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DATUM TRANSFORMATION ANALYSIS FOR PRODUCTION PART APPROVAL USING 3D NON-CONTACT MEASUREMENT

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16. Abstract

This paper presents a comprehensive dimensional validation methodology, known as datum transformation analysis (DTA). The DTA approach utilizes 3D non-contact (3DNC) measurement to obtain a full part dimensional representation at all critical matching interfaces of a part ***assembly*** to the vehicle. Next, a part measurement *re-alignment* process is applied to identify new positions for the assembly datum locators that optimize the overall product quality at these matching interfaces. Next, datum locations are adjusted at the ***component*** level (at the same physical location as the corresponding assembly) to improve mean conformance of the assembly dimensions. The adjustments to the datum locators at the component level are not necessarily made to improve component quality, but rather to optimize final part assembly. This DTA methodology is demonstrated using an automotive headlamp assembly. In this case study, we identify tooling rework moves using DTA to increase the percent of critical assembly dimensions whose mean values are within ±0.25 millimeters from 20% to 90%.

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3D non-contact measurement system, 3DNC, sheet metal stamping, automotive body, PPAP, die tryout, white light measurement, photogrammetry, headlamp assembly, measurement system capability, tolerance analysis

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Executive Summary

Increasing competition in the automotive industry to improve customer perceptions of final vehicle fit and finish quality is driving tighter dimensional specifications for manufacturers of body exterior assemblies such as closures, headlamps, and tail lamps. Achieving these tighter specifications is complicated by historical limitations with stamping and molding processes to produce complex-shaped components used within these assemblies with all dimensions centered at their nominal specification, particularly within the shorter tryout periods now characteristic of aggressive vehicle product development plans.

This report presents a comprehensive dimensional validation methodology for exterior body assemblies to help manufacturers achieve higher dimensional capability during the preproduction phase of new product development. We refer to this methodology as datum transformation analysis (DTA). The DTA approach utilizes 3D non-contact (3DNC) measurement to obtain a full part dimensional representation at all critical matching interfaces of a part assembly to the vehicle. Next, a part measurement *realignment* process is applied to identify new positions for the assembly datum locators that optimize the overall product quality at these matching interfaces. Next, datum locations are adjusted at the component level (at the same physical location as the corresponding assembly) to improve mean conformance of the assembly dimensions. Of note, the adjustments to the datum locators at the component level are not necessarily made to improve component quality, but rather to optimize final part assembly. In some cases, an individual component may be purposely adjusted away from its design nominal if the final part assembly is closer to its nominal specification.

We demonstrate the usage of this DTA methodology for production part approval of an automotive headlamp. Here, we show the potential of DTA to minimize mold tooling rework and produce a complex-shaped headlamp assembly whose assembly mean dimensions are centered close to nominal and capable of meeting desired tolerance levels even though the individual headlamp lens and housing *components* are not within their specifications. In this case study, we identify tooling rework moves to increase the percent of critical assembly dimensions whose values are within ±0.5 mm from 50% to over 95%.

1. Introduction

As vehicle manufacturers strive for tighter final vehicle specifications, they cascade these requirements down to suppliers, making it difficult to meet criteria for the Production Part Approval Process (PPAP[1]). This has implications to suppliers in terms of both their quality reputation and financial success as attainment of PPAP quality standards often is tied to suppliers' new tooling investment recovery and unit costs.

Unfortunately, the mere assignment of tighter specifications by vehicle assemblers does not make the specifications achievable. For processes such as injection molding or stamping, limitations exist in precisely predicting material flow through forming and molding operations and final resultant shapes after cooling. Past studies have shown that manufacturers of such complex-shaped parts often are unable to simultaneously produce all critical part features with mean values centered at their nominal specification, hindering their ability to meet part approval capability requirements such as Ppk > 1.33 (Hammett et al., 1999). Moreover, injection molding and stamping processes have no simple adjustment factors to simultaneously shift all these dimensions to nominal without unintended consequences. For instance, the rework of a mold or die in one area may change material flow conditions resulting in a problem in another area that is not reworked.

Specification changes such as a "nominal re-target"[2] (Guzman et al., 2003) often are feasible for underbody or other non-visible components provided they yield an acceptable finished body. However, these changes are less likely to be granted for exterior assemblies that are directly visible to the customer or closely related to a finished vehicle-level specification. For instance, a true high condition on a headlamp assembly relative to the fender position of the body (i.e., top of the headlamp is positioned high relative to design nominal of the fender-headlamp interface) is detectable by the end customer (see Figure 1). This condition affects customer perceptions of vehicle fit quality.

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[1] Production Part Approval Process, Automotive Industry Action Group, 2000.

[2] Type of tolerance adjustment that typically occurs when a dimension has a mean value that deviates from its design nominal, but with low variation. This usually results in a dimension that passes a Pp or Cp process capability requirement, but fails its Ppk or Cpk requirement.

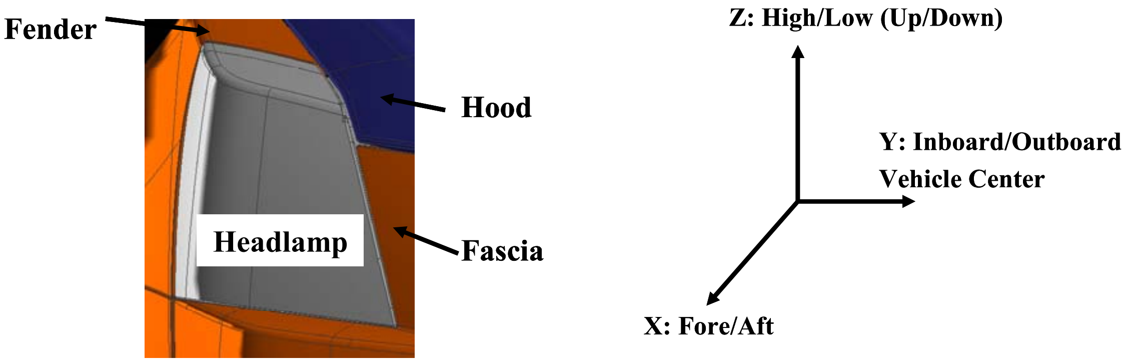

Figure 1. Automotive Headlamp-to-Fender/Hood/Fascia Interface

As a result, these visible automotive exterior assemblies must be reworked as close to nominal as possible. A challenge facing manufacturers is how to achieve these improvements with minimal rework costs and avoidance of unintended consequences. Unintended consequences occur when an acceptable part dimension becomes unacceptable due to an unforeseen issue resulting from process rework of another part area or component.

For an exterior product like a headlamp assembly, a conventional improvement approach is to utilize one of the following:

- rework tooling for the lens and/or housing component to get them closer to their design nominal in hopes that their subsequent assembly also will shift closer to nominal,
- add design features to affect the locating of the lens and the housing component during the assembly process to correct assembly deviations,
- rework component-housing assembly tooling to move dimensions on outer lens of the assembly closer to their desired nominal, or
- utilize more expensive fasteners or vehicle assembly techniques to allow assemblers to adjust each headlamp's assembly relative to its mating component.

Although each option above has merit, each also adds extra development cost and typically requires several trial-error adjustments (i.e., it is difficult to correct in one rework loop). Furthermore, even with extensive rework, manufacturers often are unable to simultaneously improve all of the part dimensions and will still make numerous adjustments during regular production.

The intent of this report is to provide a systematic methodology to help complex-shaped exterior part manufacturers meet tighter specifications with significantly fewer dimensional rework loops. We refer to this approach as datum transformation analysis (DTA). It requires adherence to a functional build quality evaluation philosophy that places a greater emphasis on optimizing end-customer fit requirements versus meeting specifications for individual components (Hammett et al., 1995; Gerth and Baron, 2003).

With DTA, rather than validating components solely to their print specifications, manufacturers evaluate them relative to their mating parts or mating conditions during assembly. The DTA approach is enabled by advances in 3D non-contact (3DNC) measurement[3] (Hammett et al., 2005). Here, one may obtain a full part dimensional representation of an assembly at all critical matching interfaces and then systematically explore different part alignment strategies.

To perform DTA, iterative alignment algorithms within 3DNC measurement software are utilized to find a best-fit assembly position that minimizes error across all of the selected critical assembly dimensions[4]. Once the critical mating features are optimized, one may determine the location (i.e., position) of all the datum locators used for part measurement and assembly in this new, more optimal orientation. Next, the assembly datum locators are adjusted at the component level equal in magnitude, but opposite in direction. The net effect is to improve mean conformance of all the assembly dimensions relative to their nominal specifications at the critical mating interfaces. Of note, adjustments to the datum locators on the component parts used to locate the assembly are not necessarily made to improve component quality, but rather to optimize the part assembly dimensions.

So, instead of using datum locators primarily to establish a part reference system for measurement and assembly, they become the rework or tuning mechanisms to optimize assembly conditions. Since DTA involves optimization of mating features in multiple directions, we recommend performing the measurements using 3D non-contact measurement and aligning with a related software tool. Where possible, once optimal locators are determined at all the datum locator points, the tool should be reworked at these positions only.

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[3] The measurement technology used for this research project is a CogniTens Optigo 200 system.

[4] This method assumes that critical part features have been identified that reference a part in all directions.

Since checking fixtures and downstream assembly tooling use these datum positions, some minor adjustments to these tools may be needed if the relative position between datum locators changes with DTA. For example, the nominal distance between a two-way and a four-way locator may be different after applying DTA. Of course, these adjustments will be unknown to the end customer as datum features are used internally for alignment of parts for measurement and assembly.

This approach contrasts with more conventional methods where a part is measured at critical mating feature locations relative to its datum locator references, usually described by geometric dimension and tolerancing (GD&T) drawings (Liggett, 1993). Then, if these features deviate from their nominal specifications, tooling is reworked to improve conformance.

We acknowledge that most manufacturers have applied similar concepts as DTA, but they typically have done so only at the component part level (e.g., stamped parts) and for individual datum locators, versus systematically across an entire part based on assembly conditions. For instance, some manufacturers will move the position of a four-way or two-way locator hole to shift part dimensional measurements in a particular direction (e.g., they shift an entire part in the inboard/outboard to vehicle center direction by moving the locator hole). However, they typically apply such corrections only after making unsuccessful rework attempts to first shift the mating features. Alternatively, they make datum tuning adjustments without a comprehensive analysis across the entire part. For instance, they adjust one direction at a time versus using a three-dimensional realignment. This typically results in a suboptimal change for a complex-shaped part.

