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Surface Flattening Assisted with 3D Mannequin Based On Minimum Energy

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Abstract**—**The topic of surface flattening plays a vital role in the field of computer aided design and manufacture. Surface flattening enables the production of 2D patterns and it can be used in design and manufacturing for developing a 3D surface to a 2D platform, especially in fashion design. This study describes surface flattening based on minimum energy methods according to the property of different fabrics. Firstly, through the geometric feature of a 3D surface, the less transformed area can be flattened on a 2D platform by geodesic. Then, strain energy that has accumulated in mesh can be stably released by an approximate implicit method and revised error function. In some cases, cutting mesh to further release the energy is a common way to fix the situation and enhance the accuracy of the surface flattening, and this makes the obtained 2D pattern naturally generate significant cracks. When this methodology is applied to a 3D mannequin constructed with feature lines, it enhances the level of computer-aided fashion design. Besides, when different fabrics are applied to fashion design, it is necessary to revise the shape of a 2D pattern according to the properties of the fabric. With this model, the outline of 2D patterns can be revised by distributing the strain energy with different results according to different fabric properties. Finally, this research uses some common design cases to illustrate and verify the feasibility of this methodology**.**

Keywords**—**Surface flattening, Strain energy, Minimum energy, approximate implicit method, Fashion design.

I. INTRODUCTION

THE process of surface flattening means developing a 3D surface to a 2D platform. This is an important technology for many manufacturing industries and it can be implemented in computer-aided design of aircraft manufacturing, shipbuilding, bag manufacturing, footwear, fashion, etc. The application of a flat 3D surface to accurate 2D patterns can cut costs as well as increasing the quality of the products. Besides, the outline of the pattern can not only influence the appearance of the clothing, but it is also an important factor in terms of comfort for the wearer. Traditionally, when master craftsmen designed garments, making them was a laborious process. The designer first had to sketch a 2D pattern of the outline, and this pattern had to be constantly revised and reproduced before the product was finished. Thus, the creating process was extremely laborious and time-consuming, let alone having to produce clothes of different textures and sizes. Apart from being able to develop costume designs of different fabric materials and sizes, 2D patterns can be revised according to the fabric's properties. Thus, a mannequin can aid clothing design and this methodology can produce a more specific design. The tailor usually cuts the style by placing the fabric on the platform of the model so that the outline of the 2D pattern can be directly flattened. This can efficiently process the development of a wide range of fashion designs. However, if customers want to order customized clothing, the fabric can be draped across the customer's body, and while this kind of product is unique, it is also comparative expensive to produce.

The implementation of computer-aided design and manufacture to develop 2D patterns can produce a variety of solutions and enable designers to think outside the box and adopt an original and practical thinking mode. Since it can obtain the same results with a 3D surface without constantly having to make revisions, 2D patterns can be directly corrected throughout 3D surface flattening. Factual results can be attained after considering the effect of the endurable force of fabric on the transformation of patterns. This means that the way in which to correctly release strain energy that has accumulated in fabrics is the important target of this study. Besides, a 3D mannequin, which suits traditional technology, can aid surface flattening, and many meaningful cracks can be directly generated in the right position of the surface in this process. This methodology is built in a system of computer-aided clothing design and enables the basic form of a variety of clothing style to be created via 3D mannequins. This system benefits the development of the 3D form and finds correct 2D patterns, especially when the fabric's properties are required to be in accordance with the revised outline of a 2D pattern.

A study of surface flattening based on minimum energy with the application of 3D mannequin is proposed to develop a methodology for surface flattening that can be applied to fashion design. Firstly, through the geometric feature of a 3D surface, the less transformed area can be flattened on a 2D platform by geodesics. Then, the iteration of an approximate implicit integration can be calculated real-time with a large time step. This can also release the strain energy that has accumulated in the mesh and revise the transforming degree to obtain surface flattening with minimum energy. A common way to fix this situation in some cases is cutting the mesh to further release the energy in it to enhance the accuracy of the surface flattening to make the obtained 2D patterns naturally generate significant cracks. In fashion design, the cutting line is commonly applied to present specific positions, which is strongly related to the feature lines on the mannequin. A 3D mannequin constructed by feature lines will applied to this methodology in order to achieve surface flattening that fulfils actual commercial requirements and this development is beneficial for enhancing the level of computer-aided fashion

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design. On the other hand, when different fabrics are applied to fashion design, it is necessary to revise the shape of the 2D patterns according to the properties, especially the tightness for wearing. In the proposed revised module, the outline of 2D patterns can be revised by scattering the strain energy to obtain a result with different conditions. Last, but not least, the methodology is constructed on a systematic platform for computer-aided fashion design, and case studies with common costumes will be applied to illustrate and verify the practicability of this methodology.

