Title:
GPU-Based Visualization of Knee-Form Contact Area for Safety Inspections

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Introduction:
Safety is an important concern in automobile design. In driving an automobile, acceleration and deceleration are realized by the driver's leg and foot motion. If the shape of the instrument panel hinders the smooth motion of the knee, the operability of the automobile is significantly impaired. If the knee touches electric switches while driving, it may cause traffic accidents in the worst case. To prevent such problems, the United Nations (UN) defines a safety regulation based on the possible collision between the knee and the instrument panel [1]. Fig. 1 illustrates the UN regulation No. 21 concerning the knee collision. In CAD models of the automobile design, the instrument panel is positioned so that it faces the positive direction of the x-axis, and an apparatus imitating the knee shape during driving is defined. This "knee-form" has an equilateral triangle-like shape and a thickness, t, of 120 mm. It has a rounded corner that can be represented by a cylinder with a radius of 60 mm (see Fig. 1(a)). To inspect for compliance with the regulation, the knee-form is represented as moving linearly in the negative direction of the x-axis, where it eventually pushes into the instrument panel. In this way, as shown in Fig. 1(b), surface areas on the panel are detected where the knee can make contact during driving. Before representing the movement, the apparatus can be rotated above and below the horizontal by up to 30 degrees to represent different orientations. According to the regulation, any switches, nobs, buttons, and levers are not allowed in the knee contacting area.

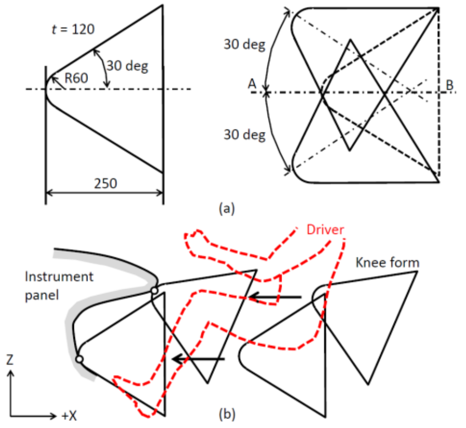

Fig. 1: UN regulation No.21.

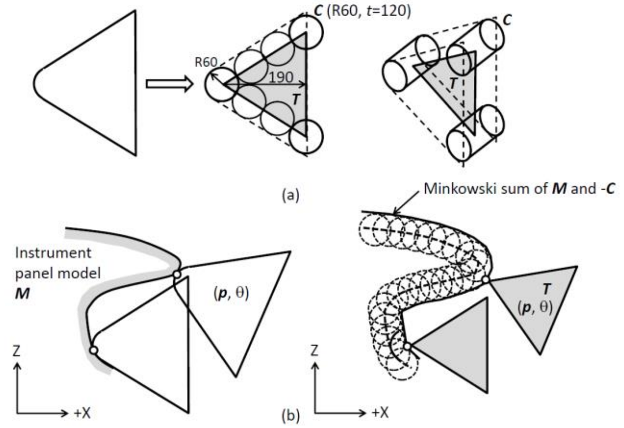

Fig. 2: Approximation of knee-form as Minkowski sum of ***T*** and ***C***.

Because interior components, especially the instrument panel, significantly affect the appearance and comfort of the automobile, they are often designed in terms of their function and aesthetics. Knee-form contact detection is manually inspected by specialists in the final design stage with a physical apparatus and with models. This work is difficult, time consuming, and prone to human errors, and detection of safety problems at this stage causes costly re-design and fabrication. Therefore, a fast and automatic inspection method that allows the designers themselves to check the regulations during the shape design process is desirable.

Main Idea:

Algorithm outline

One possible attempt for detecting the knee-form contacting area is to use the collision detection technology of 3D objects. In this method, manual inspection with physical apparatus is replaced by a virtual process with solid models in computers. Prepare a knee-form model in a various orientation allowed in the rotation range given in Fig. 1(a). The knee-form model is then moved in a straight line toward the instrument panel model to detect its first colliding point on the instrument panel. This collision detection process is repeated for knee-form models in various initial positions and a set of colliding points representing the knee-form contacting area is derived. Although this approach is simple and easy in the implementation, necessary cost for the detection is estimated to be very large because tremendous number of collision detections with knee-form models in different orientation and initial positions are required.

To assist the designers, this paper proposes a novel method for automatically detecting the knee-form contacting area on the instrument panel. In order to reduce the computation cost, our UN regulation inspection method uses the Minkowski sum of a polyhedral object and a horizontal cylinder. In the instrument panel design, the designer is requested to define a curve on the panel surface that subdivides the upper part and lower part of the panel. This curve is referred to as the instrument panel level or IP level. Because the knee can contact only the lower part of the panel, the knee-form contact analysis for the upper part of the panel is not necessary. During actual driving, the steering wheel also limits the knee motion. In the analysis, the linear motion of the knee-form can be disregarded when the knee-form collides with the steering wheel before contacting the instrument panel. To simplify the problem, the IP level and the effect of the steering wheel on the analysis are not considered in this work; therefore, only contacts between the knee-form and the upper part of the instrument panel and contacts to the panel area behind the steering wheel are allowed.