The methodology described here entails a more comprehensive approach that includes:

- identification of DTA opportunities (conditions that increase the likelihood of successful application)
- establishment of design-friendly features for datum adjustment
- recommendations for data collection and measurement including a technique for selection of representative part(s) to establish optimal alignment corrections
- selection of part features to use within an iterative alignment algorithm
- creation of DTA datum locator tuning matrix
- verification techniques for mold tuning recommendations using mock-up parts

To illustrate the DTA methodology, we utilize an automotive headlamp case study. In this particular case, the manufacturer was asked to produce all critical part mating features on its headlamp assembly within ± 0.5 mm at a Ppk quality level of at least 1.0 (Production Part Approval Process, 2006).

For this headlamp, the tooling design, construction, and initial tryout process yielded assemblies with only 7% of dimensions meeting this desired Ppk quality standard. Furthermore, ~20% of the mean values for the critical headlamp assembly dimensions were within ± 0.25 mm from nominal (i.e., 80% of dimensions had mean values using up over 50% of the allowable design tolerance due to mean-off-nominal conditions only). By using DTA, the percentage of key assembly dimensions having a mean value within ± 0.25 mm was improved from ~20% to ~90% with all observed sample points within specification (± 0.5 mm).

The DTA methodology and sample case study are described in this report as follows. Section 2 provides an overview of dimensional challenges achieving production part approval for complex-shaped parts such as molded assemblies. Section 3 then discusses the DTA methodology. Section 4 provides an example of this methodology using a headlamp assembly. Section 5 considers part design criteria to facilitate DTA based on observations from this case study. In Section 6, we summarize the findings of this report and identify opportunities for future research.

2. Manufacturing Validation Dimensional Challenges for Complex-Shaped Parts

The manufacturing validation phase of new product development for supplier parts traditionally has been an iterative, inspect-and-rework process that begins with an initial tryout at a tool construction facility and concludes with part approval at the component or assembly production source. For suppliers, the part approval process often yields significant cost overruns, particularly as vehicle manufacturers require suppliers to commit toward meeting tighter specifications in order to receive business.

A major reason for these cost overruns is tooling rework costs (Hammett et al., 1995). In some cases, these tooling rework costs are exacerbated by component specifications that are not necessary to meet final vehicle fit and finish quality requirements. For example, some tooling rework has minimal effect because the components are weak contributors to final assembly quality (Takezawa, 1980; Liu et al., 1996). In some cases, it may not even be feasible to fix an issue through tooling rework based on the product design, particularly within the tooling and unit cost targets provided to suppliers by vehicle manufacturers (Majeske and Glenn, 2007).

Another reason for high tooling costs is ineffective rework. Here, a manufacturer may rework tooling only to find that the part does not behave as predicted or unintended consequences occur. Unintended dimensional consequences are where a manufacturer reworks one area of a tool to correct a dimensional problem only to create another problem somewhere else. Computer simulation tools used to identify physical rework moves are rarely able to predict all dimensional outcomes of a complex-shaped part within tolerance bands for surface profiles of ± 0.5 mm. Manual rework moves are typically even less precise. Some rework is inevitable as manufacturers try to meet high dimensional quality standards.

Tooling rework for dimensional issues derives from difficulties producing parts such that the mean for every feature is centered at its nominal (see Figure 2 for an example from this case study). For injection molded parts, these initial mean deviations usually result from limitations predicting warp or shrinkage. Even with extensive tool modifications, simultaneously reworking all mean values to nominal is rarely achieved as simple process adjustment factors do not exist to move some features independent of others.

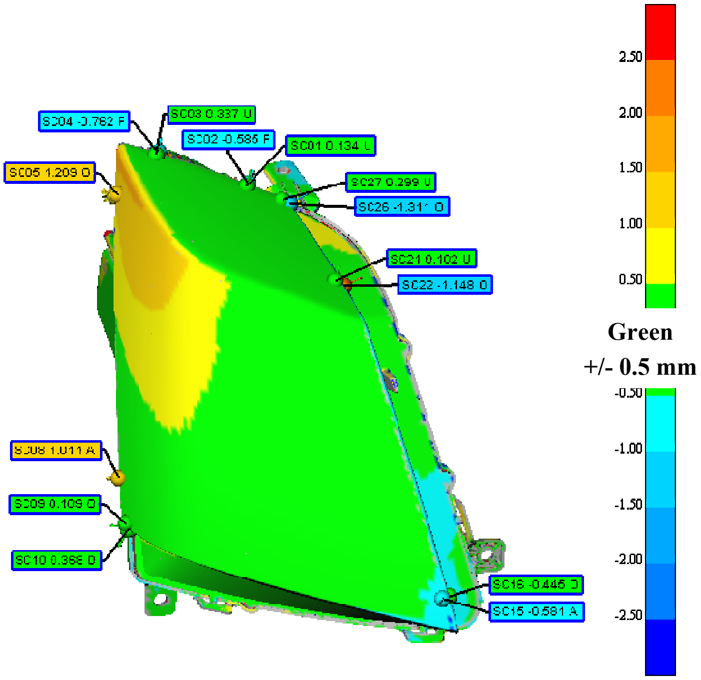

Figure 2. Initial Headlamp Assembly Quality – Average Color Map

Although manufacturers rarely produce parts with all features having mean values close to nominal, they often achieve their process variation objectives (Hammett et al., 1999). For instance, they may produce a stable part with dimensions that meet a Cp (or Pp) criteria but fail Cpk (or Ppk) due to mean deviations from nominal (see Figure 3).

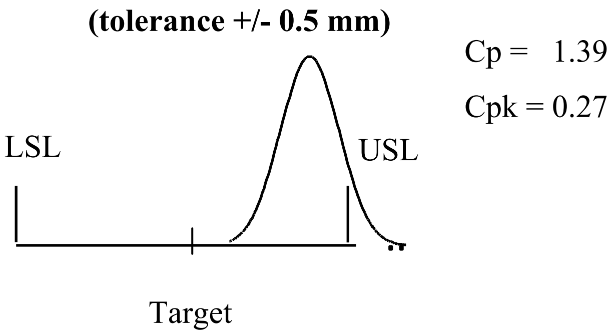

Figure 3. Sample Dimension with Mean Off Target but Low Variation
(Note: LSL and USL represent lower and upper specification limits)

In some cases, if a mean for a particular dimension is stable with low variation relative to its tolerance width specification, an assembly processes may be robust to the mean deviation. For example, in this case study, several dimensions on the housing component were significantly off nominal. These deviations, however, did not affect the final assembly dimensions as many housing dimensions adhered to the more rigid exterior lens. In practical terms, the dimensions of the headlamp assembly may be built closer to nominal than the components that comprise it.

This condition results in the recurring challenge of manufacturing validation where one wants to rework only those component dimensions that inhibit one from meeting vehicle level fit requirements. This requires effective rework loops where one shifts problem dimensions in the desired direction and appropriate magnitude with minimal unintended consequences. DTA provides a methodology to identify and perform such improvements.

3. Datum Transformation Analysis (DTA)

Datum transformation analysis (DTA) is a methodology to identify tooling tune-in adjustments to datum locators in order to optimize the best functional fit of the overall product.

DTA involves adjusting datum reference locations to optimize mean dimensions of the critical part features that are off target yet are produced from a stable process with acceptable inherent variation. The proposed DTA methodology is outlined in Figure 4.

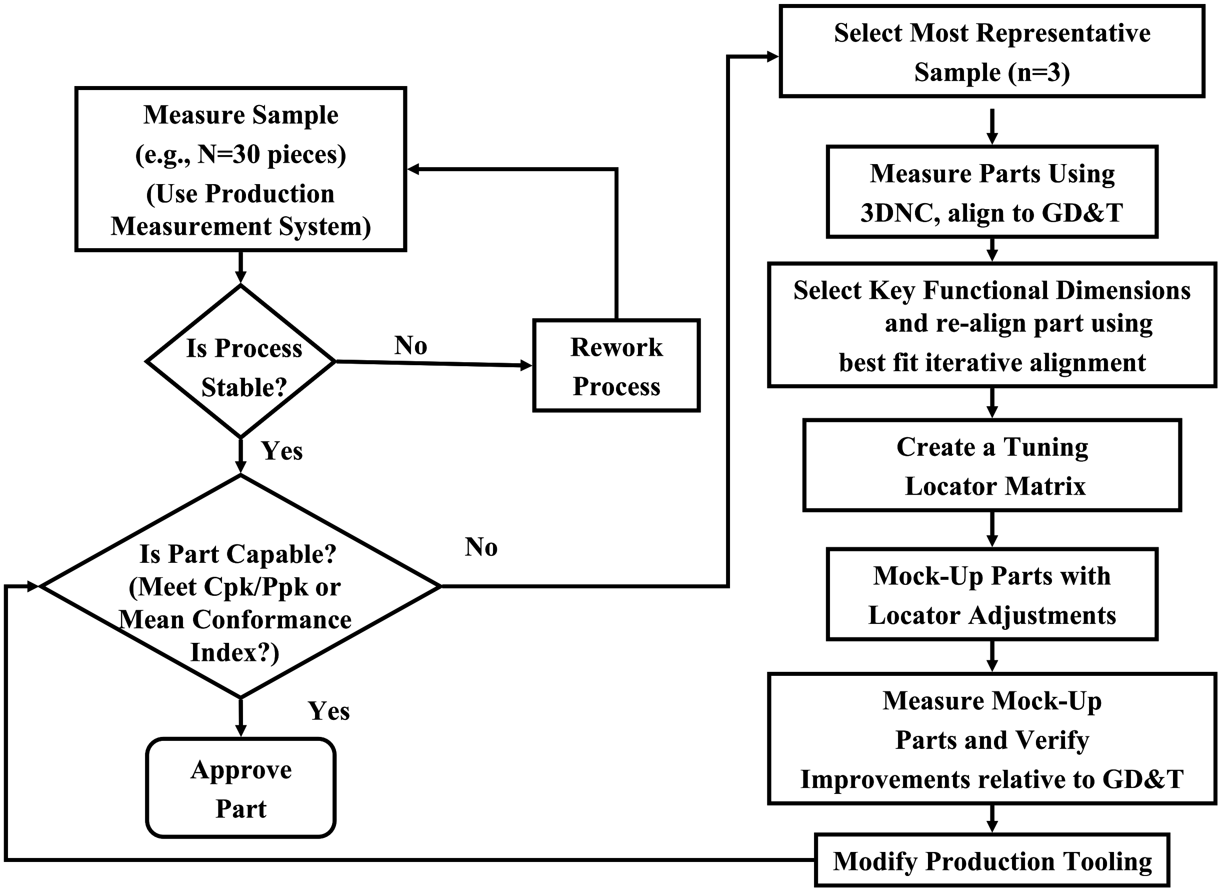

Figure 4. DTA Methodology

3.1 Assess Process Stability

Before making tooling adjustments that affect mean values, manufacturers must have confidence that the process yields predictable mean deviations. In other words, until a process is deemed stable, the observed mean for various part dimensions should not be considered reliable and representative of production conditions. Thus, the first step in applying DTA is to evaluate process stability[5].

