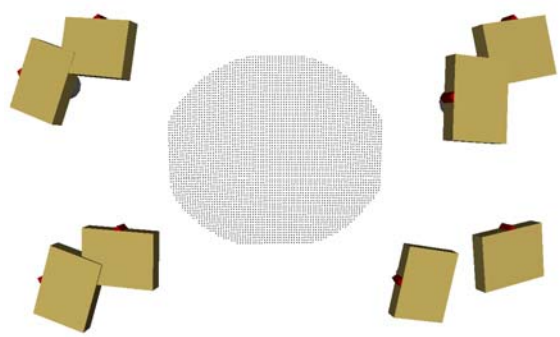


FIGURE 10 – Network and point cloud for projected target case

A comparison of the two measurements is shown in TABLE 3. The comparative column is an estimate of the time and money that would have been needed to collect the same volume of data as that of the projection measurement.

Category	*Retro*	*Retro (comparative)**	*Projection*
Number of targets	283	4500	4500
Targeting	10 minutes	120 minutes	1 minute
Target removal	5 minutes	20 minutes	0 minutes
Photography	2 minutes	2 minutes	3 minutes
Processing	3 minutes	4 minutes	4 minutes
TOTAL TIME	**20 minutes**	**146 minutes**	**8 minutes**
Target Cost	$20	$320	$0
Target Density (Points per inch^2)	0.11	1.73	1.73

* Estimated figures

TABLE 3. Comparison of the two measurements

It is clear from TABLE 3 that there are significant advantages to the projection system. One of these advantages is the difference in target density. The projector density was nearly 16 times greater. The benefit of the enhanced target density is clearly shown in FIGURE 11. The highlighted area denotes a problem area on this particular antenna. The projected target case clearly shows this area. It also visibly highlights the general error map of the antenna. By contrast on the retro reflective data almost fails to detect the problem area. Had the target strips been placed either side of the area, no problem would have been found. It is also harder to get a general feel for the antenna topography with such a sparse distribution of points.

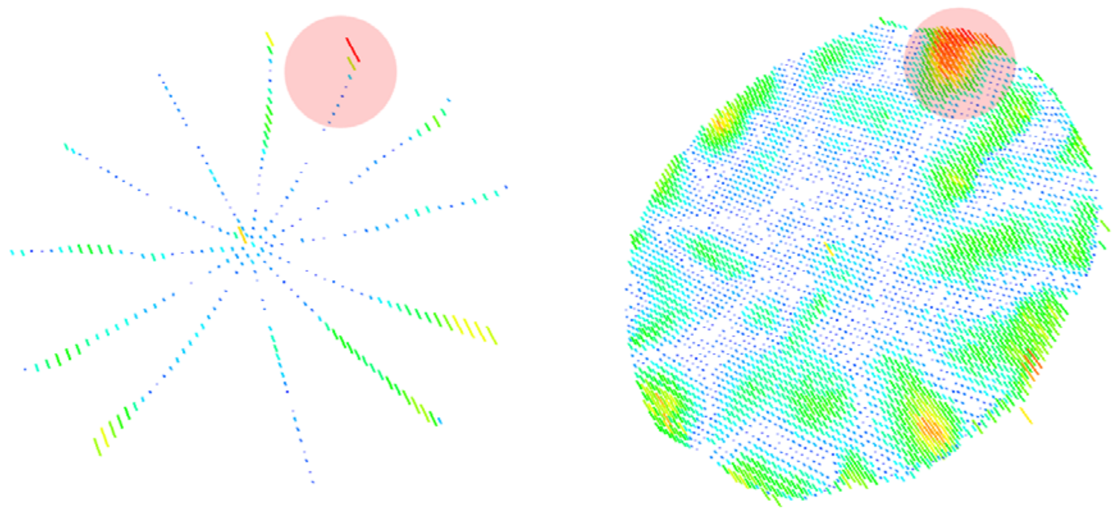


FIGURE 11 – Graphical representations of the best-fit parabolic surface.

Targeting time and cost is yet another advantage of the projection system. The projection system was approximately 12 minutes faster and $20 cheaper than the retro reflective system. The comparative figures highlight how this difference is magnified when one tries to duplicate the point density. The time difference was estimated to be close to 2.5 hours while targeting would have cost approximately $320. No consideration has been given to the associated hardware cost of the projection system but it is evident that the system would recover its cost within the context of a modest measurement program.

CASE 2 – Antenna Repeat Measurement

In the second case study, a series of repeat measurements was completed on the antenna shown in FIGURE 12. The objective was to demonstrate the projection system's ability to work in a production environment where measurement speed is of paramount importance. Measurements were repeated ten times using both the single and dual camera system. After each measurement the antenna was rolled out of position and then back into it to simulate the measurement on the next antenna.

