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VIRTUAL FUNCTIONAL BUILD FOR BODY ASSEMBLY

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ABSTRACT

Functional build (FB) is a critical process in launching a vehicle, whereby individual prototype parts are stamped and then sent to a central location to be assembled into a prototype vehicle body. FB is premised on the realization that from a functional viewpoint the relationship between parts is important, not the relationship of the parts to their respective nominal dimensions.

FB has been widely adopted in the automotive industry, and the financial benefits have been large and well documented. This paper describes Virtual Functional Build (VFB) where point cloud representations of parts are assembled virtually using assembly modeling software. The potential benefits of VFB over traditional FB techniques are reduced capital investment in tooling and, more importantly, reduced lead time due to earlier collaboration between geographically remote part and sub-assembly suppliers.

This paper will contrast the FB and VFB processes on an actual automotive case study.

INTRODUCTION

The automotive body is perhaps the most important vehicle system in terms of impact, time, cost, and customer satisfaction.

- Impact: The body defines the vehicle platform, which has many model variants. Models are often redesigned, often requiring completely new bodies.
- Time: The body is always on the critical vehicle development path, as obtaining and installing the tooling to stated quality requirements in an organized fashion always seems to take more time than is available. Often tooling is reworked until the project schedule dictates that it be finished.
- Cost: The body is arguably the most costly vehicle system, second only to the power train. However, the power train is often developed once for many vehicle models, whereas the body is redesigned for every model. When introducing a new vehicle model, costs associated with changes in the body are usually dominant.
- Customer satisfaction: A customer’s first impression, and hence their willingness to consider the vehicle further for purchase, is often based on the physical appearance of the vehicle body.

The vehicle body is also one of the most complex systems to design and manufacture. It requires the coordination of many disparate groups (product design, formability analysis, assembly design, ramp team, die suppliers, assembly tool suppliers, stamping suppliers, etc.) under tight time constraints to build and manufacture a system that is not well understood. Not only are the interrelated systems not well understood, but the underlying technology is also constantly changing.

- Die design and stamping is still considered an art, although recent research has made it much more of a science [1]
- The geometric effects of welding are still considered an art, although recent research has made it much more of a science [2]
- New manufacturing forming technologies, such as hydroforming [3] and hot metal gas forming [4, 5], as well as new joining technologies, such as laser welding and adhesives are being introduced.
- New materials, such as aluminum, high strength steels, and plastics are constantly being developed and introduced [6]

Basic science and software has struggled to keep pace with these developments. Car companies are expending tremendous resources in such areas as springback prediction, welding effects prediction, deviation of compliant parts during assembly, etc. The knowledge of these new materials, processes, and technologies varies widely from company to company. In addition, the specific domain expertise that affects the cost, quality, and time of vehicle development and launch is distributed among hundreds of suppliers around the world.

Another difficulty is that the business environment is constantly changing. There is intense pressure to introduce new models in order for automobile companies to remain competitive in the marketplace, but cost is often the limiting constraint. Everyone is under increasing competitive pressure to reduce lead time, reduce cost, and improve quality. This translates into changing business models, increased collaboration and outsourcing, and new manufacturing and business practices. Suppliers are being asked to develop and deliver entire modules at lower cost, which results in outsourcing of engineering and project management functions from the car companies to the supply base. Joint ventures and other forms of cooperative agreements are being formed between suppliers to provide a wider range of integrated services. Lean concepts are being pushed further down the supply chain to die shops and other custom product providers. And these changes are occurring while price pressures require suppliers to reduce the price of their goods and services every year.

While much effort has been focused on the design of the vehicle and manufacturing system, much less effort has focused on the launch of the vehicle. The launch phase of the vehicle is when the design is implemented and includes the manufacturing and tryout of the dies and the assembly tooling. Typically a launch takes 12 +/- 2 months and costs approximately $1,000,000/day. While launch costs are significant, and certainly delaying a launch, and thereby the introduction of a new product to the market, is even more costly, there are other consequences that must be considered.

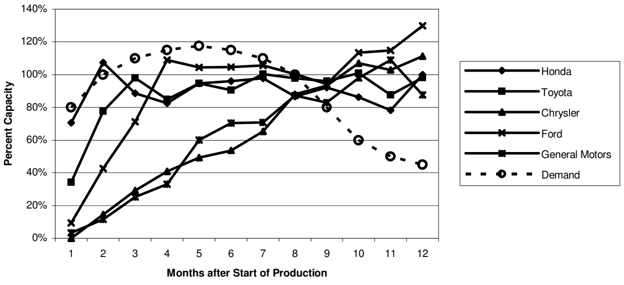

Figure 1. Number of months to achieve 100% capacity post launch of a new model.

When shifting from one model to the new model, all car companies experience a dip in their production [7]. Companies that experience a good launch will have a lower dip and be able to recover their full capacity much more quickly. This is particularly important during the early period when a vehicle is most popular with the public. Figure 1 shows the ramp curves for 5 automakers. The ramp curves show the percent of capacity the manufacturers were able to produce over time after the start of production. If one superimposes a hypothetical demand curve, the difference between the demand the production is the lost sales potential. While there are many factors that drive launch performance, such as vehicle inventory of the previous model, the basic conclusion that faster launches are more desirable holds true.