To evaluate process stability, one needs to measure a representative sample from normal production conditions. During the manufacturing validation phase of new product development, the number of available samples to measure under such conditions is often limited. Still, most manufacturers should be able to generate a 30-piece sample which should be sufficient to evaluate short-term process stability. Of note, in some cases, a manufacturer may assess stability with even fewer samples if it has extensive historical knowledge of a process and the variation observed in the smaller sample is significantly less than the tolerance width and is similar to historical variation levels (Hammett and Guzman, 2006).

Although we recommend using 3D non-contact measurement to identify datum adjustment recommendations, one should utilize the production measurement process for assessing stability. Stability may effectively be assessed using numerous systems including check fixtures with data collection probes, coordinate measuring machine (CMM), 3D non-contact measurement, or other measurement tools (Hammett et al., 2005). If a manufacturer is using production check fixtures with data collection probes to measure key features, it may be faster to use this system to measure a sample of 30 parts than to rely on a portable 3D non-contact measurement device.

The most common analysis tools used to evaluate process stability are statistical process control charts. Although not all of the potential sources of production variation may be present during manufacturing validation for processes such as injection molding or stamping, most manufacturers should be able to use control chart methods to assess short-term stability. For instance, process variation typically is predictable relative to historical data for injection molding, provided the key manufacturing process parameters such as fill pressures are appropriate and consistent across a sample.

One challenge with applying control charts for complex-shaped parts is that they typically have numerous quality characteristics being measured. For some parts, measurement may consist of 10-20 dimensions; for others, it may be several hundred. As the number of

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[5] This assumes that the measurement system has been validated. In the automotive industry, measurement systems are typically validated by passing a check fixture certification test and passing a gage capability study such as a gage R&R.

dimensions on a part increases, it is not uncommon to have a few subgroups of a few dimensions exhibit out-control conditions using conventional control charts, especially given the small sample sizes typically available to assess stability during manufacturing validation. Here, the process may be stable even though some observed out-control conditions for a few part dimensions are observed. To mitigate this effect, one could use multivariate statistical analysis methods (Guzman et al., 2004), or classify the part as stable if, say, over 95% of the part dimensions are in statistical control and the range for all dimensions is sufficiently less than its tolerance width.

3.2 Assess Process Capability and Overall Mean Conformance

Once a part is deemed stable, we recommend assessing the overall part mean conformance before assessing the potential improvement of DTA realignment. To do so, we first recommend evaluating mean values. As an initial guideline, we recommend evaluating the percentage of mean values that are within half their original tolerance widths. We refer to this as the mean conformance window. For instance, if a critical mating assembly feature has a profile tolerance of ± 0.5 mm, we would seek to get mean values for all related dimensions within a mean conformance window of ± 0.25 mm. Of note, a more effective evaluation would involve using coordinated exterior assembly-to-vehicle builds to determine how close individual *mean dimensions* must be to their nominal specification to meet end vehicle quality specifications.

If a significant percentage of dimensions (e.g., at least more than 20%) are outside the mean conformance window (e.g., ± 0.25 mm), we would proceed with datum transformation realignment analysis. Of note, this critical decision clearly involves some experience-based decision making. For example, if the vast majority of mean dimensions are within the mean conformance window, then more localized tooling rework corrections may be appropriate.

3.3 Select Representative Sample for Realignment Analysis

If one decides to use DTA, we recommend using a biased sampling technique (Hammett et al., 1997) to select a representative subset of parts to identify tooling corrections. The selection of a representative sample within a larger sample is sometimes referred to as the best-of-the-best (BOB) part (Bhote and Bhote, 2000). Of note, the selection of this representative subset using 3D non-contact measurement may not be critical if the process is stable with very low part-part variation (i.e., all of the samples exhibit similar deviations).

Several strategies may be utilized to identify a representative subset within a measurement sample. One approach to selecting the most representative sample (or subset) is based on finding the samples that are closest to the quadratic mean of the various dimensions across a part. Another approach is to select the individual sample(s) whose values are closest to the design nominal specification. Of note, if the mean values for the majority of dimensions are off nominal, then these two methods will yield different results. Figure 5 highlights this difference for the simple case of a part with a single dimension whose mean is off nominal. Since DTA involves datum locator adjustments to simultaneously shift multiple mean values closer to their nominal specification, we recommend a variant of the first approach to find the sample (subset) that is most representative of the various part dimensional distributions.

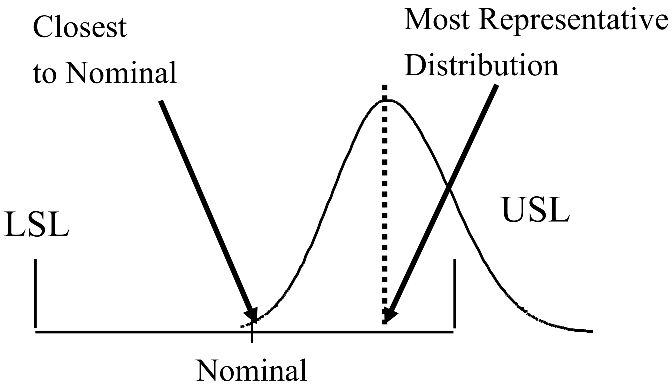

Figure 5. Most Representative Part

Determining the most representative part(s) within a sample may be determined by computing a representative part index, Rp, for each sample using Equation 1. We suggest obtaining Rp by computing the squared deviation of each measured value from its median for each dimension on a part and then averaging these deviations based on the number of dimensions measured. We recommend using the median instead of the mean to represent the center of the distribution for the following reasons. First, since observed measurements may not be normally distributed, the statistical median provides a more robust measure of the distribution center.

Second, the intent here is to select a physical part to apply DTA, and the median more closely relates to actual observed measurements of a physical part versus a calculated center point.

$$\mathrm{Rp}_j = \frac{\sum_{i=1}^{k} (X_{ij} - Md_i)^2}{k} \qquad \textbf{(Equation 1)}$$

where,

X_{ij} = deviation from nominal specification for dimension i of sample j.

Md_i = the median of the distribution for each dimension i.

i 1..k check point dimensions

j 1..n samples (n is the number of samples)

After computing the Rp index for each sample part, one may rank order the sample parts according to their respective index values. The part with the smallest Rp value represents the sample that is closest to its respective medians across all the dimensions on the part (i.e., minimizes the median-squared error). Of note, large Rp values indicate those parts with dimensions that are farthest from their distribution centers. To assess the sensitivity of a datum adjustment recommendation, a manufacturer may also wish to perform DTA using the least representative part (i.e., the sample part with the highest Rp value).

Once a subset of at least three parts has been identified, we recommend using 3DNC measurement to comprehensively measure the sample parts. Our recommendation for using 3DNC instead of a coordinate measuring machine is as follows. First, 3DNC systems provide a better graphical representation of the complete measured part. Thus, a user is better able to visualize the rotation of the part in 3D space per different realignment alternatives. Second, most 3DNC measurement systems have the capability to either quickly perform virtual realignments or their results may be exported into a common format (such as a *.STL), which may be used by several CAD measurement software packages to perform iterative realignment analysis.

3.4 Identify Tooling Corrections Based on Part Realignment

Figure 6 shows the average deviation of all surface measurements relative to their product design nominal using a color map based on 3DNC measurements for a headlamp assembly. This figure suggests that the part is consistently outboard relative to the vehicle center across the upper half of the part and has a twist in the fore-aft direction from the top of the part to the bottom (i.e., fore condition at the top of the headlamp; aft condition at the bottom). Thus, optimizing this part will likely involve a rotation top to bottom and shift outboard to improve the mean values for these dimensions.

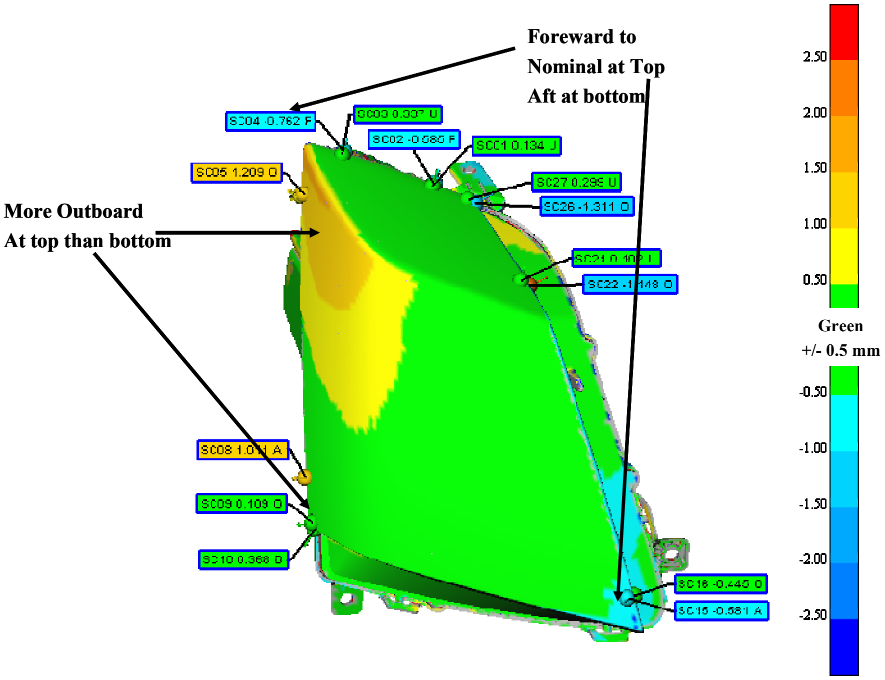

Figure 6. Initial Measurement Condition (Aligned using Assembly GD&T Locators)

To perform a datum transformation re-alignment, one must select critical dimensions on the part for this secondary alignment. Although the selection of these secondary alignment dimensions requires an understanding of the part's function and product design, some general guidelines may be identified.

