

Development of Class A Surfacing CAD System

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ABSTRACT

Class A data (or Class A surface data) is high-quality surface data used to express product styling. During the process of design development of four-wheeled vehicles, Class A CAD is used to generate Class A surface data based on 3D scanned data from clay models. An original CAD system for the generation of Class A styling data has been developed in order to respond to the increasing complexity and diversity of shape expression in four-wheeled vehicle styling, and at the same time to increase the precision of Class A data and the development efficiency of the process of generating Class A surfaces. The new system has displayed positive results in the areas of shape expression, shape accuracy, and development efficiency.

1. Introduction

In the final phase of the styling design development process, shape data for styling called Class A surfaces are created referring to 3D clay model measurement data. “Class A surface” is a collective term for smooth and continuous high-accuracy and high-quality surfaces that represent the interior and exterior shapes of the vehicle.

While the increasing density of today’s styling necessitates the use of Class A data that expresses styling shapes with a high degree of accuracy, it is also necessary to respond to further reductions in the development period, demanding the simultaneous realization of accurate reproduction of styling shapes and a high level of work efficiency from systems for the creation of Class A data.

When using conventional CAD systems, it is necessary to repeat shape operations and shape evaluations in order to create the styling shapes projected by the styling designer, and the designer must be aware of the mathematical formulas for expression of curves and surfaces when conducting these shape operations. In order to resolve these issues, the new technology discussed in this paper offers intuitive surface operations based on the behavior of plate-shaped bodies in the real world and referencing the evaluation method used by styling designers, also offers a method of correcting subject surface and curve shapes by directly operating the visualized shape evaluation result. In addition, the use of new algorithms in shape-processing calculations has

simultaneously reduced calculation time and increased the quality of the output shapes.

The new Class A data generation system was realized using original methods. This paper will provide an overview of three representative functions of the system [(1) a scanned data fitting function, (2) a high-speed and high-accuracy surfacing function, and (3) a global deformation function], and will discuss the results of using the system to create Class A surfaces in the product development process.

2. Development Goals

The development of the new system aimed to increase the speed with which Class A surfaces are brought to appropriate quality levels and to reduce the period for modeling. The target for the developed CAD system was to halve the man-hours expended on the creation of Class A data.

2.1. Developed System and Process of Creation of Class A Data

Figure 1 shows the process by which the new system creates Class A surface data using 3D scanned data from clay models.

2.2. Method of Reducing Man-hours Employed in Creation of Class A Data

In order to increase both data quality and the efficiency

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of modeling work, the development of the new system divided the process up to the stage of completion of the styling design data into the following three phases, and realized the established targets by employing new technologies for CAD functions in each work phase:

- (1) Phase 1: Surfacing based on scanned data
- (2) Phase 2: Creation of high-accuracy Class A surfaces
- (3) Phase 3: Correction of Class A surfaces

Figure 2 shows representative technologies used in each of the three work phases.

3. Outline of System Configuration

Figure 3 shows an outline of the configuration of the

new system. The lower section of Fig. 3 represents the system platform, while the upper section indicates its practical functionality. While the efficiency of system development was increased through the use of certain components available on the market, the system configuration was designed to help enable the efficient application of the three new technologies shown in Fig. 2, in order to realize the target of a 50% reduction in the man-hours employed in the creation of Class A data. The main characteristics of the system are as follows:

- (1) Loose coupling of the platform and functional sections of the system helps to ensure independence of the functions incorporated in the system.
- (2) The platform geometry kernel is provided with an original