The various factors and complexity mentioned above require ever increasing interaction between the various parties around the world to create a successful vehicle launch: product design, formability and stamping analysis, assembly design, ramp team, stamping, die suppliers, tooling suppliers, other part suppliers, etc. These groups can better interact with each other within a formalized structured methodology. Most formalized, science based methodologies are design oriented [8-10]. There are no such formalized methodologies that deal with the launch of a vehicle body. There are, however, certain assembly and validation philosophies that are dominant in the industry. In this paper these philosophies are called net build, functional build, and a new concept: virtual functional build.

NET BUILD

Net build is the traditional design, manufacturing, and assembly approach. Parts are designed (i.e., specified geometrically with a nominal and tolerance specification), manufactured to the specification (at a required quality level or production yield) and assembled into a product. It is assumed the parts are rigid bodies, and the assembly process does not affect the individual part dimensions. Given these often unstated assumptions (and a few other mathematical ones), the assembly quality can be predicted using tolerance analysis techniques [11].

Tolerance analysis simply states that the variation in an assembly is a function of the sum of the variation of the individual part dimensions. Hence, if one knows the desired assembly tolerance, one can derive acceptable part tolerances. It then follows that good parts will result in good assemblies. In other words, assembly quality is maximized if individual part means are produced to target specification with minimum variation. Similarly, it follows that to tighten assembly tolerances one must tighten component tolerances.

Thus, simultaneous engineering is often concerned about determining the appropriate part tolerances based on manufacturing process capability. This often becomes a negotiation between the tolerances product design requires for the assembly (and from tolerance analysis has determined is required for the individual component) and what manufacturing can produce. The agreed upon tolerances then decouple design from manufacturing. This leads to a sequential process of design and manufacturing validation based on individual component dimensions meeting Cp and Cpk requirements.

Generally in an NB process, design and manufacturing validation are relatively independent of one another. Specifications (both nominal and tolerance) are finalized by design using tolerance analysis techniques, and manufacturing must determine how to make parts, sub-assemblies, and final product that meet the specifications. Most, if not all design methodologies, such as concurrent / simultaneous engineering environment and design for manufacturing and assembly (DFMA), assume that the specifications set by design on the individual parts are rational and must be met to ensure a quality assembly or product.

In car body manufacturing practice, manufacturers allow manufacturing systems validation to occur with non-conforming parts, or delay validation while they wait for suppliers to correct parts or integrate late engineering change orders (ECOs). The problems are exacerbated in final assembly validation, as new problems are discovered and parts and systems are reworked. In addition, some problems that could not be resolved in component validation are not a problem in assembly validation. Hence, one questions the validity of the original part specifications as well as the significance of achieving the required Cpk. Although more effort in design may alleviate some of these problems, the vast majority are not design problems and transcend our current ability to eliminate them in design.

Case Study 1

A study was conducted of 500 dimensions on a single set of body stampings that were evaluated according to a net build philosophy: the stampings are acceptable if all part dimensions meet a stated Cpk requirement. All dimensions that fail to meet this requirement must be fixed. Of the 500 dimensions, 45% failed their Cpk requirements and had to be fixed (see Fig. 2). Of those only 10% (22 dimensions) resulted in assembly build problems. The remaining 90% had no impact on the assembly, but significant effort was expended in attempting to bring them into specification (false alarms).

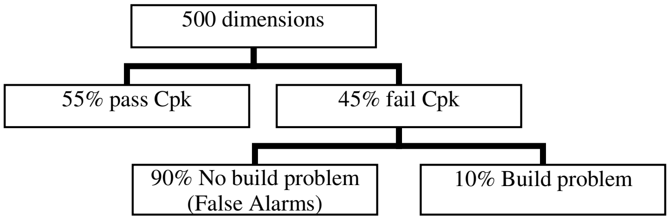

Figure 2. Results of Stamping Evaluation based on Net Build Philosophy.

The question, of course, is how could this happen? Were the specifications not rationally established? The main reason for this situation is that the fundamental assumptions of NB, namely rigid parts and assembly systems that do not change component dimensions do not apply in sheet metal assembly. The sheet metal components are often flexible or compliant, and assembly systems routinely bend and deform components through clamping and heat distortion.

What is necessary is an understanding that product design and manufacturing system validation are not separate activities, but rather concurrent activities; specifically, that final specifications should not be set until manufacturing validation is complete. This is a radical departure from the net build philosophy. It implies that component specifications (in sheet metal assembly) are and should be a function of what manufacturing can achieve. Further, it is currently difficult to predict what manufacturing can achieve, because so little is known about the impact of assembly on the dimensional quality of the final assembly.

FUNCTIONAL BUILD

Functional build (FB) is an alternative to net build and is gradually gaining acceptance by many OEMs in the world today [12, 13]. It was first introduced by Baron in 1992 [14] and has been further developed at the Center for Automotive Research in Ann Arbor. FB bases the acceptability of individual components on functional requirements, in this case on the assembly specifications, and not on the component specifications. If the assembly is acceptable, then the part is acceptable, regardless of whether the component meets its original design specifications.