First, we recommend using at least six points to control for six degrees of freedom, as is customary with three-dimensional part measurement (Liggett, 1993). Beyond the six control points, we recommend additional points to iteratively explore multiple alignment configurations to find a solution that minimizes total error. Although we recommend using more than six points, we do not necessarily recommend using all inspection points. Here, one may optimize an entire part without necessarily optimizing the most critical mating interfaces. In general, we recommend limiting the number of iterative alignment points to approximately 20[6].

A second guideline is to spread dimensions across a part with multiple points in each alignment direction (i.e., X, Y, and Z axis). Third, the secondary alignment features should focus on measurement points at all key part interfaces (assumes that the part has more than one mating interface). A fourth guideline is to include a weighting factor if a particular area is deemed the most critical. With most alignment software, this may be done by forcing a feature(s) into an alignment model and iterating a best-fit part condition across the remaining secondary alignment points.

The figure below shows the secondary alignment points versus the assembly GD&T locators used for this headlamp case study. The orange balls represent the location of critical part dimensions to realign the part.

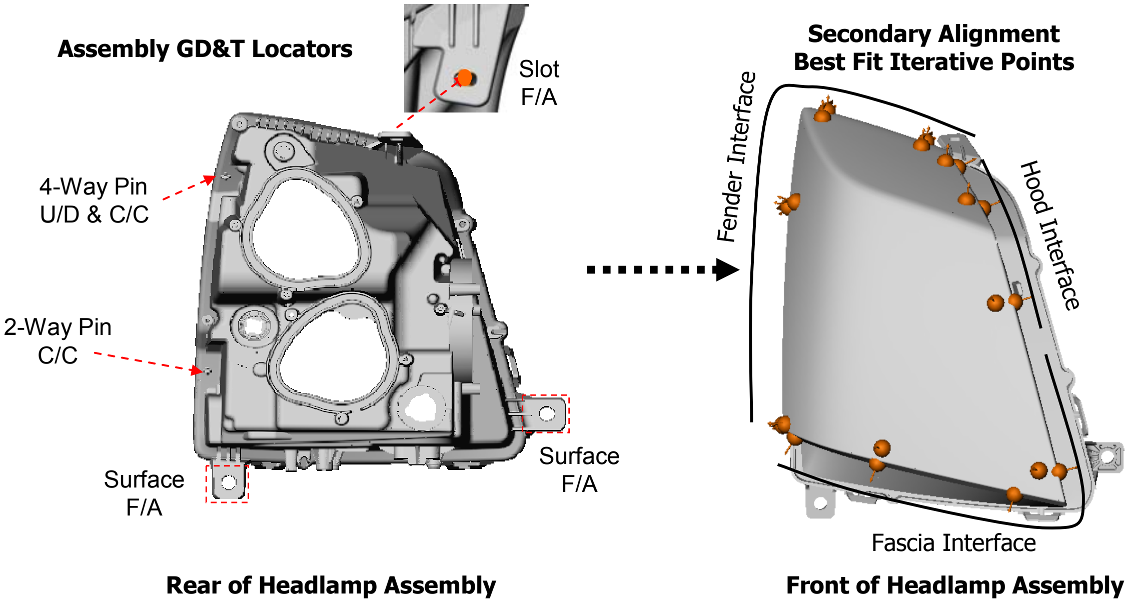

Figure 7. Part GD&T Locator Points vs. Secondary Alignment Points

Once a part is realigned using the secondary alignment points, the resultant position of the datum locators relative to this alignment may be determined. From here, one may create a

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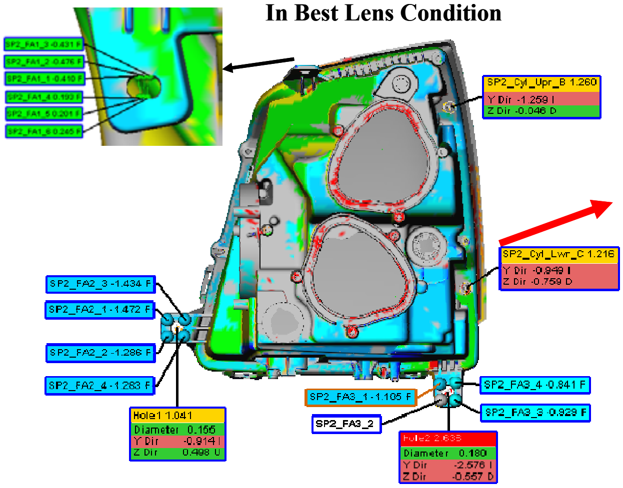
[6] Future research is recommended to further explore optimal alignment point selection guidelines.

locator tuning matrix to identify rework moves (see Figure 8 for example). In general, tuning adjustments for each locator should be equal in magnitude, but opposite in direction, as the secondary best-fit alignment results. So, if a cross-car datum locator is 1.0 mm inboard from nominal based on the best-fit condition, then a tooling adjustment of 1.0 mm outboard at this datum location would be recommended.

In identifying adjustments, one may wish to consider measurement noise. For instance, we typically would not recommend making physical tooling surface moves if the calculated adjustment is 0.2 mm or less. Here, we believe that a rework move of this magnitude would unlikely have an observable effect on the assembly dimensions. Of note, an exception to this recommendation may involve a hole or slot. In general, a hole or slot positional move may be done with greater precision than a surface change.

Position of Locators
In Best Lens Condition



Locator Tuning Table

Locator	Dir	Average (3)		Recommendation
Top Pin (4-Way)	C/C	1.3	inboard	**move 1.3 outboard**
	U/D	0.0	up	**none**
Lwr Pin (2-Way)	C/C	1.0	inboard	**move 1.0 outboard**
Attachment Tab: Lower I/B	F/A	1.3	fore	**increase wall thickness by 1.3 mm on backside**
Attachment Hole: Lower I/B	C/C	0.9	inboard	**move 0.9 outboard**
	U/D	0.5	up	***move 0.5 down***
Attachment Tab Lower O/B	F/A	1.0	fore	**increase wall thickness by 1.0 mm on backside**
Attachment Hole: Lower O/B	C/C	2.6	inboard	**move 2.3 inboard**
	U/D	0.6	down	***move 0.6 up***
Top Tab (fore edge of slot)	F/A	0.4	fore	
Top Tab (rear edge of slot)	F/A	0.2	fore	
Top Tab (Slot Center)	F/A			**move slot center 0.25 aft**

Figure 8. Best Fit Datum Locator Measurements and Tuning Table

To fully benefit from datum transformation analysis, one should make all of the recommended adjustments to properly re-position the part in three-dimensional space. Adjustment recommendations for a datum locator should be considered correlated to other recommendations. In other words, we strongly caution against making datum moves one at a time if the analysis suggests changes at multiple locations.

To check the proposed datum adjustments, we recommend first creating mock-up parts. In most cases, this approach should be feasible without physical changes to the production tools.

For example, mock-ups may be created by adding spacers at locator surfaces, grinding off material, or changing the center position of a hole, slot, or molded pin[7]. Next, one should measure the mock-up parts relative to their part GD&T to verify that the changes result in the intended improvements. If acceptable, one may then make physical changes to the production tooling.

One potential issue with datum transformation analysis is part rigidity. To perform a virtual alignment, one assumes the part measurements are taken from a rigid structure. If DTA is applied to a part assembly, as in the case of a headlamp assembly, we maintain that this assumption likely will be reasonable. However, if DTA is applied to a complex non-rigid component, then the secondary alignment recommendations may be unreliable[8]. Of note, even if a component by itself is not rigid and easily influenced by its orientation during measurement, it still may be rigid after assembly. In other words, the component orientation becomes rigid after assembly. Here, changes to the component datum locators may be different when measuring a detail component versus measuring this same component within a larger assembly. As such, we recommend performing the realignment in the more rigid assembly state.

Another possible issue with DTA tuning recommendations is that realignment may not yield a tuning locator matrix solution that optimizes all part dimensional mean values. In other words, once a part is realigned, it may still have dimensions that pass Cp criteria, yet fail Cpk criteria due to a mean deviation from design nominal. At this point, we would recommend using a coordinated part-assembly part evaluation process to determine if the adjusted part is sufficiently close to produce a dimensionally acceptable finished vehicle without further tooling rework. If not, some localized rework or conventional adjustment methods may be necessary to secure final part approval.

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[7] Changes to molded pins or hole positions are likely more difficult than moving a surface. See Section 5 for details on designing for DTA.

[8] We leave the issue of DTA for complex, non-rigid components as a subject for future research.

4. Case Study – Headlamp Assembly

To demonstrate the application of DTA, an automotive headlamp case study is used. As shown in the following figure, this headlamp assembly consists of an outer lens (vehicle interface) and main housing (attachments to vehicle)[9]. The headlamp assembly has several critical vehicle functional interfaces including fits to the fender, hood, and fascia (Figure 9).

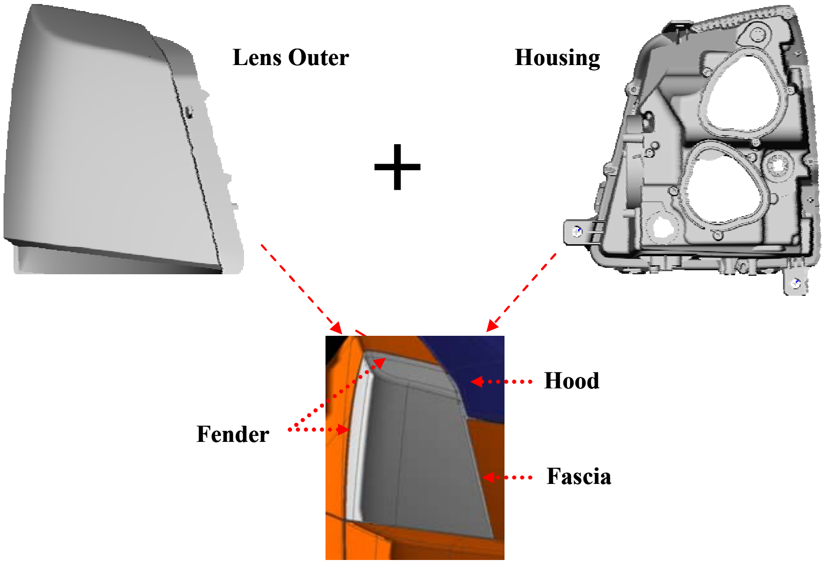

Figure 9. Headlamp Assembly and Main Components

To assemble this headlamp to its vehicle, three mounting tabs (fore/aft), a four-way (cross-car and up-down), and a two-way locator (cross-car) are used (see Figure 10). Once the assembly is positioned using the locator pins, bolts are used to attach the headlamp to the body at the three mounting tab locations. Of note, these vehicle level alignment points also are used as the datum reference points for assembly part measurements.