The input data for the method proposed in this paper consists of a polyhedral model $\boldsymbol{M}$ that approximates the panel shape with a high degree of accuracy. The system can visualize the knee-form contact area on the display and can output the area data as a set of small polygons in the STL format. The position and orientation of the knee-form can be uniquely described using a configuration ($\boldsymbol{p}$, θ) where $\boldsymbol{p}$ represents the position of the center point of the knee-form, and θ represents the knee-form's orientation around $\boldsymbol{p}$. The knee-form can be approximated by the Minkowski sum shape of a vertical equilateral triangle $\boldsymbol{T}$ and a horizontal cylinder $\boldsymbol{C}$ of radius 60 mm and length 120 mm, as shown in Fig. 2(a). The contacting condition of the knee-form to the instrument panel model $\boldsymbol{M}$ thus can be analyzed by evaluating the contacting condition of the equilateral triangle $\boldsymbol{T}$ with respect to the Minkowski sum shape of $\boldsymbol{M}$ and the inverted horizontal cylinder $-\boldsymbol{C}$, as shown in Fig. 2(b). $\boldsymbol{C}$ and $-\boldsymbol{C}$ have the same geometry if their local coordinate frames are assigned on the center of the cylinder. If the knee-form at configuration ($\boldsymbol{p}$, θ) contacts $\boldsymbol{M}$, then $\boldsymbol{T}$ in the same configuration contacts the Minkowski sum shape and vice versa.

Based on this concept, our method analyzes the knee-form contacting area on the instrument panel in the following three steps, as shown in Fig. 3. In Step 1, the Minkowski sum shape of the instrument panel shape $\boldsymbol{M}$ and the inverted cylinder $-\boldsymbol{C}$ is computed, and the surface of the Minkowski sum shape facing the driver's side $\boldsymbol{E}$ (the positive direction of the x-axis) is obtained. In Step 2, possible contacts between the vertical equilateral triangle $\boldsymbol{T}$ and $\boldsymbol{E}$ are analyzed, and the triangle contacting area on $\boldsymbol{E}$ is computed as a set of points densely covering $\boldsymbol{E}$'s surface. In the final step, the Minkowski sum shape $\boldsymbol{M'}$ of the points obtained in Step 2 and the cylinder $\boldsymbol{C}$ is computed. The surface intersection of $\boldsymbol{M}$ and $\boldsymbol{M'}$ corresponds to the knee-form contacting area on $\boldsymbol{M}$. Minkowski sum computations and the detection of possible contacts between a triangle and objects are generally very time consuming [3].

However, the parallel processing capability of a graphics processing unit (GPU) allows our system to detect and output the knee-form contacting area in a practical time period.

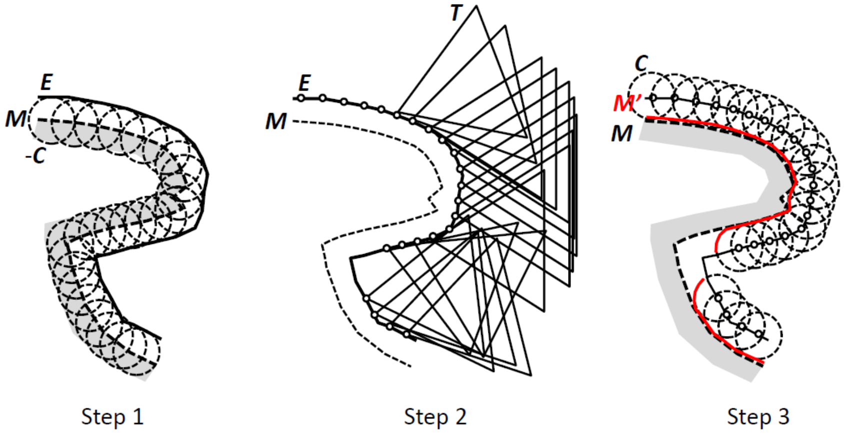

Fig. 3: Algorithm outline.