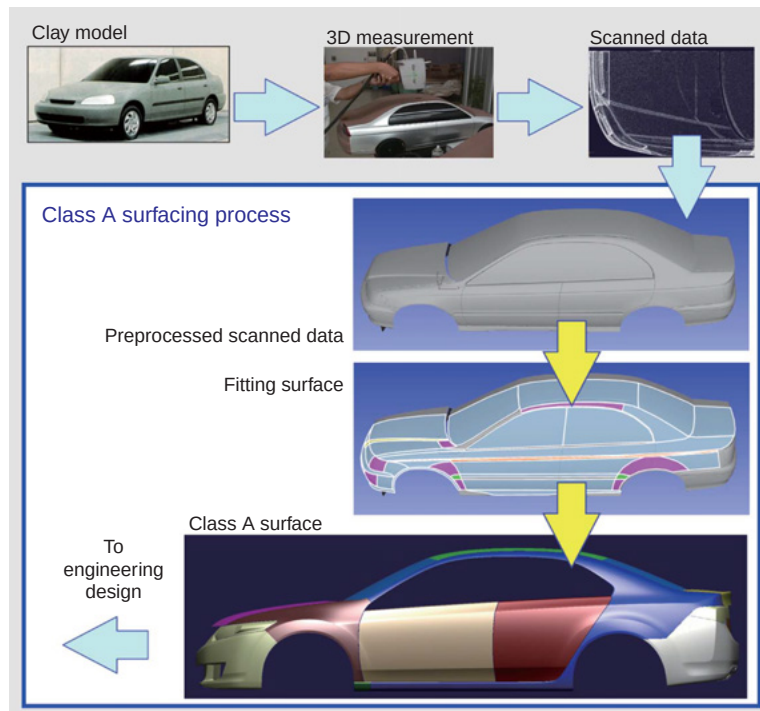


Fig. 1 Class A surfacing in styling process

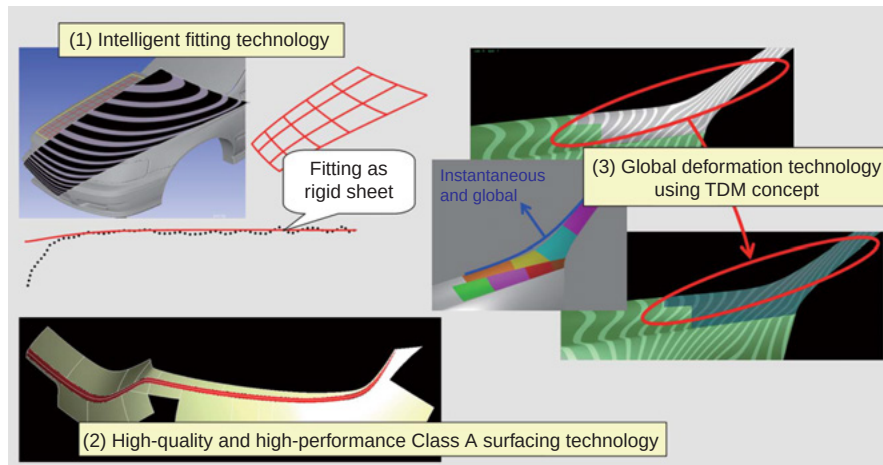


Fig. 2 Three typical technologies corresponding to three phases of Class A surfacing process

polygon kernel to help enable efficient management of large scanned data. This is shown as (A) in Fig. 3.

- (3) The three new technologies shown in Fig. 2 are incorporated in the functional section, which is unconstrained by the platform section. These are shown as (B), (C), and (D) in Fig. 3.

(A) to (D) in Fig. 3 have the following roles:

(A) is the original polygon kernel, and helps to enable efficient memory management for the use of large scanned data.

(B) is the fitting surface creation technology, the most upstream segment of the process of creation of Class A data. This technology helps to enable high-quality surfaces to be created from clay model shapes that include miniscule undulations and noise.

(C) is the core technology for the creation of Class A data. This was also regarded as the most important technology in the previous system, but the output surface calculation speed and quality have been increased in the new system.

(D) is the core technology that realizes the modeling method, the unique concept of the new system. Helping to enable intuitive deformation operations, this technology has contributed significantly to the realization of the system targets.

Due to the loose coupling described in (1) above, in addition to Class A CAD, the platform of the new system can support other CAD systems that aid styling design development.

4. Outline of CAD Functions

This chapter will provide an outline of technologies (A) to (D) above, and will introduce the main functions that have been realized through the use of these technologies.

4.1. Original Polygon Mesh Kernel

Pre-processing, including polygon mesh shape analysis of the scanned data input to the system and cutting out at the necessary points, should be conducted in the phase of preparation for Class A surfacing. The new system has been provided with an original polygon mesh shape processing kernel as the base technology to support these functions.

This kernel is the core processing section for polygon mesh shape processing, and exists as a standalone independent module. The application system links to the kernel for reference. The fact that the kernel is self-contained helps to enable it to be easily used with other applications, thus increasing versatility.

The 3D scanned data handled by the new system is large data with several million vertices. It was necessary to make it possible to work with this data interactively. The data storage and memory management systems were therefore the major issues for the system. These issues were resolved through the employment of three element technologies: (1) Half-edge structure technology; (2) Original memory pool technology; and (3) Original garbage collection technology. These technologies will be discussed below.

4.1.1. Half-edge data structure

In order to conduct efficient polygon mesh shape processing, it is necessary to be able to efficiently refer to the mutual contiguity and reference relationships of three topological elements of the polygon mesh: edges, faces, and vertices. The kernel therefore employs half-edge data structure⁽¹⁾. Figure 4 shows an overview of the half-edge data structure. The introduction of the concept of the half-edge at both sides of an edge helps to enable the efficient construction of reference relationships for mutual contiguity between topological elements. The