Functional build as practiced by US companies consists of ensuring that components meet an assembly processing window, as opposed to a component tolerance window. The processing window is typically much wider than the tolerance window. This is because the assembly process is often very robust to incoming part variation. For example, compliant sheet metal parts that deviate from their nominal shape in their free-form state are often held very close to their nominal shape during assembly process by clamps on the welding fixtures. When the parts are welded together and the assembly is released, the assembly is often closer to the desired nominal shape than would be predicted from a net-build based tolerance analysis of the original free form parts. The reduction in the stack-up of variation is manifested in the residual stress in the assembly.

Since FB is focused on obtaining assemblies that are functional, as opposed to individual components that meet specification, the serial NB component evaluation methodology that is based on the Cpk index is no longer appropriate. The FB evaluation process typically involves the construction of “screw-bodies” or other form of body assembly evaluation methods. The FB evaluation typically occurs in two phases. The first occurs when parts are produced at the die source, and it is used to determine whether the dies can be shipped to the production facility (“die buy-off”). The primary concern is to correct problems that are known to cause assembly problems, while delaying die rework decisions for non-conforming issues with unknown impacts. The second FB evaluation occurs when parts are produced by the home-line, and is used to determine the final acceptability of the dies. The evaluation process varies between manufacturers, but generally consists of stamping three to several hundred parts over multiple setups. The first requirement is that the stamping process indicates stability. If the process is stable, then the mean of each checkpoint is evaluated for acceptability in the assembly. If the assembly is acceptable, then the parts should be accepted and the specifications should be changed to match the dimensional results of the manufacturing process. If the assembly is not acceptable, there generally four possibilities:

1. Change part A;
2. Change part B;
3. Adjust the assembly tooling ;
4. Some combination of the above.

The specific decisions will be a function of what can be achieved at least cost within the available time frame. Note, the decision may not be simply to make the parts conform to specification.

FB also improves body quality by having an acceptable level of residual stress in areas while maintaining the desired level of dimensional quality. Under NB, one can argue that since not all parts of a vehicle body are made completely to specification, that all vehicle bodies have some level of residual stress. Unfortunately, it is not known how much or where. With FB the vehicle team will be able to make conscious decisions of where residual stress can be accepted and where not. For example, through the screw-body evaluation the team will see areas that exhibit unacceptable levels of part interference or gaps, and require something be done to remedy the situation, regardless of whether the parts meet specification or not. Conversely, areas where there are no interference or gaps will not require any alteration, even if both parts are not within specification. Hence, the team will now know where residual stress may be a problem and have some control as to the degree of stress built into a vehicle body.

Since FB focuses on part function as opposed to part specifications, the evaluation criteria are also different (see Table 1). Several parts (30) are measured and evaluated, and the mean and range or variance of each part dimension is computed. Unlike NB, where meeting specification is important, and a Cpk or similar criteria is used, the FB approach evaluates the mean and variance separately. First, part variation must be stable, and in general, a Cp = 1 is considered acceptable. Second, it is known that many assembly operations can compensate for mean deviations. However, excessive deviations will also result in poor assemblies. A general FB criterion is to require 80%, of the means of each point distribution to be within tolerance with no mean greater than 0.5 mm beyond the tolerance. If these two conditions are met, then the part will have a high probability of acceptance. If not, the part may have to be reworked.

Table 1. Comparison of Net Build versus Functional Build Die Buyoff Criteria.

Type of Variation	Net Build Criteria	Functional Build Criteria
Mean Conformance	Cpk > 1.67 (100 piece sample)	80% means < tolerance 100% means < tolerance + 0.5 mm
Part-to-Part		Cp > 1.33 (30 piece sample)

It is important to note that the evaluation criteria presented above are based part tolerances of +/- 1 mm. The current trend is to create parts with +/- 0.5 mm tolerance. This drive to tighter component tolerances is generally indicative of a NB philosophy: tighter component tolerances should lead to tighter assembly tolerances. Remember, this is not true, because of flexible components and assembly processes that alter component dimensions. Part tolerances should be based on physical requirements, such as assembly process sensitivity to incoming part variation, or assembly tolerance allocation. Unfortunately, they are often based on past practice or the designers' desired level of quality based on a NB philosophy. Hence, part tolerances are almost always tighter than the required assembly or vehicle tolerances. The increase in assembly tolerance relative to individual part tolerance is indicative of a net build philosophy that dictates part variation is additive in an assembly.

Case Study 2

One western European company claimed to practice integrated build. They had a thorough data collection system during tryout at the die source and home line for the individual components and the assembled components. They utilized cross-functional teams that poured over the data, noting each out-of-spec dimension, and constructed a prioritized list of die changes. In general, if the cost and time was insufficient, and the assembly was acceptable, then the dies were not reworked. In a desire to improve their process, they requested an analysis of their procedures based on data from their latest vehicle launch [15].

The data represent dimensional measurements on a door inner panel and a door assembly. Each tryout run they would measure 300+ dimensions on one door inner panel and 25+ dimensions on 7 to 25 door assemblies. Further, they would conduct a capability analysis at the second tryout run and have production data after start of production (SOP).