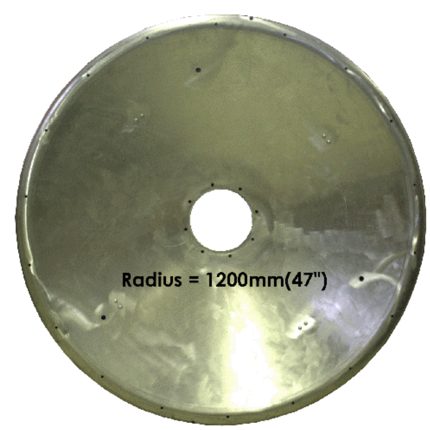


FIGURE 12 – Typical single camera set-up

Initially, eight reference targets and one AutoBar were added to the area surrounding the antenna. For the dual camera system, these points were coordinated initially and used to form a known work volume for subsequent measurements. For the single camera case, this frame was re-measured each time as part of the antenna measurement.

In the single camera case, ten images of the antenna were collected from ten stations. The camera was rolled through 90 degrees at every other station. Refer to TABLE 4 for a network diagram. The network used in the dual camera case is also shown in TABLE 4.

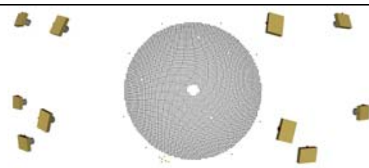
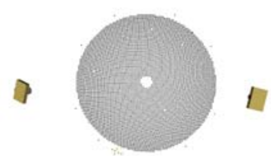
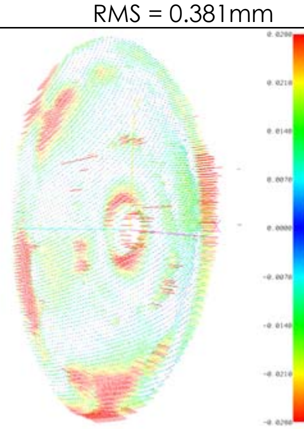
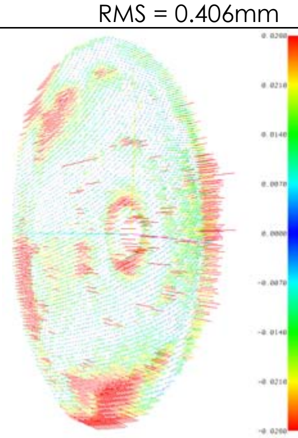
2.4m Diameter Antenna **Category**	**Single Camera** 	**Dual Camera** 
Reference frame establishment	0 minutes	3 minutes
Setup – positioning and focus	3 minutes	3 minutes
Network		
Points measured	5600	5600
Photography	3 minutes	Instant
Processing	4 minutes	1 minute
Accuracy estimate (XYZ)	(0.025, 0.016, 0.017) mm	(0.050, 0.045, 0.045) mm
Antenna FOCUS and RMS	FOCUS = 903.486mm RMS = 0.381mm	FOCUS = 903.630mm RMS = 0.406mm
Parabola fit		
Single unit total time (Note that the processing can be carried out during the setup of the next antenna)	7 minutes	4 minutes
Ten unit total time	70 minutes	43 minutes (3 minutes added for initial set up)

TABLE 4. Comparison of the single and dual camera measurements

It is clear from TABLE 4 that the projection system is a very capable production system. Based on a manufacturing estimate of ten minutes per unit, it is evident that either system could keep up with the production rate. The system configuration ultimately used will depend on the accuracy specification. While the dual camera is faster, it does have a lower inherent accuracy. Despite this lower accuracy the focus and RMS are very similar as are the error maps for the best-fit parabolic surfaces.

CASE 3 – Car Door Measurement

FIGURE 13 – Projector setup

The final case study involved the measurement of a car door. The car door was measured in small dense sections and then "stitched" together through the use of the global control on the door. The basic setup used to collect the data is shown in FIGURE 13. The projector was set back approximately a meter and focused on the areas of interest. A total of four networks were collected. Each of these was made up of eight stations. The networks were named A-D respectively. These networks are shown in FIGURE 14. Networks A and B were used to collect dense data in the two areas of the door with the most detail, that is, the mirror and handle assembly points. Networks C and D were used to collect general surface data on the door.