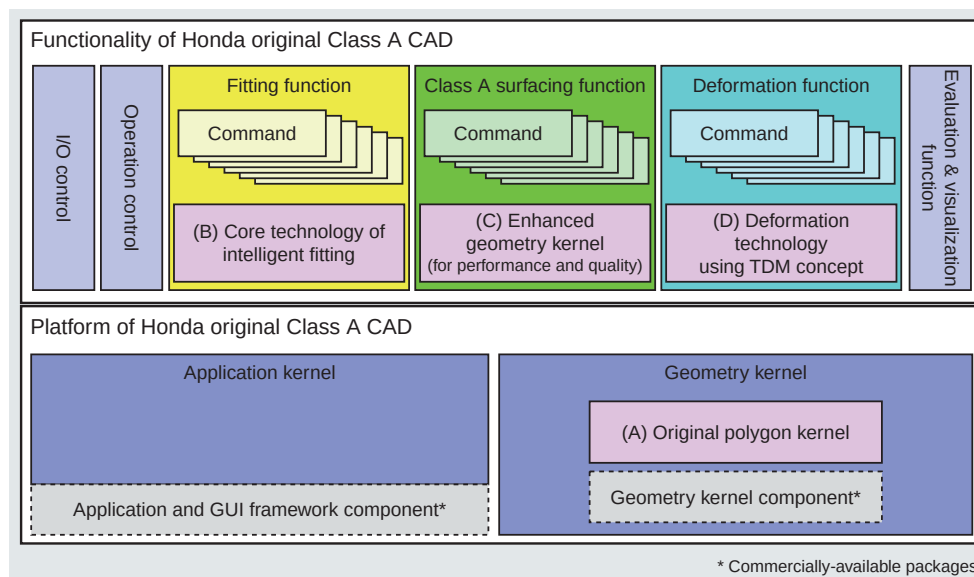


Fig. 3 Outline of system configuration

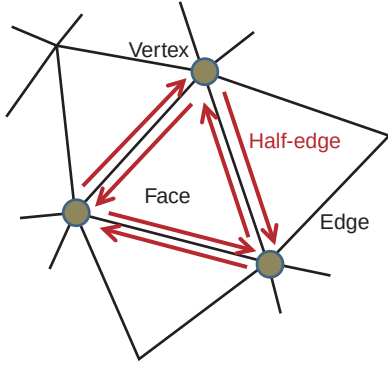


Fig. 4 Half-edge data structure

reference methods are as follows:

- For each half-edge, the vertex that forms the point of origin, the parallel edge and the half edge on the opposite side, the face in the same category, and the other half edges that share that face, are referenced.
- For each vertex, an arbitrary half-edge that is taken as its point of origin is referenced.
- For each face, an arbitrary half-edge above it is referenced.
- Finally, for each edge, one of the half-edges on the sides of the edge is referenced.

4.1.2. Fast and efficient memory fragment allocation via unique memory management

In order to help ensure memory allocation for an enormous number of objects in the range of several million and to efficiently release memory, the kernel employs a unique form of memory management based on a small object allocator⁽²⁾. Figure 5 shows an overview of the memory management mechanism. The system allocates and releases memory regions using small units of memory called “chunks.” The youngest generation of chunks are called “current chunk,” and memory fragments are provided from this chunk for each request for memory from the application. When the current chunk is filled, they are added to the chunk manager list, and new chunk is generated.

Because the number of categories of objects to be managed is limited, the kernel is provided with a total of five chunk lists, one for each of five topological elements (faces, edges, loops, half-edges, and vertices). The design of such an exclusive memory pool specialized for the polygon mesh topological element objects has helped to implement a simple and high-efficiency memory pool.

4.1.3. Garbage collection function

The repetition of shape processing operations results in objects that are no longer being referenced from the interior or exterior of the kernel being left over, and this impedes efficient memory use.

The polygon mesh kernel employs garbage collection (GC) based on a mark-sweep-compact garbage collector⁽³⁾. The GC monitors the reference status of all objects and

efficiently sweeps and releases regions occupied by unnecessary objects, and also applies anti-fragmentation processing to help prevent fragmentation of regions occupied by objects which are being referenced.

In addition, the employment of GC has made explicit memory release for individual topological elements unnecessary, and thus offers the advantage of resolving issues such as memory leaks and double free errors. An overview of the GC mechanism shown in Fig. 6 is provided below.

In panel (1) in Fig. 6, referenced and unreferenced nodes are mixed in each memory chunk while the user is repeating operations. If GC was not applied and this situation was allowed to continue, the memory chunk lists would continue to be filled with unreferenced nodes, and the system memory capacity would be used up to no effect.

Panel (2) in Fig. 6 shows the marking of all the referenced nodes to help discriminating between nodes which are referenced and unreferenced from the interior and the exterior of the kernel.

Continuing on from panel (2), panel (3) shows defragmentation for all the referenced nodes, at the same time as memory occupied by chunks containing no referenced nodes is successively released. In addition,

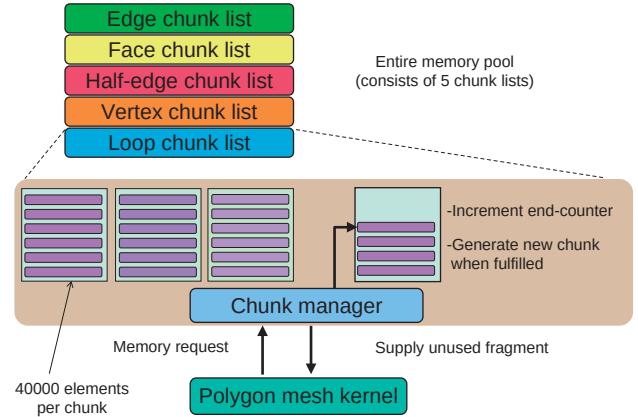


Fig. 5 Memory pool for topological nodes

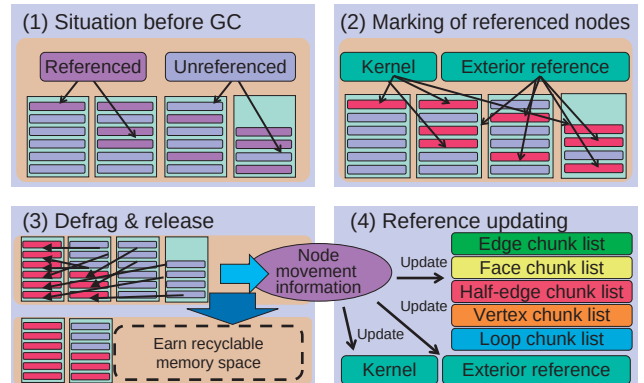


Fig. 6 Garbage collection

during this process movement data is recorded for the nodes.

Panel (4) in Fig. 6 shows updates of the reference sources for all the nodes in the kernel and exterior to the kernel, based on the node movement data recorded in (3).