The analysis results are quite revealing. Figure 3 shows the percent of points on the inner panel that were within specification, out-of-specification (OOS), and accepted beyond the specification, as well as the percent of points within specification on the door assembly at each die rework cycle. First, the percent of inner panel points within specification remains approximately constant between 55% and 65% across all rework cycles. This implies that the rework cycles did not actually bring more points within specification. Second, the percent of assembly points within specification is much higher than the percent of inner panel points indicating that many of the OOS inner panel points had no impact on the assembly. Third, one can see the assembly quality improving, i.e., the percentage of points within specification is increasing over time, whereas there is no change in the inner panel quality. Lastly, the percent of points that were accepted beyond the specification rises sharply just before SOP. This is a strong indication of a net build philosophy, where components are accepted OOS when time runs out.

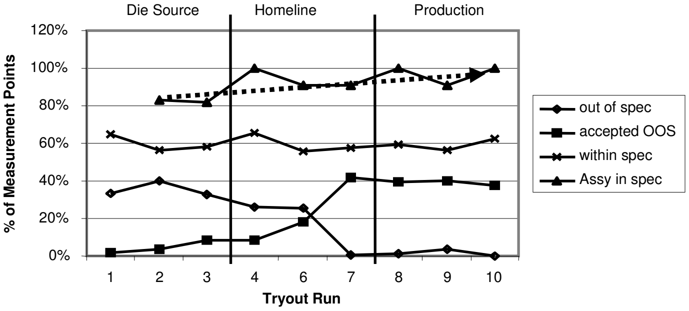

Figure 3. Percent of Inner Panel (IP) and Door Assembly points within specification, out-of-specification (OOS) , and accepted OOS.

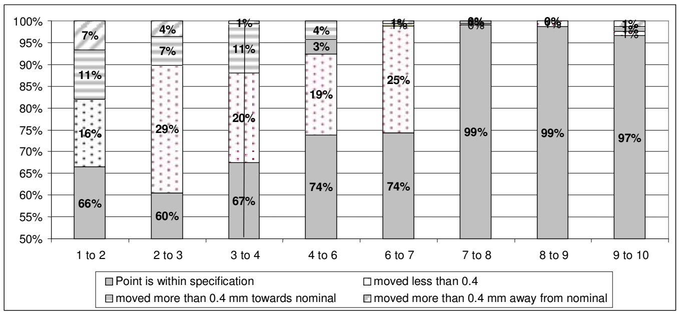

Figure 4. Die rework effectiveness over 9 die tryout cycles.

From a functional build point of view, Figure 3 shows that many die changes were not necessary, i.e., assembly quality improved without an appreciable improvement in component quality. Figure 4 shows that many die changes were not effective, i.e., a change in the die to get OOS points within specification did not result in more points moving within specification. A common perception within the industry is that when a part dimension is OOS, a die change correction will alleviate the problem. Figure 4 shows the effectiveness of the die changes between each die rework cycles. Changes are classified into 4 categories:

1. the point was within or accepted as within specification and remained within specification,
2. the point was beyond the specification and moved closer to the nominal dimension,
3. the point was beyond the specification and moved further away from the nominal dimension, and
4. the point did not move.

The concept of a point moving was dependent on the stamping process capability, determined from process capability data. If a measurement point differed by less than its 3-sigma limit computed from the process capability data, it was not considered to have moved a statistically significant degree. In other words, any die rework that resulted in a change of less than 3 sigma was considered insignificant – one would never see the change in actual production because of the inherent process variation.

If die changes were effective, one would expect the percentage of points moving towards nominal to be large, the percentage of points moving away from nominal to be small, the percentage of points that do not move to be small, and the percentage of points that are within specification to increase. As one can see, the first 3 rework cycles were somewhat effective, in that a relatively large percentage of points were moved closer to nominal, with fewer points moving away from nominal. Thereafter, the percentage of ineffective die changes increases. Few points are moved at all, and more points seem to move away from nominal than towards nominal. Please remember that after SOP, the percentage of points within specification jumps not because the points were fixed, but because they were accepted out-of-specification, as was shown in Figure 1.

Conclusions: If one defines functional build as accepting parts beyond the specification, then one can conclude that they practiced a form of functional build. All companies are forced to accept parts that do not meet their dimensional requirements when deadlines are upon them. However, the company did not practice functional build using the FB evaluation criteria, although they had assembly data. The data clearly showed that die changes after the 4th rework cycle were not value added. They would benefit from the FB process, which would have shown that parts could have been accepted earlier, die rework would not have been necessary, engineering resources could have been refocused, and time and money could have been saved. Since we presented our results, they have implemented some of our recommendations and have reduced their validation lead time for a new model launch by 8 weeks.

VIRTUAL FUNCTIONAL BUILD PROCESS

The next evolution of functional build is virtual functional build (VFB). Stamped parts exhibit significant physical differences from their nominal CAD shapes due to factors in the tooling and forming processes. The most common method of measuring stamped metal parts is to take point measurements using a coordinate measuring machine (CMMs). This requires engineering to identify specific measurement points on the part. Without knowing where problems are likely to occur it is temping to specify a high number of measurement points. However, the more points that must be measured, the more time it takes to program and operate the CMM. Further, if the part is still being measured at the die shop, it is unknown whether points beyond the specification will cause a problem. And the more points that are required to be measured, the less likely the part will pass its Cpk requirement on all points. Even if functional build is employed, there are still part submittal requirements (see Table 1), and the more points that are specified, the less likely the part will pass the submittal requirements.