Minkowski sum of instrument panel model and cylinder (step 1)
In the first step, the instrument panel shape is expanded by a horizontal cylinder of radius 60 mm and length 120 mm, and the surface of the expanded shape facing the positive direction of the x-axis is computed. The Minkowski sum shape of one triangle ***f*** and the cylinder is obtained as a combination of the following two component shapes. (1) For each edge of the triangle, the linear swept volume of the cylinder moving along the edge is defined. (2) Three swept volumes on the edges of triangle ***f*** form an approximately doughnut shape, as shown in Fig. 4. The hole of the doughnut is closed with two triangles f_1 and f_2. The Minkowski sum shape of the entire object is obtained as a Boolean union of the small Minkowski sum shapes defined for all polygons of the object.

An exact computation of the Boolean union of many component shapes is time-consuming and unstable because of inevitable numerical errors in the geometric computation. Because the knee-form linearly approaches the instrument panel in the negative direction of the x-axis, only the part of the Minkowski sum shape visible from the negative direction of the x-axis is necessary. This visible surface of the Minkowski sum shape is obtained using the hidden surface elimination mechanism for rendering 3D objects [2]. In this method, the Minkowski sum shape visible from the negative x-axis direction is thus derived as a set of grid-like points aligned with respect to the pixel grid of the display. The computation is completed by simply rendering the component shapes placed on the polygons.

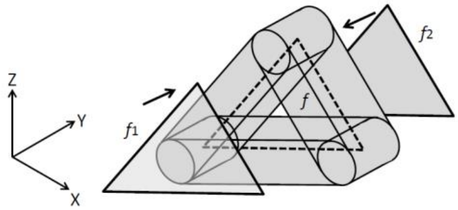

Fig. 4: Minkowski sum of ***f*** and a cylinder.

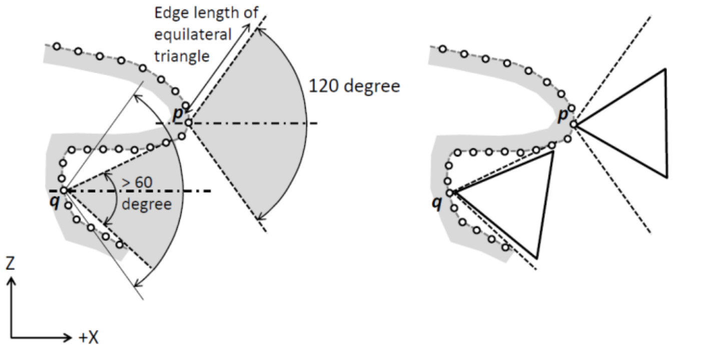

Fig. 5: Contact analysis of equilateral triangle at its vertex.

Contact analysis of an equilateral triangle (step 2)
This step evaluates the contact condition between the vertical equilateral triangle corresponding to the core part of the knee-form and the surface of the expanded instrument panel model obtained in Step 1. The shape of the expanded instrument panel model is defined as a set of grid-like points aligned with

respect to the y-axis and z-axis in the object coordinate frame. Because the vertical triangle is positioned to be parallel to the zx-plane in the object space, the evaluation of the contact condition can be decomposed into a contact analysis between the triangle and a series of points corresponding to each column of grid-like points, and can thus be realized in 2D. Consider that the triangle contacts the polygonal line at its vertex (see Fig. 5). To realize such contact, there must be a fan-like space adjacent to the contacting point that contains an arc of more than 60 degrees and that has a radius equal to the edge length of the triangle. Before the approach, the triangle can be rotated around its center point. Because the rotation angle is in a range from –30 to +30 degrees, the fan-like space must be contained within a larger fan containing an arc from –60 to +60 degrees, with respect to the horizontal center line. For each point on the polygonal line, the placement condition of an equilateral triangle mentioned above is checked, and points where the triangle can make contact are marked.

Because this contact analysis can be executed for multiple points on the polygonal line simultaneously, we accelerate the computation using the parallel processing capability of a GPU. Compute Unified Device Architecture (CUDA) is used to implement the parallel contact analysis software. After checking the contact of the triangle at its vertex, possible contact of the triangle on its edge is evaluated. Convex points on the polygonal line unmarked in the previous step, where contact at the triangle's vertex is not possible, become candidates for contact on the triangle's edge. For each candidate point, a pseudo-normal vector is defined as the bisector of its supplementary angle. A tangent line through the candidate point and perpendicular to the pseudo-normal vector is defined, and the triangle is placed on the line as shown in Fig. 6. The triangle is translated along the tangent line in small intervals, searching for a position of the triangle where the triangle does not intersect the polygonal line. If such a collision-free position is identified, its corresponding point on the polygonal line is marked as a point where the triangle can realize an edge contact.