Mark-sweep-compact garbage collection was applied in the system because the polygon mesh half-edge data structure used in the kernel employs reciprocal loop reference between the nodes, and other GC paradigms which are not able to work with reciprocal loop reference (such as reference counters⁽⁴⁾) would therefore have been unsuitable for topological element management in the system.

As indicated in the previous section, in this kernel space is allocated in response to memory requests from current chunks. However, memory spaces which have not yet been secured for which sweep processing⁽³⁾ and compact processing are unnecessary always exist in the current chunks, and there are therefore frequent exceptions in relation to other chunks. Full mark-sweep-compact processing is therefore only applied to saturated chunks other than current chunks. By this means, the algorithms could be defined with saturation of all the chunks other than the current chunks as a precondition, making exceptional processing for the current chunks unnecessary. This not only made it easier to incorporate the garbage collection function, but also offered advantages from the perspective of performance.

The design discussed above helped to enable the realization of a simple, practical, and high-efficiency GC function.

4.2. Fitting Technology

In the process of generation of Class A data, 3D scanned data from clay models is input, and Class A surface data that accurately represents the styling shapes is generated. Previously, this involved a repeated process in which the surfaces were generated manually, the match or discrepancy between the scanned data and the surface data was evaluated, and corrections were made manually. Because this process necessitated an enormous expenditure of man-hours, numerous mechanisms for the automatic generation of surface shapes that represent the styling shapes from scanned data have been considered. This will be defined as “technology to fit scanned data.”

Because undulations in clay models and measurement

errors were incorporated without alteration in the output, the previous fitting technology was unable to ensure the necessary surface quality for Class A data. The new system therefore removes clay model undulations and measurement errors while accurately representing the styling shapes, thus generating surfaces that fulfill Class A data quality demands. This is termed “intelligent fitting technology.” The rest of this section will provide an overview of this technology, and will discuss the differences in output quality between this technology and the previous technology.

First, the results output by the previous technology will be considered. Figure 7(a) shows a simulated reproduction of a highlight in scanned data. This image demonstrates that minute levels of noise and unevenness exist in the scanned data. Figure 7(b) shows the highlight resulting from least square fitting (LSF), a conventional technology, and Fig. 7(c) shows G2 (curvature) values. Noise in the scanned data produces unevenness and bending in the output surface, and the G2 curves also display undulations. The existence of these disturbances prevents the data from achieving Class A quality.

Next, an overview of the intelligent fitting technology will be provided and its output will be considered.

In order to maintain both surface quality and continuity between surfaces, it is necessary to control the tangency (G1) and curvature (G2) of the surfaces. In addition, as indicated above, undulations in the curvature affect quality, and because of this it is also necessary to control the rate of change of G2.

The concept of stiffness has been employed in the new system to help enable these parameters to be controlled. As Fig. 8 shows, when a metal ruler is pressed over an actual model, it follows the tendency of the surface, but the minute concavities and convexities are ignored. This is because the ruler has a specific degree of hardness, and will not bend more than a specific amount. Substituting a mathematical constraint for this concept and employing it as a condition during fitting of surfaces helped to enable surfaces obtaining Class A quality to be output.

Figures 9(a) and 9(b) show output surfaces incorporating this concept. Compared to the results shown in Figs. 7(b) and 7(c), these surfaces obviously obtain smooth highlights and changes in G2, while keeping the tendency of the scanned data. However, because fitting was conducted up to this point for each individual surface,