Optical measurement technology is not necessarily new, if one considers optical comparators have existed for over 50 years. However new optical technology has matured both in hardware and software, and it is capable of capturing many more measurements points than a CMM. For example, on a typical door inner there may be anywhere from 300 to 600 CMM measurements specified, often every 25 to 50 mm around the edge of the part. Optical measurement technology will capture over 1,000 points per mm^2. These point clouds are so dense that one can visualize the entire part being measured. And depending on a number of factors, these technologies can be quite fast compared to a CMM.

There are a variety of optical measurement technologies ranging from laser scanners, such as Perceptron's ScanWorks, to white light systems, such as CogniTens' Optigo and Opticell, and holographic systems, such as Coherix's ShaPix. These technologies provide precise part representations in virtual form. Sophisticated software, such as Innovmetric's Polyworks or Raindrop Geomagic's Qualify, exists to manipulate the point cloud data for a variety of applications, such as reverse engineering or inspection.

Rather than sending physical parts to a central location to be assembled, in VFB suppliers optically measure their parts and send the virtual part representation to a central web site. The virtual parts are then assembled, and the problem areas are identified. The major advantage of virtual assembly is that one is freed from the logistical requirements of having to send all parts to a central location at a scheduled time. Coordinating the timing and shipment of up to 30 different suppliers and hundreds of different parts is extremely difficult. Also, the screw-body process itself takes generally 4 to 6 weeks or longer to complete. If critical parts are delayed, then the build can be further delayed. VFB can be completed in a far shorter period of time. Assembling the virtual part representations is much faster than physically placing parts in fixtures and riveting or screwing the parts together. Furthermore, any part that has not yet been manufactured may be replaced by its CAD nominal as a best guess for what the part will look like. There is also no longer the need to design and manufacture the FB fixtures, which can cost between $1 million and $5 million. VFB saves the time and cost of assembling a physical prototype, and allows users to create many more virtual prototypes than physical prototypes. This is particularly important during the iterative die tryout process. The capability to quickly evaluate the effect of a die change on the body assembly is a functional evaluation of the part, as opposed to a pure specification based evaluation.

Optical Measurement Technologies

A description of two common optical measurement technologies is presented here: laser scanning and white light photogrammetry systems. A typical laser scanning system consists of an articulated measuring arm (CMM or robot), a laser scanning probe and point cloud handling software (see

Fig. 5). The probe uses solid state, non-contact, laser-based technology to optically generate a line of points at the rate in excess of 20,000 points/second. This is far beyond the rate of traditional contact or single-point acquisition technology.

Figure 5. Laser Scanning System with Portable CMM Arm (photo courtesy Perceptron Inc.)

The probe is attached to either a portable CMM, automated CMM, or a robot. The envelope of the arm determines the size of the part that can be measured. Arms range in volumetric length from approximately 1.2 M (4 ft.) up to 3.7 M (12 ft.). Portable CMM arms typically are available in 6 and 7 axis configurations; 7 axis being the most common for scanning applications.

A part is scanned by moving the laser line over the part in overlapping swaths. The measuring arm encodes the position of the probe and resident software ensures that the scans are properly aligned relative to each other.

The important parameters for laser based systems are the speed of scan and the density of the points. The speed of scan is a function of the length of the laser line and how fast the probe is moved. The density of points is a function of the density of points in the laser line, the laser line generation rate and how fast the probe is moved.

The white light system used was the CogniTens Optigo 200 (see Fig. 6). The system consists of a measurement head containing three high-resolution CCD (Charge Coupled Device) cameras mounted on a wheeled tripod, complemented by a control station, where the captured images are processed for analysis.

The camera takes multiple simultaneous 2-D images (called 'tiles') which are stitched together to provide the complete part point cloud information. The image acquisition cycle is less than 1 millisecond, allowing operation in automotive plant environment, where vibrations and changing illumination conditions may exist. A typical tile is approximately 300-400 mm in length and width, containing about 300,000 points per tile. Thus, the time it takes to measure a part is a function of the number of tiles, which is a function of the part size [16].

Figure 6. Whtie Light Photogrammetry System (photo courtesy CogniTens Inc.)

Unlike laser systems that are attached to measuring arms which provide the global coordinate system, the white light system uses a grid of targets on the part or fixture. The process of determining a global coordinate system from the targets is called mapping. The mapping process requires taking a few pictures of the targets with a single camera. The process enables the white light system to measure parts of any size, as they are not limited by the measurement space of a measuring arm.

A limitation of most optically based metrology systems is the reflectivity of the part. Highly reflective surfaces (chrome, polished surfaces, stamping dies) may not be measurable by all systems without some coating or powder to lessen the reflectivity of the surface. Manufacturers continue to work on developing systems that will be able to measure any kind of surface.