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[9] The other components of a headlamp assembly (e.g., lighting system) do not have any affect on final assembly mating dimensions to the vehicle.

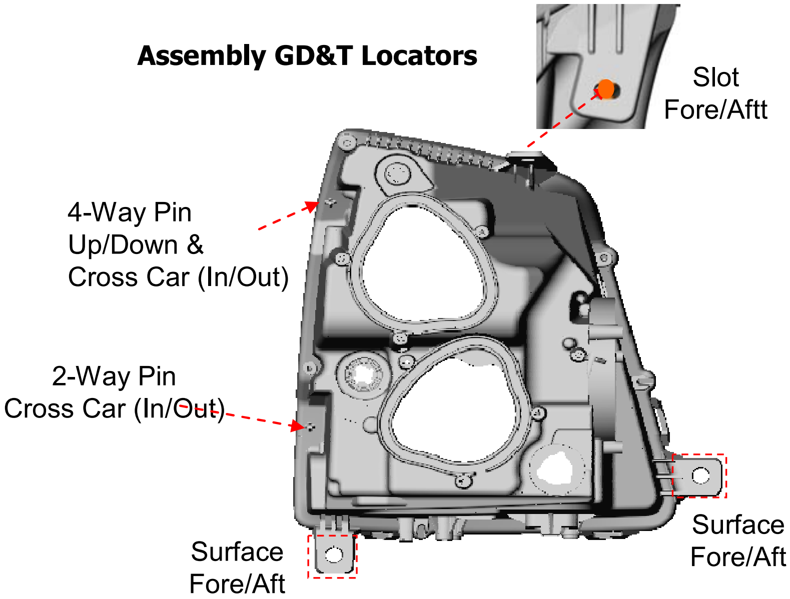


Figure 10. Headlamp Assembly GD&T and Vehicle Alignment Features

(Note: Assembly shown from rear view)

4.1 Initial Dimensional Capability

A review of the initial measurement data indicates that this part is not capable of meeting its Ppk expectations for tolerances of ± 0.5 mm at its critical vehicle interface dimensions. Although the process exhibits stability based on statistical process control charts, numerous dimensions have mean values off nominal and some have inherent variation slightly larger than the original tolerance width.

This is illustrated using several dimensions in the following run chart of the check fixture data based on a sample size of 80 head lamp assemblies (see Figure 11). This charts shows that the measurements for each critical part dimension are consistent but exhibit large mean deviations. In fact, control charts for the individual points indicate that the process is in statistical control with each individual check point exhibiting a range of about 0.5-to-1.1 mm. Thus, the primary concern with this assembly is mean deviation from nominal, making it a good candidate for datum transformation analysis.

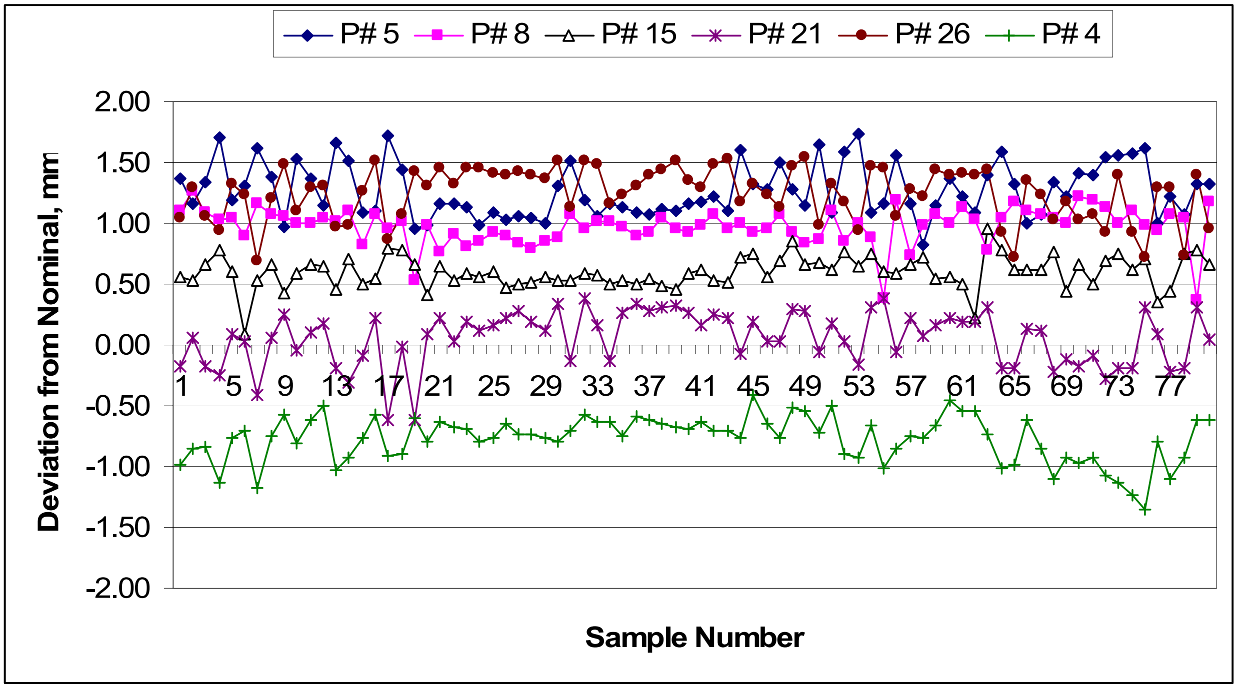


Figure 11. Run Charts for Six Critical Check Points

Given this stable condition, three parts were chosen from the sample of 80 as the most representative of the median distribution across all dimensions. Measurements for the first 40 samples (out of 80) and the overall summary statistics for each dimension are shown in Table 1. This table also shows the Rp_i calculations for the first 40 samples. In this particular case, we may note the median and mean dimensions are very close for nearly all of the check points. However, this may not always be the case. Samples #22, #35, and #40 are deemed the most representative of the full sample. These three samples were then measured using 3D non-contact measurement.

Table 1. Sample Data and Most Representative Part Rankings

(Note: Only partial table shown)