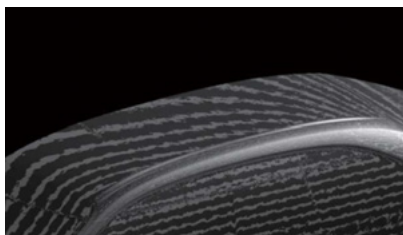


Fig. 7 (a) Scanned polygon

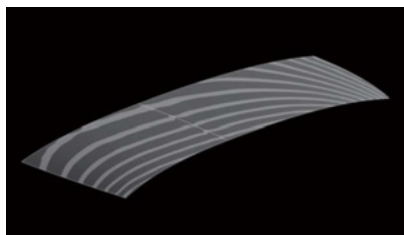


Fig. 7 (b) Highlight of LSF surface

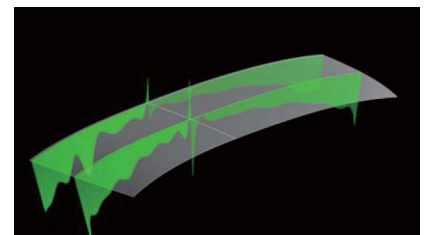


Fig. 7 (c) Curvature plot of LSF surface

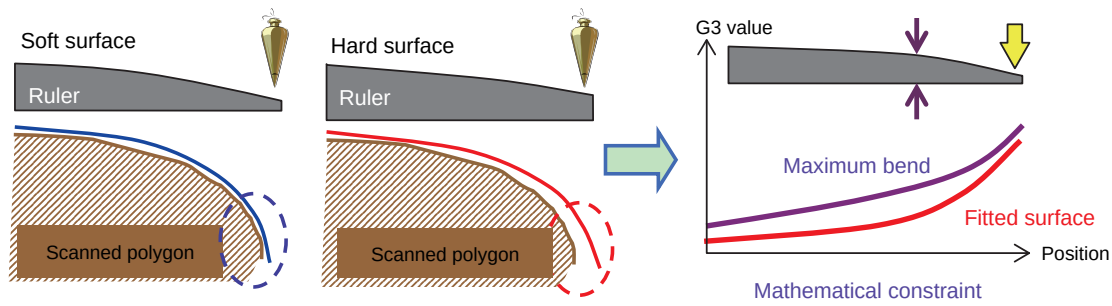


Fig. 8 Concept of stiffness

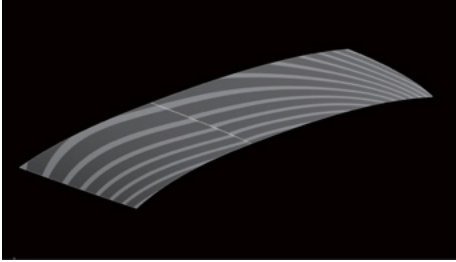


Fig. 9 (a) Highlight of intelligent fitting surface

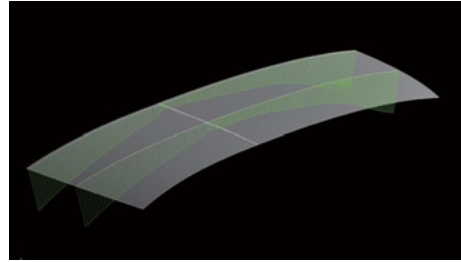


Fig. 9 (b) Curvature plot of intelligent fitting surface

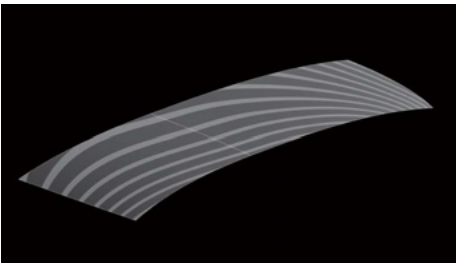


Fig. 10 (a) Highlight of merged surface

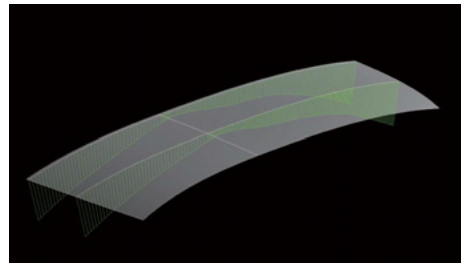


Fig. 10 (b) Curvature plot of merged surface

there was unevenness in terms of position and curvature at the boundaries between surfaces.

A “merge” technology was developed to resolve this issue.

Ultimately, Class A data is composed of multiple surfaces which have mutual continuity. “Continuity” here refers to position, G0; tangency, G1; and curvature, G2. In the past, the continuity was ensured by uniquely specifying the state of connection. However, because this method resulted in conspicuous undulations at the exterior of areas in contact, it was inadequate for Class A quality.

In the new system, mathematical constraints have been utilized for maintenance of continuity, and degrees of freedom have been granted to states of connection. This has helped to ensure continuity with minimal overall undulation. Figures 10(a) and 10(b) show output surfaces generated using the new system. Surface undulation has been controlled while continuity of position and curvature has been achieved in areas in contact.

4.3. High-speed and High-accuracy Class A Surfacing Technology

In order to realize the images produced by styling

designers, the method adopted by Honda for the generation of Class A data has necessitated the production of surface structures across which highlights flow, using curves termed “character lines” as a guide. In addition, a high level of accuracy has been demanded in order to satisfy engineering design conditions. Due to the inability of market CAD systems to satisfy the necessary conditions, and in order to simplify the generation of complex shapes necessitating the expenditure of a huge volume of man-hours, the company has developed original CAD systems using the latest technologies. However, the shapes used in recent automotive styling have become increasingly complex, and the number of surfaces employed has approximately doubled against the situation five years ago. Increased speed and increased accuracy were demanded for the process of creating Class A data. The Class A surfacing functions of the new system carry over the practical expertise incorporated in traditional data generation commands. At the same time, their speed and accuracy have been increased, and a command set extending to 185 functions has also been developed.

As a representative example, Fig. 11 shows the curve-smoothing function. The curve-smoothing function realizes

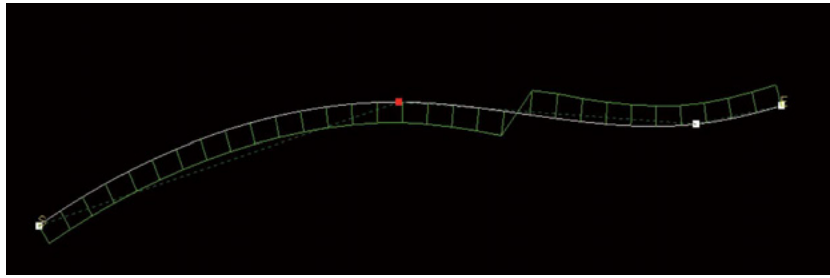


Fig. 11 Curve editing

intuitive operations that make it possible to directly select and move edit points, and has reduced the man-hours employed in correcting curves. In addition, the function also makes it possible to make corrections using control points and to make corrections while maintaining G2 continuity on the terminal using 5-degree curves, and has therefore expanded the scope of curve correction, reduced the man-hours involved in curve correction, and increased the accuracy of continuity.

For surfaces, an original Honda four-boundary surfacing command applying four-boundary Coons surfaces was developed. Because the previous system used 3-degree surfaces, the tendency of the curvature of the interior of the surfaces was sometimes erratic. The new system generates four-boundary surfaces using 5-degree C2 surfaces, significantly increasing interior continuity. Figure 12 shows the curvature of cross-section curves of four-boundary surfaces generated using the old and new systems.