Process

Figure 7 shows a simplified schematic representation of the VFB process flow. First parts are optically measured. This involves fixturing the part, identifying alignment features, and conducting the activities necessary to obtain the point cloud data. The fixturing method is still an open research question. One aspect appears certain, however. The specific fixturing method is a function of the measurement purpose, such as individual part inspection (comparing part to CAD nominal), reverse engineering, virtual functional build, or measuring parts to obtain specific feature information for other applications. For example, if the purpose is inspection, then it is acceptable to fixture the part in a conventional measurement fixture. However, if the purpose is virtual functional build, then the part cannot be fixtured on its datums, because the datum features must be captured in the part scan so that a virtual alignment is possible. If the part is fixtured on its datums, then the fixture features may obscure the part datums.

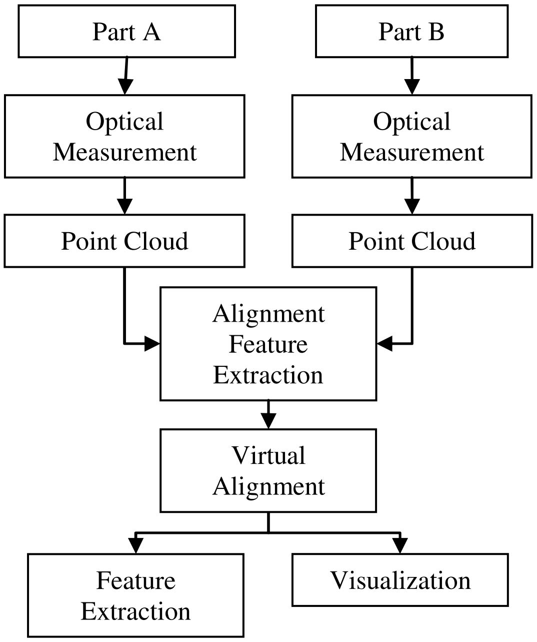

Figure 7. Virtual Functional Build Process Flow.

Once the point cloud data has been generated it is necessary to process the point cloud data. It is beyond the scope of this paper to discuss computational metrology in detail. Suffice it to say that there are a large number of algorithms, many of them proprietary, that have been developed to extract features from point cloud data. Some measurement system developers, such as CogniTens, also utilize 2D image processing on raw 2D images to extract feature information. Besides algorithms for part extraction, there is also a particular file format for visualization, called an STL file. STL files create small polygonal surfaces – a 'connect the dots' approach to visualization. Since, point cloud files are often quite large and as a result, difficult to manipulate (rotation, zoom, etc.), often STL files are created by filtering points based on curvature: areas of high curvature retain their original point cloud densities, whereas areas of low curvature will have many of their point deleted.

Once the alignment features of the parts have been extracted, the parts are aligned to their assembly coordinate system. Typically this is determined from a CAD file that is in the appropriate coordinate system. The measured features are simply aligned to the corresponding CAD features. When this is done to all parts in the assembly, the technical portion of the VFB process is complete. The launch team now examines and interrogates the virtually assembled model looking for gap and interference conditions, as well as other functionally inadequate measurements.

Case Study

The functional build of a front engine compartment was observed. The compartment consisted of 5 subassemblies: a left and right rail assembly, a dash panel assembly, a cross member, and the front bumper (see Fig. 8). The subassemblies were assembled in special fixtures that simulated the planned production fixtures. The launch team identified and documented all the problems they encountered. The goal of the case study is to determine whether a virtual functional build (VFB) would identify the same problems seen during the physical functional build (PFB) event.

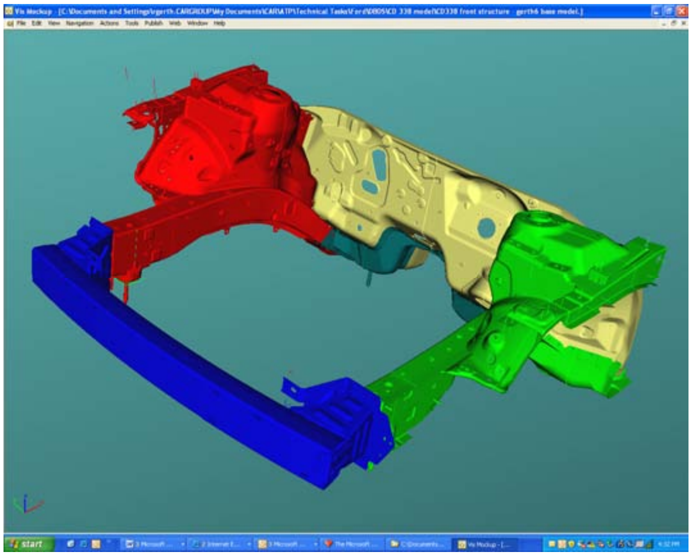

Figure 8. Front Engine Compartment

A second set of parts were scanned in free form state with a Perceptron Scanworks laser scanner and a CogniTens Optigo system. Due to scheduling constraints, not all parts could be scanned on both sides of metal using both systems. The bumper was also not measured. Since the parts were all sub-assemblies they were reasonably rigid and did not require any special fixtures. The parts were simply placed on floor without any locating pins, pads, or clamps and optically measured.