Sample	1	2	3	4	5	6	8	9	10	15	16	21	22	26	27	RPi	RP Rank
1	-0.05	-0.77	0.19	-0.98	1.37	0.43	1.11	0.29	-0.25	0.56	0.41	-0.18	1.21	1.04	0.16	**0.18**	**50**
2	0.19	-0.77	0.37	-0.86	1.17	0.41	1.26	0.14	-0.32	0.53	0.55	0.06	1.26	1.30	0.34	**0.12**	**26**
3	0.01	-0.72	0.06	-0.84	1.35	0.70	1.09	0.05	-0.24	0.66	0.27	-0.18	1.27	1.06	0.25	**0.19**	**52**
4	0.10	-0.90	0.30	-1.13	1.71	0.27	1.03	-0.06	-0.36	0.78	0.59	-0.25	1.34	0.94	0.32	**0.26**	**69**
5	0.19	-0.68	0.49	-0.77	1.19	0.19	1.05	-0.08	-0.14	0.61	0.31	0.10	1.22	1.32	0.33	**0.13**	**35**
6	0.24	-0.60	0.72	-0.71	1.32	0.49	0.90	0.04	-0.49	0.09	0.58	0.03	1.43	1.24	0.46	**0.20**	**55**
7	-0.13	-0.89	-0.01	-1.17	1.63	0.59	1.16	0.04	-0.11	0.54	0.36	-0.41	1.27	0.69	0.11	**0.33**	**80**
8	0.04	-0.58	0.30	-0.75	1.39	0.72	1.08	0.06	-0.49	0.66	0.51	0.07	1.16	1.21	0.21	**0.12**	**32**
9	0.03	-0.47	0.30	-0.57	0.98	0.48	1.06	0.15	-0.41	0.43	0.34	0.25	1.14	1.48	0.23	**0.11**	**22**
10	-0.04	-0.58	0.23	-0.81	1.54	0.35	1.00	-0.11	-0.41	0.60	0.52	-0.04	1.20	1.11	0.18	**0.15**	**42**
11	0.13	-0.62	0.43	-0.62	1.37	0.27	1.00	0.16	-0.46	0.67	0.38	0.11	1.15	1.29	0.33	**0.08**	**6**
12	0.18	-0.38	0.46	-0.50	1.15	0.35	1.05	0.04	-0.61	0.65	0.26	0.18	1.09	1.31	0.32	**0.12**	**30**
13	0.16	-0.78	0.17	-1.03	1.67	0.44	1.01	-0.23	-0.32	0.46	0.44	-0.19	1.54	0.97	0.28	**0.25**	**68**
14	0.00	-0.74	0.22	-0.92	1.52	0.39	1.10	-0.18	-0.37	0.71	0.53	-0.32	1.12	0.98	0.16	**0.21**	**60**
15	0.08	-0.59	0.24	-0.76	1.09	0.63	0.83	0.23	-0.36	0.50	0.65	-0.08	1.19	1.26	0.29	**0.11**	**23**
16	0.20	-0.43	0.44	-0.57	1.11	0.27	1.08	-0.15	-0.55	0.55	0.38	0.23	1.30	1.51	0.41	**0.13**	**36**
17	0.13	-0.64	0.13	-0.91	1.72	0.33	0.95	0.04	-0.52	0.80	0.68	-0.62	1.57	0.87	0.37	**0.31**	**79**
18	0.04	-0.67	0.28	-0.90	1.45	0.39	1.02	0.05	-0.52	0.79	0.53	-0.01	1.20	1.08	0.23	**0.14**	**39**
19	0.10	-0.35	0.31	-0.60	0.96	0.50	0.53	0.38	-0.48	0.66	0.88	-0.63	1.17	1.43	0.21	**0.27**	**71**
20	0.07	-0.63	0.27	-0.80	0.99	0.45	0.98	0.18	-0.16	0.42	0.18	0.09	1.14	1.31	0.20	**0.13**	**34**
21	0.04	-0.45	0.61	-0.63	1.17	0.11	0.77	0.10	-0.59	0.65	0.54	0.23	1.09	1.45	0.25	**0.14**	**41**
22	0.17	-0.40	0.32	-0.67	1.16	0.25	0.91	0.14	-0.46	0.53	0.59	0.04	1.10	1.33	0.35	**0.07**	**1**
23	0.16	-0.37	0.42	-0.69	1.14	0.35	0.81	0.17	-0.36	0.59	0.34	0.19	1.14	1.46	0.31	**0.09**	**10**
24	0.11	-0.43	0.21	-0.80	0.99	0.28	0.85	0.15	-0.42	0.57	0.75	0.12	1.06	1.45	0.29	**0.11**	**24**
25	0.12	-0.44	0.25	-0.77	1.10	0.26	0.93	0.12	-0.44	0.61	0.69	0.17	1.10	1.41	0.35	**0.08**	**4**
26	0.09	-0.45	0.21	-0.65	1.04	0.27	0.89	0.03	-0.40	0.47	0.65	0.23	1.13	1.40	0.34	**0.09**	**12**
27	0.15	-0.48	0.36	-0.73	1.07	0.30	0.84	-0.01	-0.56	0.50	0.62	0.29	1.15	1.43	0.23	**0.10**	**18**
28	0.13	-0.36	0.44	-0.74	1.05	0.33	0.79	0.06	-0.53	0.52	0.49	0.20	1.09	1.39	0.26	**0.10**	**15**
29	0.10	-0.41	0.58	-0.76	1.01	0.40	0.85	0.08	-0.50	0.57	0.51	0.13	1.07	1.37	0.24	**0.11**	**21**
30	0.26	-0.58	0.21	-0.80	1.32	-0.01	0.88	0.19	-0.55	0.54	1.39	0.35	1.15	1.51	0.33	**0.28**	**74**
31	0.22	-0.97	0.42	-0.70	1.52	0.19	1.07	0.41	-0.27	0.53	0.56	-0.14	1.31	1.13	0.41	**0.20**	**56**
32	0.28	-0.46	0.41	-0.57	1.19	0.32	0.96	0.18	-0.48	0.59	0.60	0.38	1.25	1.51	0.39	**0.12**	**27**
33	0.03	-0.43	0.23	-0.63	1.06	0.56	1.02	0.27	-0.31	0.58	0.44	0.16	1.11	1.48	0.22	**0.10**	**16**
34	0.07	-0.45	0.22	-0.63	1.17	0.35	1.01	0.20	-0.38	0.50	0.45	-0.14	1.26	1.16	0.38	**0.10**	**14**
35	0.15	-0.40	0.36	-0.75	1.14	0.45	0.97	0.24	-0.34	0.53	0.42	0.27	1.15	1.23	0.37	**0.07**	**2**
36	0.16	-0.37	0.35	-0.59	1.10	0.48	0.90	0.22	-0.36	0.51	0.40	0.35	1.09	1.31	0.24	**0.10**	**17**
37	0.02	-0.33	0.40	-0.62	1.08	0.43	0.93	0.18	-0.40	0.55	0.38	0.29	1.08	1.40	0.26	**0.10**	**13**
38	0.12	-0.41	0.24	-0.64	1.12	0.39	1.04	0.27	-0.31	0.49	0.43	0.31	1.16	1.44	0.38	**0.09**	**11**
39	0.17	-0.84	0.23	-0.67	1.11	0.51	0.95	0.26	-0.37	0.46	0.43	0.33	1.12	1.51	0.40	**0.12**	**33**
40	0.10	-0.45	0.28	-0.69	1.16	0.53	0.93	0.25	-0.33	0.60	0.45	0.27	1.10	1.35	0.19	**0.08**	**3**

Sample Size	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**	**80**
Average	**0.10**	**-0.61**	**0.32**	**-0.77**	**1.27**	**0.41**	**0.98**	**0.10**	**-0.40**	**0.60**	**0.50**	**0.06**	**1.23**	**1.24**	**0.31**
Median	**0.10**	**-0.60**	**0.30**	**-0.75**	**1.20**	**0.41**	**1.00**	**0.10**	**-0.40**	**0.60**	**0.45**	**0.10**	**1.20**	**1.30**	**0.30**
Maximum	**0.44**	**-0.33**	**0.72**	**-0.41**	**1.74**	**0.93**	**1.26**	**0.61**	**-0.09**	**0.96**	**1.39**	**0.38**	**1.69**	**1.54**	**0.60**
Minimum	**-0.13**	**-0.98**	**-0.01**	**-1.35**	**0.83**	**-0.03**	**0.37**	**-0.50**	**-0.81**	**0.09**	**0.18**	**-0.63**	**0.98**	**0.69**	**0.08**
RANGE	**0.57**	**0.65**	**0.72**	**0.94**	**0.91**	**0.96**	**0.89**	**1.10**	**0.72**	**0.87**	**1.21**	**1.00**	**0.71**	**0.85**	**0.52**
STD. DEV.	**0.09**	**0.18**	**0.14**	**0.19**	**0.22**	**0.19**	**0.16**	**0.17**	**0.16**	**0.13**	**0.19**	**0.22**	**0.15**	**0.22**	**0.10**

In examining the results across the entire sample, only 20% of the 15 critical headlamp assembly dimensions exhibited a mean value within ± 0.25 mm of nominal and nearly half the points have the *mean* out-of-specification. In general, the critical vehicle assembly interface dimensions are outboard (O), forward at the top (F), and aft (A) at the bottom (see Figure 12).

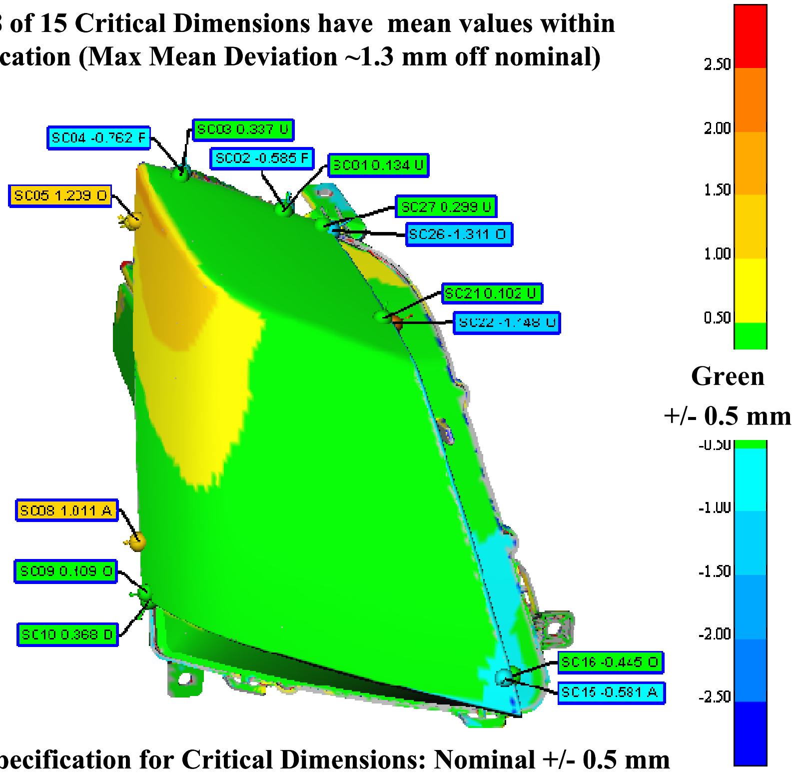


Figure 12. Initial Mean Conformance

As with conventional problem solving, an initial question is the contribution of the detail components to these assembly mean deviations. Figure 13 shows measurements from the two main detail components (outer lens and housing). Of note, both individual components exhibit some mean deviations from nominal, though this condition is much more pronounced on the housing component. In particular, one may observe the severe inboard warp condition in the middle of the part (over 2.5 mm inboard).

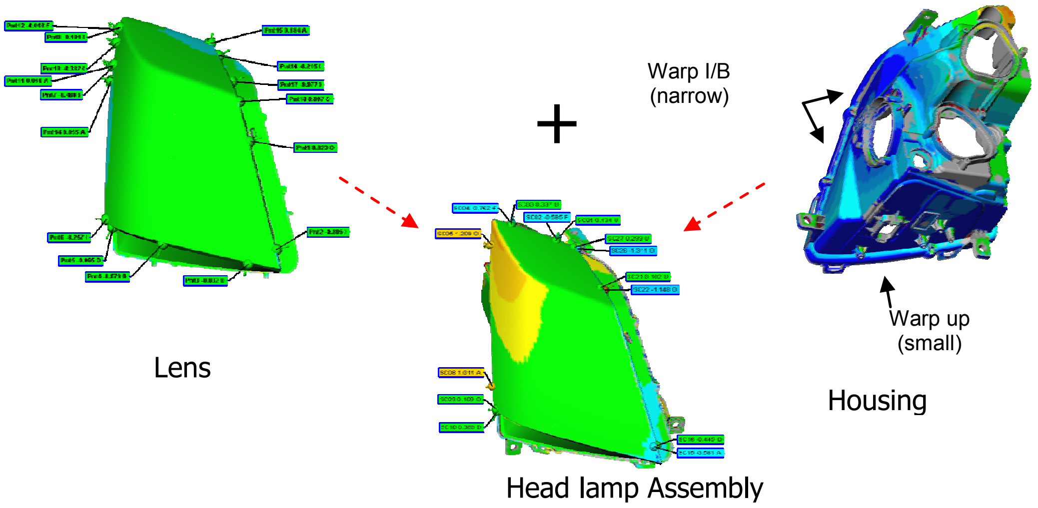


Figure 13. Component and Assembly Measurement Deviations

The high warping effect observed in the housing, however, is not being transmitted in similar magnitude to the assembly. In other words, a large proportion of the narrow condition of the housing is conforming to the outer lens during assembly. Thus, reworking the housing tooling to correct this severe inboard condition would likely have minimal improvement on the assembly. This illustration represents a common challenge with assembling non-rigid components in which the components continue to change or deform during assembly. As such, optimizing component dimensions may have minimal effect on improving the final assembly dimensional quality that interfaces to the vehicle.