In addition, the generation of fillet surfaces has been increased in speed, and the quality and accuracy of the surfaces have been increased. A fillet is a shape that rounds the angle formed by two surfaces. Fillets are important elements in satisfying the safety standard that stipulates that automotive surfaces must have no projections with a radius of curvature of less than 2.5 mm, and they make up approximately 10% of the total number of Class A surfaces. Redevelopment of the fillet-generation algorithms in the new system has increased computation speed and helped to enable the generation of fillet surfaces obtaining greater G2 continuity with support surfaces. In order to increase calculation speed, a method of calculating fillets using normal vectors of the support surfaces, the normal vectors of section planes, and the

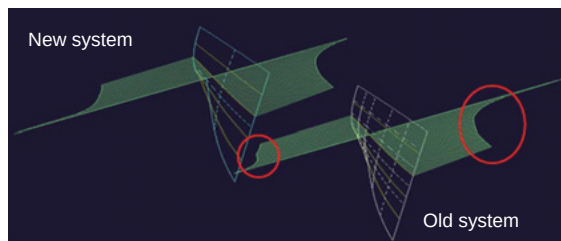


Fig. 12 Four-boundary surface

normal curvature of support surfaces was developed to replace the traditional calculation using intersections. To achieve greater G2 continuity with support surfaces, fillet surfaces were designed so that G2 continuity with peripheral surfaces was satisfied by means of staged Gordon surfacing with the cross-boundary derivative (CBD), which provides information concerning the derivative values for the peripheral surfaces, as an input. In addition, not only were the fillet-generation algorithms extensively redeveloped, but an interface was developed that synchronizes the creation of fillet surfaces with a surface quality evaluation (Fig. 13), contributing to a reduction in the man-hours employed in fillet creation.

4.4. Global Deformation Technology

When clay models are altered during the maturation process of a styling design, the Class A data created on the basis of the clay models should also be updated. In the previous system, data was corrected by means of repeated manipulation of the mathematical parameters of the existing surfaces. Because this was an indirect method of correction in relation to the target surface shapes, an enormous amount of time was required for operations conducted by trial and error. At times, it was faster to simply regenerate the surfaces. Using this method of creating Class A data, updates to the data were unable to keep pace with alteration of the clay models.

For the new system, technologies were developed to

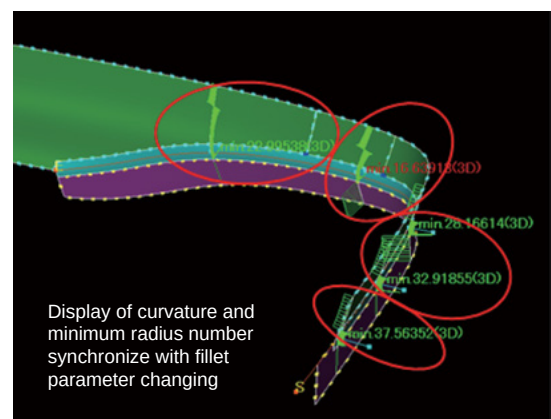


Fig. 13 Creation of fillet with dynamic evaluation

make the correction of existing surfaces more intuitive and efficient, using a method of correction of surface shapes in which styling designers directly input shape targets in accord with their aesthetic intention. Because shape targets are directly input in this method, it is termed target-driven modeling (TDM). This section will provide an example of the application of this new technology.

4.4.1. Highlight control

Highlight control applies the concept of target-driven modeling to the 2D highlights which represent one of the standards for quality evaluation of Class A data. When a styling designer designates the target highlights, this function deforms the existing surfaces to produce those target highlights. Figure 14 shows the results produced by the function in relation to the target highlight. The upper image shows the situation prior to deformation, and the lower image shows the results of deformation. The blue lines in the images are the surface highlights rendered visible. In this example, the highlight shown by the yellow line was deformed in order to follow the white line. Rendering the highlight visible shows that the highlight traces the specified white line on the surface following deformation.

4.4.2. Curvature control

Curvature control is a function that deforms existing curves by means of input of target focal curve for a

curvature plot in relation to the existing curves. In the previous system, the target curves were obtained by repeatedly adjusting the positions of the control points or pass points of the curves one-by-one. Based on the concept of target-driven modeling, in the new system the existing curves can be deformed to produce the target curvature plot simply by inputting the existing curves and the target curvature plot. Figure 15 shows that specifying a target curvature plot in relation to an existing curve has resulted in the achievement of a curve that follows the specified target.

4.4.3. Surface tension control

Surface tension control is a function that adjusts surfacing tension in relation to the existing surface. A curve is defined to help enable tension to be controlled on the surfaces which are being corrected. If the current tension of the surface is defined as 0, adjustments can be made in the range of $\pm 100\%$. By this means, the surfaces can be controlled when styling designers wish, for example, to apply slightly more tension. Figure 16 shows the results of applying tension increases of 10%, 30%, and 50%. Because the tendency of original input shapes is successfully kept well in the image as a whole, the difference is barely noticeable. When cross-sections at the curve defined for tension control are compared, however, it is clear that the tension of the surface has been increased to the degree specified.