The point cloud data from the Perceptron laser scanner were processed in Polyworks, and the CogniTens point cloud data were processed in their own proprietary software system. The first step was to convert the point cloud data into an .STL file. Figure 9 shows the .STL and the nominal CAD representation for a rail assembly. The next step was to align the parts on their datums (see Fig 10). There are a variety of algorithms to create features from point cloud data. Also it may be better to create the locating features from the original point cloud data than from the .STL files, because the original points cloud data have a greater density. For the data analyzed within Polyworks, all holes were computed as the minimum diameter holes that are projected onto the surface plane. Lastly, when aligning parts, one must take care to ensure that the measured and nominal alignment features are on the same side of the metal surface. This is particularly important since many automotive manufacturers do not use solid 3-D models for their stamping designs. They use 2-D surfaces and indicate the metal thickness on the part. Thus, if only one side of metal is scanned, one must ensure that the measured features are properly offset to account for metal thickness.

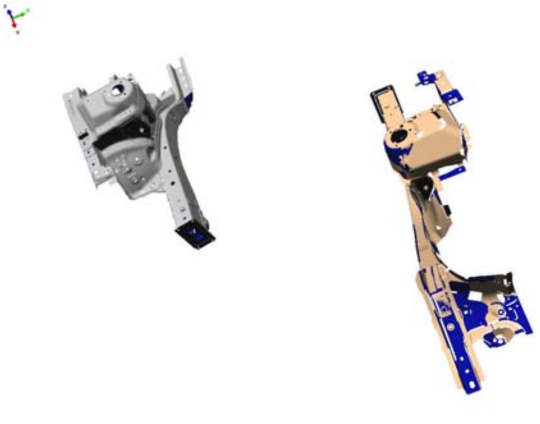

Figure 9. Unaligned Measured and Nominal Rail.

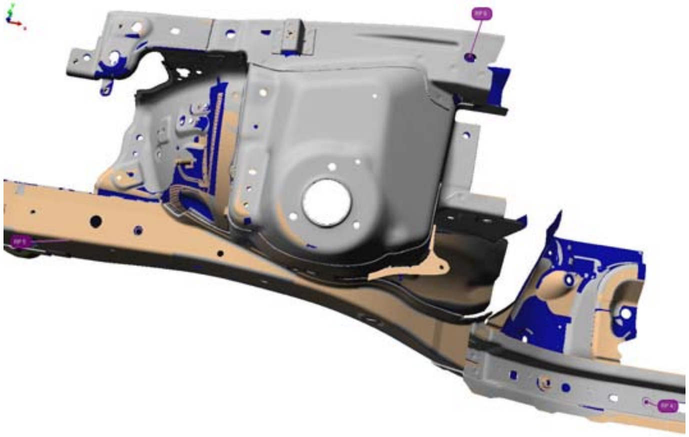

Figure 10. Aligned Measured and Nominal Rail.

Once all parts have been aligned in vehicle coordinates (see Figure 11), the virtual assembly can be visually inspected for gaps and interference conditions. Since the VFB was conducted in parallel to a PFB, the areas of concern were known. Specifically, there appeared to interference conditions in multiple directions between the rails and the crossmembers on both sides. According to the PFB, the cross member was built too wide. Figure 12 shows an enhanced cross section between the left rail and the crossmember within the area of concern. One can see the interference between the cross member flange and the rail side in y.

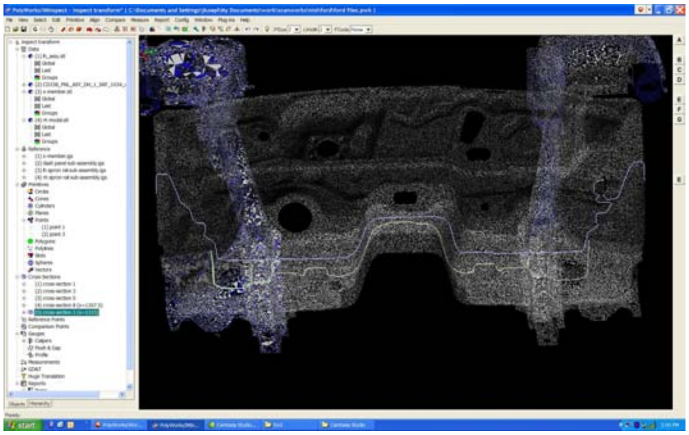

Figure 11. Point Clouds of Crossmember and Rails.

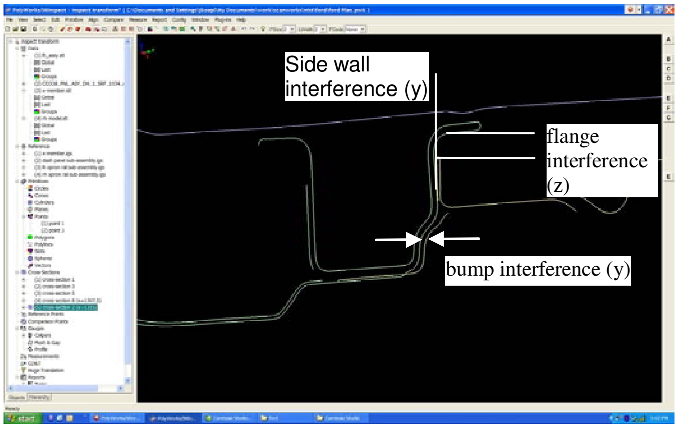

Figure 12. Enlargement of Cross Section of Left Hand Rail and Crossmember

However, the other interference conditions seen in the PFB are not as evident. In the PFB here was also interference between the cross member flange and the rail flange in z, and the cross member bump and the rail bump in y. There are two likely reasons for this. First, the parts used in the PFB were not the same physical parts as those used in the VFB. Thus, within stamping and subassembly variation, the parts could differ. Second, the parts were fixtured differently in VFB versus PFB. In VFB, the parts were scanned in free form state, whereas in PFB, the parts were held in assembly fixtures in an overconstrained state. For example, the cross-member had 4 z datums. There was significant twist in the part in the free state that was eliminated in the fixture during PFB. This caused the flanges to rotate around the y axis and raise sufficiently in the z direction to cause interference with the flanges.