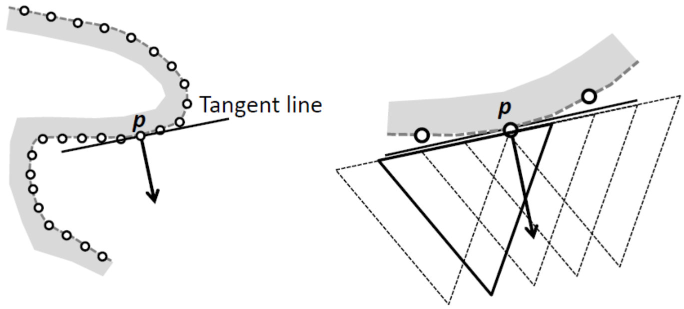

Fig. 6: Contact analysis of equilateral triangle on its edge.

Evaluation of the knee-form contact (step 3)

In Step 3, the Minkowski sum shape of the marked points and the cylinder is computed. The intersecting area between the original instrument panel model and the shape resulting from the Minkowski sum computation corresponds to the knee-form contact area on the instrument panel. The Minkowski sum computation in Step 3 uses the same depth buffer-based method described in Step 1. As a result, grid-like points on the Minkowski sum shape closest to the original instrument panel model are obtained. The grid-like points are then properly connected based on the adjacency information of the grid, and the points are converted to an equivalent polyhedral surface with small triangular polygons. The intersection of the surface of the original instrument panel model and the surface of the Minkowski sum shape is derived by selecting the surface polygons of the Minkowski sum shape for which the distance to the original model is sufficiently small. As a result, the knee-form contacting area on the instrument panel is obtained as a set of small triangles. In our current implementation, $\varepsilon = 0.1$mm is used as the small distance value for selecting the intersecting polygons. The hierarchical AABB (Axis Aligned Bounding Box) and the parallel processing of GPU are used to accelerate the computation. As a result, the knee-form contacting area on the instrumental panel is obtained as a set of small triangular polygons.

Numerical experiment

The proposed knee-form contacting area computation system was implemented using Visual C++,

Fig. 7: Sample model ***M*** with 597,455 polygons.

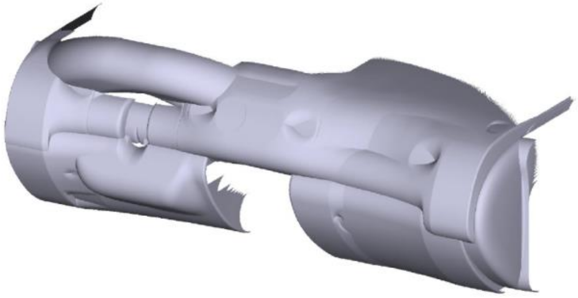

Fig. 8: Minkowski sum ***E*** of ***M*** and a cylinder −***C***.

CUDA 6.5, and OpenGL, and a series of computational experiments was performed. Fig. 7 illustrates a sample part with 597,455 polygons. The surface of the Minkowski sum shapes of the sample parts and a horizontal cylinder of 60 mm radius and 120 mm length is obtained in Step 1, and the resulting surface is shown in Fig. 8. In Step 2, some points are eliminated because the equilateral triangle cannot contact them. Fig. 9 shows the opposite side of the surface of the Minkowski sum shape of the points marked in Step 2 and the horizontal cylinder. After checking the intersection between the shape shown in Fig. 9 and the original model shown in Fig. 7, the knee-form contacting area is extracted as shown in Fig. 10. The system was found to require 4 minutes for the total process. Because the IP level is not evaluated in the current system, some knee-form contact areas are detected on the top side of the panel where the knee of the driver never collides.

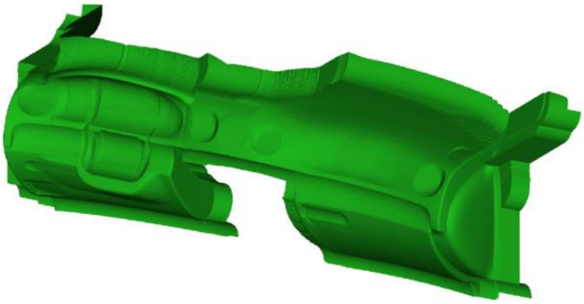

Fig. 9: Minkowski sum of ***E*** and cylinder ***C***.

Fig. 10: Detected knee-form contacting area on the instrument panel surface.

Conclusions:

In this paper, we have proposed a novel method for assisting UN safety regulation inspections of instrument panels. The driver's knee-form can be recognized as a Minkowski sum shape of a vertical equilateral triangle and a horizontal cylinder. The knee form contacting condition is geometrically equivalent to the contacting condition of the equilateral triangle to a Minkowski sum shape of the instrument panel model and the horizontal cylinder. Based on this concept, our algorithm realizes the extraction of the knee-form contacting area. With the parallel computation capability of a GPU, our system can extract the result area in a few minutes. The UN regulation describes some additional conditions concerning the steering wheel and the IP level; however, these conditions are not considered in this study. Incorporation of the conditions in the detection is an important topic for the next phase of this research.

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