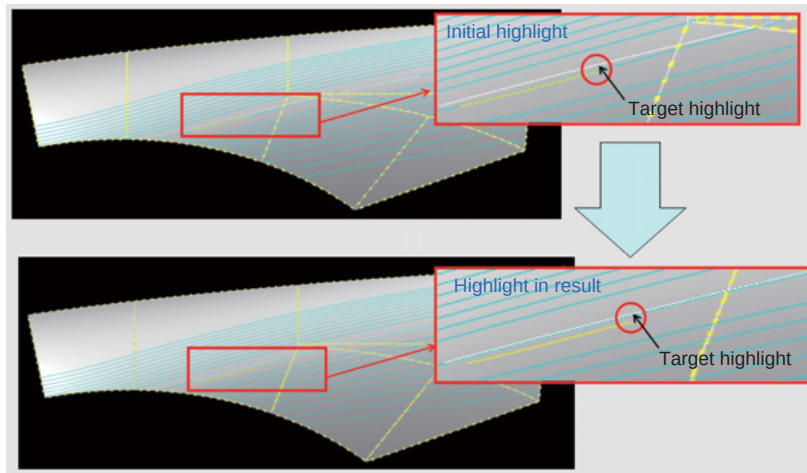


Fig. 14 Highlight control in sample case

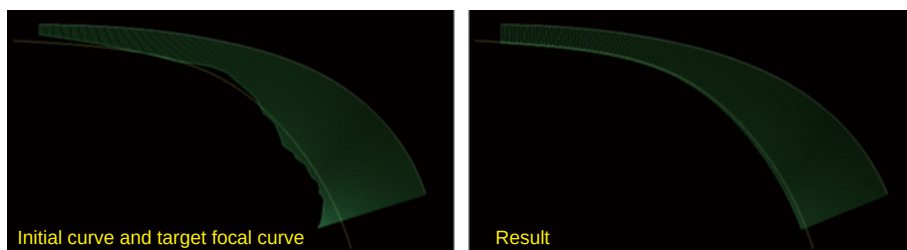


Fig. 15 Curvature control in sample case

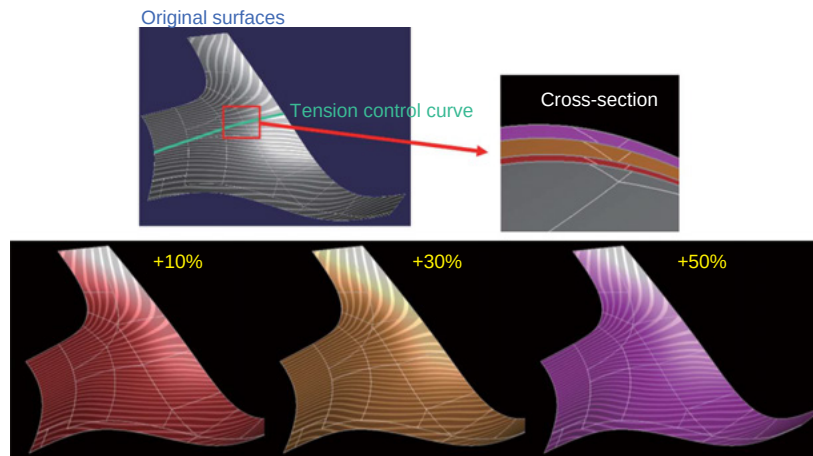


Fig. 16 Tension control in sample case

5. Effect of System in Reducing Man-hours and Analysis

The effect of the developed system in the process of product development to completion of the Class A data was evaluated in relation to the development target of the achievement of a 50% reduction in the time necessary for the creation of the data. The effect of individual functions was also analyzed.

5.1. Effect of System in Reducing Modeling Man-hours

Tables 1 and 2, respectively, show the time employed for the creation of Class A data for various parts and the reduction in modeling man-hours achieved through the use of the new system.

Tables 3 and 4, respectively, show the time employed for the creation of Class A data in different phases of styling development and the reduction in modeling man-hours achieved through the use of the new system.

While variations in the effect produced by the system of around 10% can be observed depending on vehicle

type, part, and styling development phase, it can be seen that the system has satisfied the development target.

5.2. Analysis of Effect in Reducing Modeling Man-hours

Table 5 shows the effects of the main functions incorporated in the new system, and Fig. 17 shows shapes output by the respective functions. The times in Table 5 represent the total calculation time necessitated by operations conducted until the completion of the shapes, and do not include the time necessary for shape evaluation or the selection of work methods by the system user.

A more-than-twofold difference was observed between the effect of the function that produced the greatest effect (No. 6) and that of the function that produced the least effect (No. 4), and the causes of this difference were analyzed. An effect of reduction of modeling man-hours satisfying the target established for the system was displayed by functions No. 1 and 2, for which entirely new calculation algorithms were employed, and functions No. 3, 5, and 6, for which new approaches not employed in the previous system were adopted. However, while

Table 1 Modeling time by parts (hours)

Production model	Recent model	Past model A	Past model B
Applied system	New system	Past system	Past system
Modeling time of parts L	235 h	823 h	340 h
Modeling time of parts M	134 h	188 h	440 h
Modeling time of parts N	125 h	225 h	169 h
Total modeling time	494 h	1236 h	949 h

Table 2 Reduction ratio by parts (%)

Model	vs. Past model A	vs. Past model B
Reduction of modeling time (total time)	60%	48%

$$\% = (\text{Past model X} - \text{Recent}) / \text{Past model X}$$

Table 3 Modeling time by styling phase (hours)