4.2 Dimensional Corrections

Given that this part is stable with mean values off nominal, the next step in datum transformation analysis is to evaluate the assembly in its optimal best-fit position of interface dimensions instead of relative to its assembly datum locators (i.e., the mounting tabs and assembly locator pins). To do so, we selected 20 points on the periphery of the lens assembly (see Figure 14). These points reflect gap and flush conditions for each of the key mating areas (headlamp-fender, headlamp-hood, and headlamp-fascia). The points are spread across the entire part and represent the position of the part in fore/aft (X), in/out (Y), and up/down (Z) directions relative to the vehicle coordinate system.

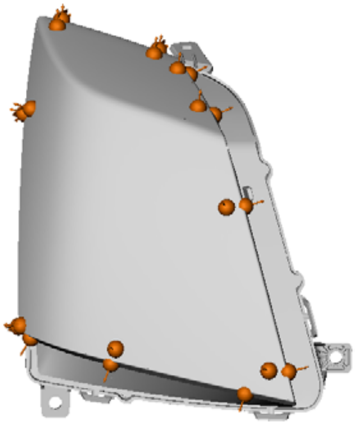


Figure 14. Best-Fit Iterative Secondary Alignment Points

Next, an iterative best-fit alignment is used to rotate the part in three-dimensional space until error is minimized across these secondary alignment points. For this case study, we used the CogniTens Measurement System iterative alignment algorithm to generate a solution. Once a solution was obtained, we measured the position of the datum locators. The results are shown in Figure 15 below.

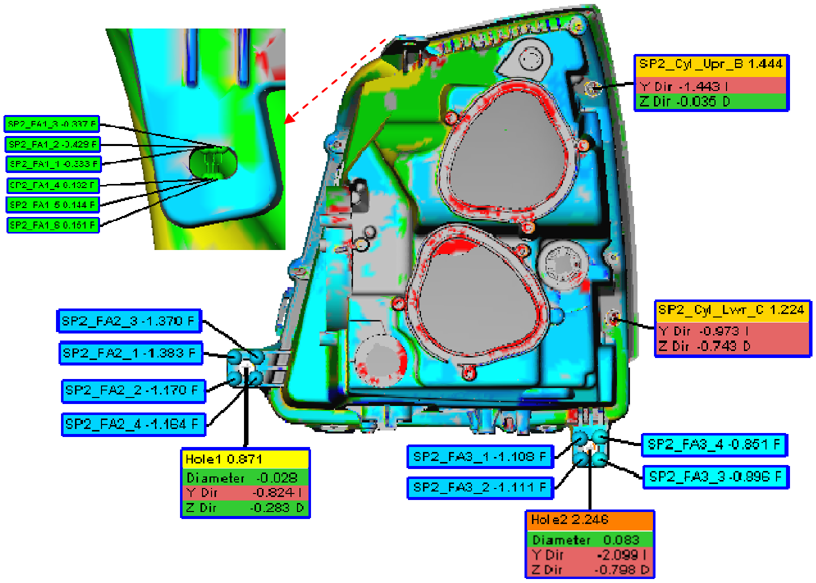


Figure 15. Deviations of Locators in Outer Lens Best-Fit Condition

We now may identify adjustments to the locators. Again, because the part is being rotated in three-dimensional space to optimize it across all of the secondary alignment points, it is important to make corrections at all positions. Making only localized adjustment to one locator, or trying to make adjustments one at a time, will not likely achieve the desired objective.

In this example, the in/out locators measure inboard relative to the optimal exterior vehicle fit condition. Thus, to realign the mating surfaces, one needs to adjust these locators outboard. In other words, by moving the cross-car locator features outboard without touching the current exterior interface condition, the resultant part (after locator adjustment) is brought inboard toward nominal.

Similarly, the upper mounting tab slot used to locate this part in the fore/aft direction is forward from nominal in the optimal vehicle fit position by about 0.3 mm. Thus, we would recommend moving the center of the slot aft by a similar 0.3 mm. The various moves for each of the locators are summarized in Table 2.

Table 2. Locator Adjustment Table

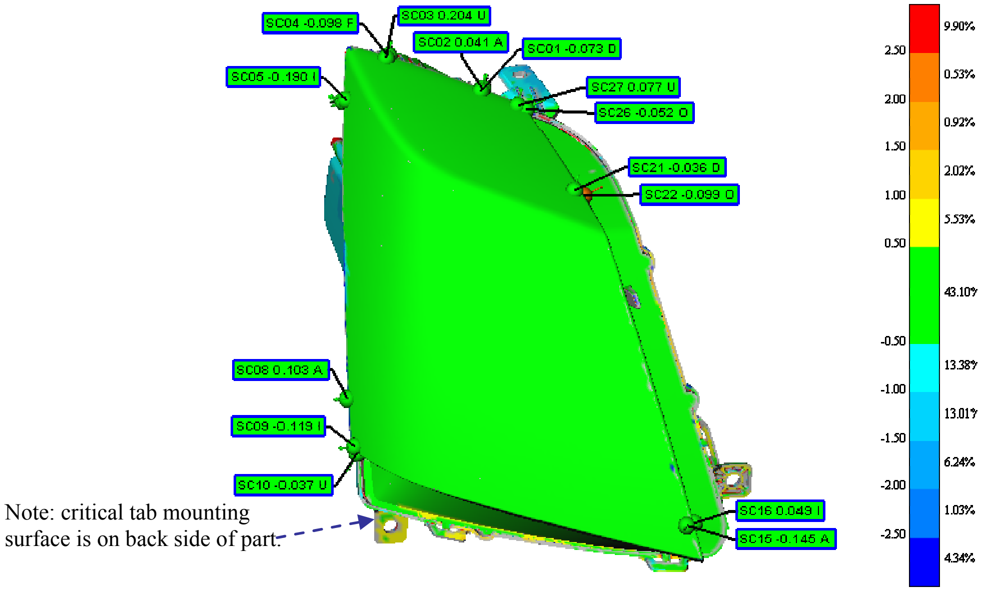
Locator	Dir	Average (3)		Recommendation
Top Pin (4-Way)	C/C	1.3	inboard	**move 1.3 outboard**
	U/D	0.0	up	**none**
Lwr Pin (2-Way)	C/C	1.0	inboard	**move 1.0 outboard**
Attachment Tab: Lower I/B	F/A	1.3	fore	**increase wall thickness by 1.3 mm on backside**
Attachment Hole: Lower I/B	C/C	0.9	inboard	**move 0.9 outboard**
	U/D	0.5	up	***move 0.5 down***
Attachment Tab Lower O/B	F/A	1.0	fore	**increase wall thickness by 1.0 mm on backside**
Attachment Hole: Lower O/B	C/C	2.6	inboard	**move 2.3 inboard**
	U/D	0.6	down	***move 0.6 up***
Top Tab (fore edge of slot)	F/A	0.4	fore	
Top Tab (rear edge of slot)	F/A	0.2	fore	
Top Tab (Slot Center)	F/A			**move slot center 0.25 aft**

4.3 Virtual Dimensional Verification

To visually assess the predicted results of the tuning adjustments, the existing part measurements may be realigned using nominal feature offsets. Here, one may use CAD measurement software to put in a mean nominal offset at the datum locator positions only. For example, if the nominal center position of the four-way locator hole is at Z=100 and Y=100, one may offset these nominal position to Z=100 and Y=101.3 in the measurement software. Of note, one should only offset the nominal positions of the locators, not the entire product CAD. In doing so, one simulates the measured dimensions in this best-fit condition.

Using this method, Figure 16 illustrates the simulated results for the most representative part using the locating adjustment recommendations. After realignment, all of the exterior points have a mean within ± 0.25 mm. The largest deviation is 0.2 mm from nominal.

Of note, one may observe that the part has been re-positioned about a nominal condition in all three directions to an overall best-fit condition. The part now has some dimensions slightly outboard, while others are slightly inboard. It also has some dimensions slightly fore and others slightly aft. Still, these results show that datum transformation analysis has the potential to significantly reduce the mean off-nominal conditions by centering the part overall relative to design nominal.



Note: critical tab mounting surface is on back side of part.

Figure 16. Simulated Realignment Using Lens Best Fit Condition

4.4 Part Mock-Up Results

Before physically reworking the tooling, mock-up parts should be made to verify the feasibility and likely effect of the tuning recommendations. In this example, the datum locators were moved by adding spacers to locator surfaces and changing the center of the holes and pins per the locator tuning recommendations. Of note, not all of the locators were easily adjusted. In particular, moving the pins proved difficult. One reason was that this part was not designed with the intention of using datum transformation analysis. By designing for such a dimensional optimization strategy, we believe this process may be greatly simplified. We discuss design for DTA issues in Section 5.

The mock-up part measurements are shown in Figure 17. As predicted, all sample points are within their specification limits, although the mock-up parts had some deviations. For instance, one of the dimensions exhibited a deviation of 0.4 mm in the aft direction (see Table 3). Still, the mock-up part measurements suggest a significant improvement may be achieved by reworking the datum locators. In this example, we wish to reiterate that although individual components will continue to have mean out-of-specification conditions, their resultant assembly is acceptable.