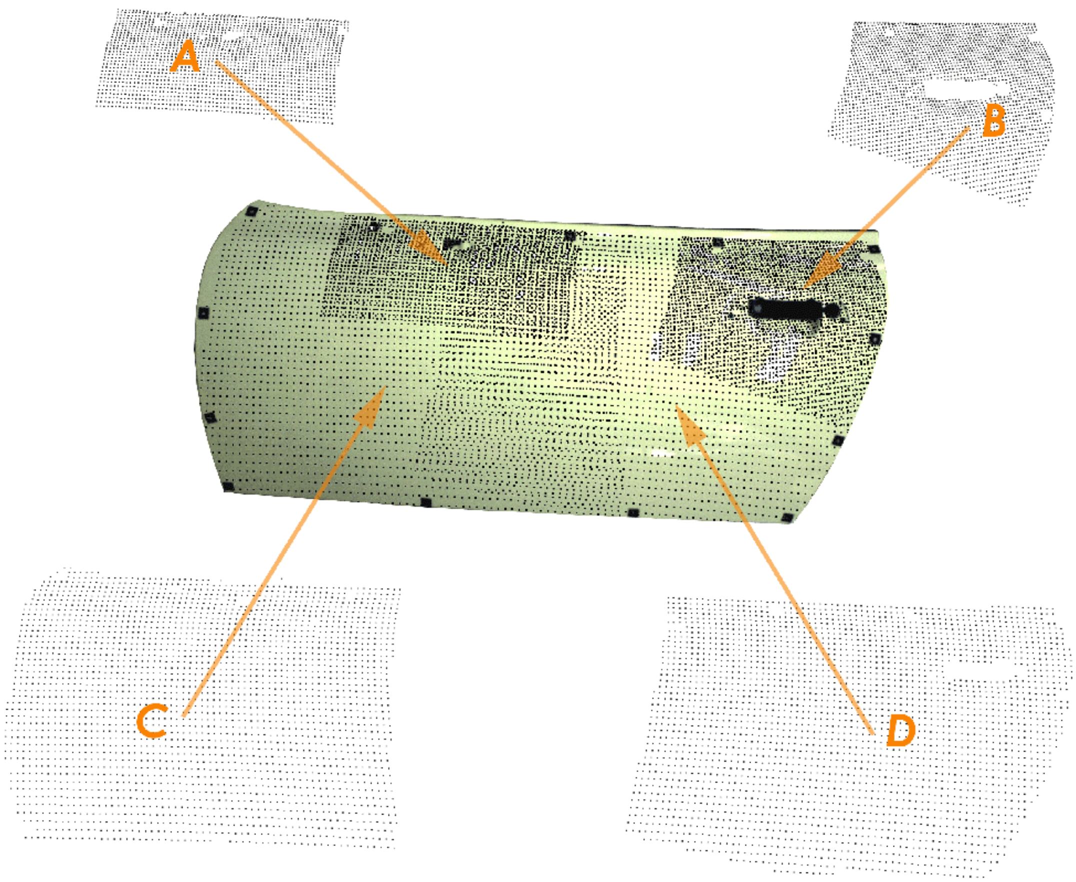


FIGURE 14 – Graphical representations of the four networks and how they are combined on the car door.

The results of the measurement are summarized in TABLE 5

Category	A	B	C	D	Total
Points	1959	2609	2558	2692	**9818**
Setup – positioning and focus	2 minutes	2 minutes	2 minutes	2 minutes	8 minutes
Photography	2 minutes	2 minutes	2 minutes	2 minutes	8 minutes
Processing	3 minutes	3 minutes	3 minutes	3 minutes	12 minutes
Stitching					5 minutes
Total					**33 minutes**
Accuracy estimate XYZ (µm) XYZ(tenths of 0.001")	 13,8,8 5,3,3	 18,13,10 7,5,4	 13,8,8 5,3,3	 10,8,8 4,3,3	

TABLE 5. Results Summary

This case study has demonstrated how easily data sets can be combined to form large more complex data sets. This is useful when trying to map larger objects or objects with complex surface combinations.

CONCLUDING REMARKS

The case studies highlight some of the advantages of a target projection system. The ability of the system to quickly and accurately map dots onto a surface makes it ideal for many applications that have traditionally shunned photogrammetry due to the inconvenience of targeting. The difference between conventional targeting and projection targeting was illustrated in the first case study. The second case study demonstrated the potential of incorporating such a system into a production process. With a minimal setup, it would be possible to implement a 100% inspection program. The final case study demonstrated how multiple sets of projected targets could be "stitched" together to form one super set of 3D data. This gives the system the freedom to map complete objects or complex surface combinations.

This paper has also illustrated some of the features of a projection system. The system is fast, versatile and, most importantly, accurate. The non-contact nature of the system makes it well suited to applications where the object is too hot or perhaps too fragile to handle.

The development of the target projection system is likely to have a substantial influence on surface measurement using videogrammetry.

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