Production model	Recent model	Past model X	Past model Y	Past model Z	Ave.(X,Y,Z)
Applied system	New system	Past system	Past system	Past system	Past system
Styling phase P	92 h	190 h	129 h	182 h	167 h
Styling phase Q	202 h	823 h	340 h	230 h	464 h
Styling phase R	932 h	2204 h	1029 h	1453 h	1562 h

$$\text{Ave.}(X,Y,Z) = (X+Y+Z)/3$$

Table 4 Reduction ratio by styling phase (%)

Phase	Phase P	Phase Q	Phase R
Reduction of modeling time (average for phase)	45%	56%	40%

$$\% = (\text{Ave.}(X,Y,Z) - \text{Recent model})/\text{Ave.}(X,Y,Z)$$

Table 5 Analysis of effect by main functions implemented on new system

No.	Function	Model	Computing time* in past system	Computing time* in new system	Reduction of computing time
1	Fitting surface on measured mesh	Fig. 17 (a)	13 min.	3 min.	77%
2	Fillet surface (Class A)	Fig. 17 (b)	14 sec.	3 sec.	79%
3	Blending surface (Class A)	Fig. 17 (c)	18 sec.	2 sec.	89%
4	Matching surface (Class A)	Fig. 17 (d)	64 sec.	35 sec.	45%
5	Global deformation (Deformation)	Fig. 17 (e)	15 h	1.5 h	90%
6	Highlight control (Deformation)	Fig. 17 (f)	1 h	43 sec.	99%

* Computing time represents the total computing time for iterative operations.

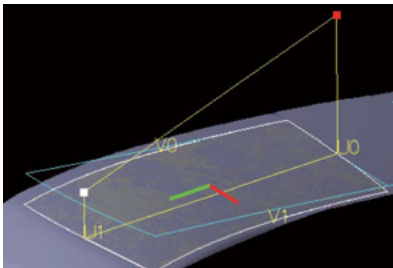


Fig. 17 (a) Fitting surface

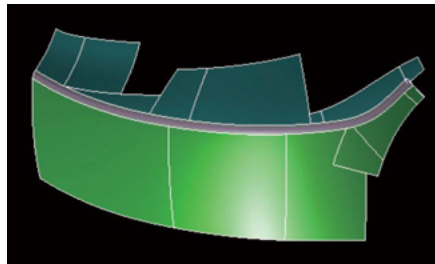


Fig. 17 (b) Fillet surface

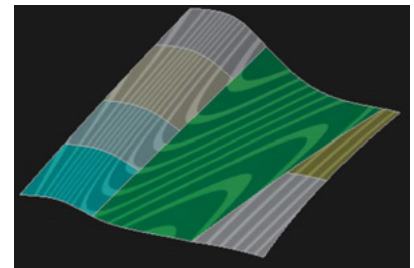


Fig. 17(c) Blending surface

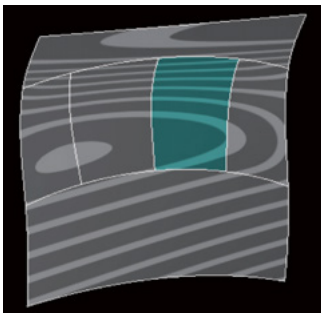


Fig. 17 (d) Matching surface

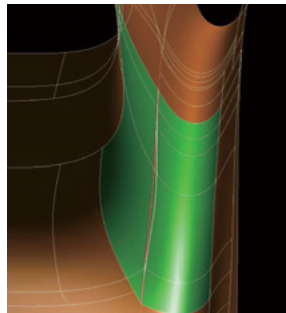


Fig. 17 (e) Global deformation

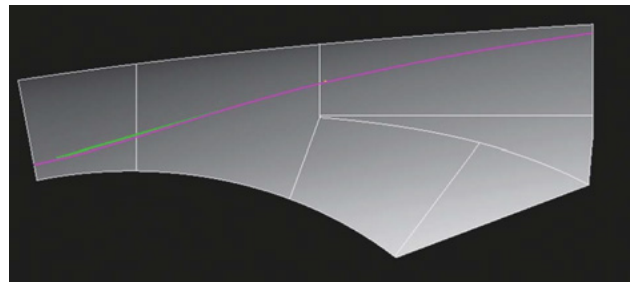


Fig. 17 (f) Highlight control

function No. 4 produced a reduction of 45% in modeling time, its effect is low in comparison with the other functions. This is because the matching surface function had already reached a high level of maturity in the previous system, and the modification of the method in the new system therefore did not result in a conspicuous change.

6. Conclusion

- (1) A new system was developed in order to reduce the man-hours employed in the creation of Class A data by 50%, and satisfied this target.
- (2) Class A data creation functions were developed for the new system on the basis of the creation of an original software platform.
- (3) The development of Class A data creation functions focused on three phases in the process of creating the data, and employed new and original technologies to realize the desired functions in each phase.

7. Afterword

Ambitious targets were realized in the development of the system discussed in this paper by bringing together system developers and the members of project teams involved in the creation of Class A data to squeeze their knowledge and hone potential solutions. The authors believe that the project produced another outcome in addition to increasing the efficiency of the creation of Class A data. This was the experience of combining the efforts of an entire team in a process of trial and error in order to resolve every issue encountered in the course of seeking to fulfill a challenging target. We believe, this must be a wonderful provision for the engineers who will continue to produce next-generation technologies into the future.

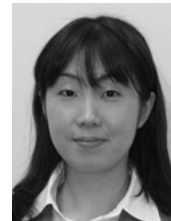
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