DISCUSSION

While the results reported were not as expected, there are a number of conclusions that can be drawn from the research. First, part fixturing is a function of the measurement purpose. While this may seem intuitive, it is not. In the traditional metrology, regardless of the measurement purpose, the part would be fixtured on its datums. There has been extensive discussion as to whether the datums should be selected so as to locate the part in a minimally constrained configuration to enable repeatable measurements, or to constrain the part as it will be constrained during production by the assembly tooling. This discussion has always focused on the datuming scheme. However, this research shows there are other considerations. First, whatever fixtures are used, they should continue to allow the part to be virtually aligned. Thus, if the fixture obscures the part locating features, then either the fixture must be changed or substitute features on the fixture should be scanned and used. For example, if the part locating feature is a hole, then it may be possible to align the part scan using the scan of the fixture pin as the locating feature.

Second, the part should be fixtured according to the purpose of the measurement. If the purpose of the measurement is to compare the part to its CAD nominals, then the part should be fixtured on its datums. If the purpose is to visually see if parts can be assembled, as was the case here, then the parts should be located as they would be in their assembly fixtures. This was not done here and is believed to be one of the reasons the VFB results did not correlate well with the PFB results.

However, the parts were measured in their true free form state. They were simply placed on the floor and scanned. This was done intentionally, for there was a third purpose for the part scans. VFB as described above is not able to predict the dimensional quality of the assembly. Even when the virtual parts are placed in their nominal body position, one cannot predict the dimensions of the resulting assembly, because simple visualization cannot account for the springback that occurs after welding and the tooling clamps are released. This requires the integration of tolerance analysis and FEA simulation. Most tolerance analysis models are Monte Carlo simulation based and assume rigid parts, i.e., the assembly process does not affect the dimensional quality of the parts, which is not true of body assembly. Tolerance analysis models begin with a nominal representation of the parts and assembly tooling, apply manufacturing variation to the part and tooling features (from design specifications or actual manufacturing data), simulate the assembly process in the appropriate sequence, and output the desired measurements. The output is typically a distribution and a sensitivity analysis for each measurement. Integration of FEA models allows the tolerance simulation to take elastic deformation of the parts induced by tooling clamps and spot welding into account. The software typically does not account for plastic deformation, and hence heat distortion effects from welding are not modeled. Conceptually, the parts are assembled in the software. Weld points are identified and the parts are forced into full contact at those points. These points are held as boundary conditions. Then the FEA program minimizes the stress in the assembly by changing the shape of the part according to the boundary conditions. Several groups have developed a joint FEA-dimensional variation simulation engine: General Motors (GM) has developed one for internal use; Dassault Systems released such an engine in Catia V5 product; and UGS PLM has incorporated this functionality in their VisVSA V5.1 product.

The idea is to take the virtual part measurements as input into these new FEA tolerance simulation tools. The simulation models assume the parts are free of any residual stress, and hence, the parts must be fixtured in free-state. The results of this experiment will be reported in future publications.

CONCLUSIONS

This paper presented both FB and VFB as methods of assembling sheet metal bodies. Many of the concepts presented here are applicable to a wide variety of other applications as well, such as plastics. The concepts apply whenever the traditional assumptions of rigid parts and independent assembly processes are not true.

The development of sophisticated optical measurement hardware and point cloud processing software has enabled VFB. VFB can drastically shorten launch time and reduce costs by reducing logistical requirements, reducing the number of physical evaluation prototypes, and eliminating the need for the specialized FB tooling.

VFB is in its infancy, and there are many process issues that must be addressed, such as purpose of the VFB (visualization or simulation), information requirements prior to measurement, fixturing requirements, etc. Also, further refinements to the process are necessary, including determining new part buyoff criteria for virtual functional build, identifying fixturing states for various part types as a function of analysis purpose, streamlining the measurement process by only measuring one side of metal on individual components (need to determine which side), and other as of yet unanticipated process issues.

The work presented here is part of a larger activity called the Digital Body Development System (DBDS) [17-19]. The DBDS is the focus of an ongoing NIST/ATP-supported Joint Venture of 14 organizations: Altarum Institute, American Tooling Center, Atlas Tool Inc., Center for Automotive Research, CogniTens Inc., UGS PLM, Ford Motor Co., General Motors Corp., Perceptron Inc., and Riviera Tool Co.

With these new optical measurement and simulation tools it is possible to virtually assemble and predict dimensional quality including variation. Thus, engineers will have a tool to understand dimensional problems with actual body parts during launch.

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