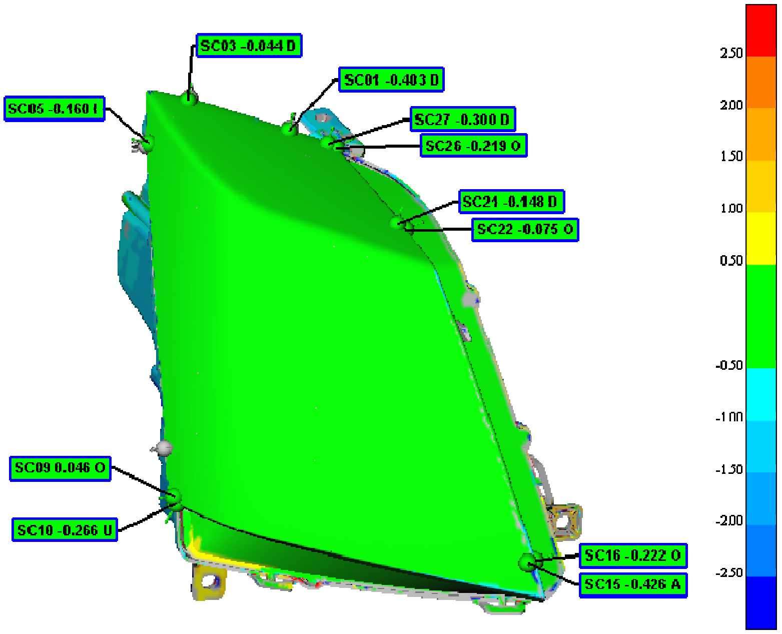


Figure 17. Measurement of Mock-Up Part (Based on Locator Tuning Recommendations)

Table 3. Dimensional Comparison: Before and After DTA

	Mean Value (N=3) Most Rep Part	Best Fit Re-align Most Rep Part	Post DTA Mock Up Part
P# 1	0.1	-0.1	-0.4
P# 2	-0.6	0.0	0.2
P# 3	0.3	0.2	0.0
P# 4	-0.8	-0.1	0.2
P# 5	1.2	-0.2	-0.2
P# 6	0.4		
P# 8	1.0	0.1	0.2
P# 9	0.1	-0.1	0.1
P# 10	-0.4	0.0	0.3
P# 15	0.6	0.2	0.4
P# 16	0.5	-0.1	0.2
P# 21	0.1	0.0	-0.2
P# 22	1.2	0.1	0.1
P# 26	1.3	0.1	0.2
P# 27	0.3	0.1	0.0
# Points	**15**	**14**	**14**
# within +/- 0.25	**3**	**14**	**11**
% within +/- 0.25	**20%**	**100%**	**79%**

Finally, although the transformed part is significantly improved, some tolerance adjustments for variation are needed to meet a Cpk objective. Here, a functional review of the finished vehicle suggested that this revised part is sufficient to meet final vehicle requirements.

5. Design for Datum Transformation Analysis

Although datum transformation analysis has been shown to be very effective for the headlamp case study, we recognize that several conditions must exist for its successful application. Even in this example, the locators were not easily adjusted due to their product design, making it difficult to apply the methodology. In this section, we discuss several enablers or pre-conditions for applying DTA and some part design recommendations to improve its applicability.

The following enablers or pre-conditions increase the likelihood of DTA success. First, the process must be stable. DTA should be viewed as a tool to improve mean off-nominal conditions. One first needs confidence that the measured mean values are representative of the process. For most processes, such as injection molding or stamping where DTA would be a benefit, we believe that this state may be reached fairly quickly once the proper process settings are established and maintained.

A second enabler is that the part datum locators used for part inspection and assembly are different from the functional requirements of the part during the end-use (i.e., vehicle) condition. For instance, one typically defines datum locators for a headlamp based on the features used to assemble the part to the vehicle. However, the end customer only observes the relationship between the headlamp and its mating or vehicle interfaces. Thus, a reasonable argument could have been made in this case that the assembly datum locators should have been on the outer lens component as this is the vehicle interface. In this case, the inspection points would have been the mounting tabs and vehicle locators. As such, DTA would have been unnecessary. Although we appreciate the merits of such an approach, it is not typical in manufacturing. In most cases, part datum reference systems are based on how the part is held for manufacture or assembly.

A third critical enabler for DTA relates to sufficient part rigidity. A part must be sufficiently rigid to allow exploration of different alignments without changing the shape of the part. If a part is significantly influenced by gravity effects, then it may not be possible to apply DTA. As such, we believe that DTA offers greater potential for improving a subassembly rather than an individual component, as subassemblies typically are sufficiently rigid. Furthermore, components, particularly non-rigid ones, may have minimal effect on assembly dimensional quality. In this example, the non-rigid housing had a relatively minor impact on the final assembly quality. Thus, reworking the housing datum locators to optimize the housing relative to its GD&T would not have been as effective.

Another reason why rigidity matters in applying DTA relates to part measurement. If one wants to evaluate the position of locators relative to secondary mating alignment features, one must collect data on both features. This is best done by measuring a part in free state (i.e., without clamps or pins through the locator holes). With free-state measurements, one obtains measurement data for both the critical interface dimensions and at the locator features. If one were to measure a part by throwing a clamp over the locator, then a 3DNC measurement system may not be able to obtain sufficient point data in this area (obstructed view). If free-state measurements are not an option, we would recommend measuring a part on surface locators but without clamps. Here, the part would effectively bottom out on the locators due to gravity, but the measurement data would be obtained on the visible side of the part.

In addition to these enablers, DTA may be enhanced through part design considerations. For instance, locating features should be designed such that they may be adjusted through rework of the tooling. For instance, a part and corresponding tool design must allow for some change in locators within an envelope. For example, the mounting tabs' thickness must be sufficient to remove material, or the tab must be made to allow some additional material to extend the locator surface. If possible, the locator surfaces should be designed with enough segmentation to allow them to be adjusted without affecting other part features. As a general rule, we would recommend allowing up to at least two millimeters in adjustment for locators on datum surfaces.

A similar argument may be made for holes and slots. Here, one must have enough surface area around the hole or slot to allow repositioning the center of the hole or slot. As a general rule, we recommend designing holes and slots to be adjusted up to three millimeters in any direction. Here, we would recommend slightly more adjustability than, say, a surface point, because holes/slots are typically easier to move without affecting other features in comparison to a surface locator.

For locator pins on molded parts, adjustments are more difficult, particularly if the locating feature is a non-cylindrical or non-diamond shape as was the case with this headlamp assembly. As a design characteristic for a molded locator pin, we recommend the use of a diamond-shaped feature with an end taper for loading/unloading. A diamond-shaped feature has the benefit of acting as either a four-way or two-way locator but it has more adjustment flexibility (see Figure 18): For instance, diamond pins

- may be reduced in size by grinding down the sides
- may easily be changed between four-way and two-way by adjusting the blade size (Note: In some cases, one might reduce overall rework by switching the four-way locator to a two-way and vice versa)
- may be expanded either by extending blade width or temporarily fitting a cylindrical cap over the diamond blade to simulate a wider or off-target dimension. Of note, the center of the diamond shape may be adjusted by extending blades unequally across the four blades. For instance, one blade may be extended while another is reduced to simulate a center position shift without changing overall width.
- may be adjusted simply by re-machining tooling inserts

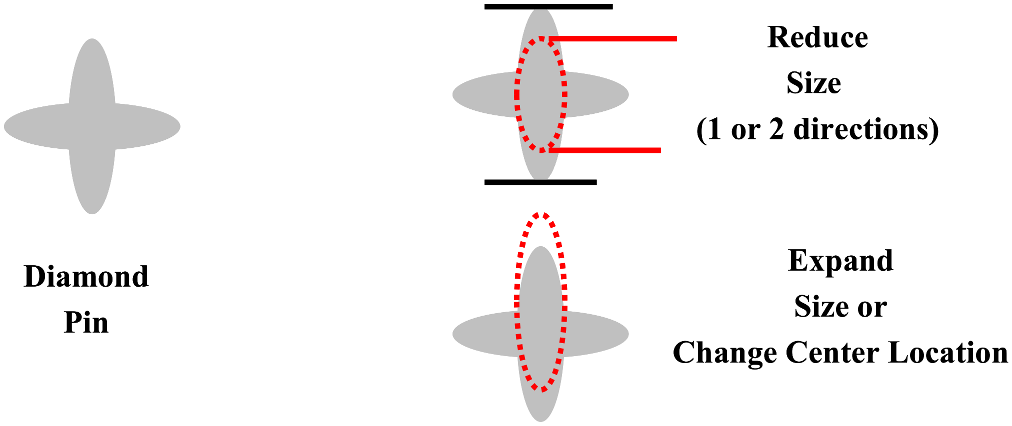


Figure 18. Diamond Pin Adjustment Capability

Although not a pre-condition for applying DTA, the success of the diamond pin adjustment process may have some limitations based on part dimensional quality prior to applying any transformations. For example, if a part area is severely off nominal requiring a very large adjustment, the recommendation may not be feasible based on the product design. For instance, a hole may only be moved within some design envelope area before it infringes upon another part feature (e.g., radius or surface wall).

As another example, if a part has a waviness condition of, say, +1 mm to -1 mm and then back to +1 mm along a mating interface, then an optimal solution will not be feasible. In some cases, one may need to resolve localized deformations before applying DTA. Fortunately, 3DNC CAD measurement software may be used to simulate different alignments to evaluate the potential of locator tuning recommendations before making physical adjustments.

6. Conclusions and Future Work

In this study, we present a methodology that we refer to as datum transformation analysis. This methodology incorporates 3D non-contact measurement within a functional build strategy to optimize assembly dimensional capability without necessarily optimizing individual components. The use of 3DNC measurements allows one to virtually explore different alignment conditions and identify locator tuning recommendations to re-position the part in a more optimal condition relative to the final vehicle.

This report presents an example of applying DTA to an automotive headlamp assembly. In this case, the percentage of means within half the tolerance band for key vehicle interface dimensions was increased from approximately 20% to over 80%. Furthermore, the sample mock-up parts exhibited 100% of points within their original specification limits.

The usage of datum transformation analysis has significant implications for streamlining manufacturing validation processes and reducing overall automotive body development time. In particular, this methodology may be used to reduce overall tooling rework among components and assemblies by minimizing corrections and making adjustments with a clear cause-effect relationship. Historically, complex-shaped components are often stable but with mean values off target. Rather than reworking non-rigid individual components, DTA offers recommendations to realign the part such that its mating dimensions are in their best-fit condition with only minimal change to the components themselves.

Like all problem-solving methods, DTA has some limitations and challenges. One of its main challenges relates to part rigidity. Future work is needed to evaluate its applicability in those cases where a part is insufficiently rigid to measure without clamps or locator surfaces. DTA is also limited by product design. If locators are not designed to be adjusted within some reasonable dimensional windows, its benefits are limited. Still, given that complex-shaped parts from injection molding or stamping processes almost universally have stable mean-off nominal conditions, we believe it prudent to plan for such an outcome and utilize DTA to minimize the amount of tooling rework.

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