II. LITERATURE REVIEW

Surface flattening is one of important research issues in computer aided design in recent years. Through systematic method, 3D surface can be flattened to 2D patterns. According to the content of method, there are two kinds of methods: Geometric method and energy method. Geometric method is to flatten surface to 2D plane by preserving geodesic curvature of mesh line [1], and the deviating degree of mesh will increase with the implementation of surface flatten. Thus, in this kind of method, the revision of meshes and generation of cracks in the position of meshes shall be operated to decrease error during the process of surface flattening. For instance, in the study of Bennis et al. [2], through the rearrangement of interactive relation among points and lines on patterns, the meshes of patterns can generate the effect of releasing, thus the goal for error revising can be reached, and the result is then be applied to texture sticking in computer graphics. In order to avoid the error during the surface flattening, Hoschek replaced approximation of surfaces which ready to be flattened with developable surfaces [3]. In the studies based on energy method, the mesh is regarded as spring which can be transformed flexibly. Through the revision of mesh, the energy in mesh is effectively reduced and the result of surface flattening with minimum energy is acquired. Moreover, how to present the degree of energy in mesh and how to effectively release energy are the key points in this study. McCartney et al. [4] operated surface flattening based on concept of minimum energy, the release of energy in mesh is reached through the movement of every mesh point in X and Y axis, techniques for surface flattening such as dart and gusset are also applied to case studies in the study. In addition, Wang et al. [5] adjusted the spring coefficient of mesh to enhance accuracy of surface flattening while operating surface flattening based on minimum energy. Meanwhile, the highest gradient on energy scatter of surface is used as path for surface cutting, thus a more accurate standard for surface flattening is then proposed how to efficiently implement iteration of energy releasing is the critical issue of energy method, especially for systematic and auto calculation of iteration. Therefore, Azariadis et al. [6], [7] combined geodesic curvature and energy method to operate surface flattening. Geodesic curvature is mainly applied to flatten 3D surface, and the optimized surface fattening can be acquired by the iteration of energy function with standards of angle and length. In the end, the further accurate surface flattening is generated by revising geodesic curvature of several selected curves on surface, and different results of surface flattening will attained with different curve revision.

In recent researches of surface flattening, many innovative research methods are proposed which are different from the previous way that emphasized enhancing accuracy of geodesic curvature and minimum energy method. McCartney et al. [8] tried to apply specific texture to the operation of triangular mesh, and the better surface flattening can be generated through the application of minimum strain energy. And the distribution for tension in every direction on texture of 2D patterns can be obtained through the result of surface flattening. The analysis of interactive relation between texture and 2D patterns can then be reached. Wang et al. [9] reset the points on the surface by perpendicular and invariable geodesic curves on 3D surface. Releasing a mesh on 3D surface by a function of minimum energy, the construction of 3D mesh can be revised. Then surface developing and flattening are completed when rebuilding the whole meshes on 3D surface onto 2D platform. Through this method, not only the whole fabric model can be reconstructed on 3D surface, but also energy distribution on 3D surface can be directly presented. Zhong et al. [10] directly operated the surface developing and flattening on 3D surface, because 3D surface is developing by a rotating force generated with normal vector of mesh, and the surface can be developed as platform through reset of speed. This causes surface flattening operated without rebuilding mesh on a 2D platform. Besides, feature lines on 3D mannequin are adopted to aid surface flattening in several studies, and patterns of cloth can be developed by preserving the length of segment [11], [12], or surface of 3D mannequin can be constructed by many sections with different sizes through the division of these feature lines. Regarding the sections as individual and developable surface, not only the surface can be flattening but required patterns of cloth are also acquired [13]. Nevertheless, when facing the issue of surface flattening for flexible textures, minimum energy is the most common method mainly used in this kind of task [14], [15].

Through contents of these mentioned studies, how to efficiently and steadily release the energy of 3D energy to attain a further accurate 2D patterns is a worth researching direction. In order to apply achievement of this study to fashion design, a methodology for surface flattening that fabric behavior is also concurrently considered for acquiring design-oriented 2D patterns mainly based on minimum energy is proposed. In proposed methods, parametric methods are applied to reach the target for fulfilling condition of minimum energy. In related literatures, Euler method is mainly applied to a real-time and stable algorithm for revising error. When system reaches steady convergence, a simulation of surface flattening can be attained. Euler integral is the most direct method for calculation, but it has the unstable problem [16] and requires a small time-step for obtaining a convergent solution that makes the simulation process takes a long time to complete. To solve the unstable problem, a large time-step implicit integral method is proposed in several related studies [17]. The method can efficiently reduce the CPU cost of time in iteration, thus implicit method is regarded as the best alternative to real-time and steadily simulate energy in surface flattening mainly based on mass-spring model. Nevertheless, the implicit method has also some problems, such as the operation of a multi-step matrix is involved during the calculation process, and the real-time simulation is unable to be reached. Due to this reason, Desbrun etc. proposed the utilization of anti-matrix in the implicit method to improve the efficiency of real-time calculation, and the anti-matrix operation cannot be omitted in this method [18]. Thus Young-Min Kang etc. proposed an approximate implicit method to solve these problems in the simulation of a 3D virtual cloth and improve the efficiency of simulation [19], [20]. A bi-layer meshes method for improving the efficiency of operation to attain the real-time result is further proposed in the study [21]. In order to reach the research target, the frame of algorithm for approximate implicit integration is applied to the proposed method of surface flattening. Through the advantages of algorithm, strain energy of meshes can be rapidly and steadily released, and the simulation of surface flattening can then be real-time acquired.

III. METHOD

When 3D surfaces are flattened to 2D patterns, how to efficiently revise deforming degree of meshes is a key point in researching method of surface flattening. The calculation for surface flattening with parametric method in the viewpoint of energy is proposed in this study. The mass-spring model is applied to construct a physical model of pattern mesh, and the deforming degree of pattern mesh can be presented with strain energy. Through approximate implicit integration, the energy is rapidly and steadily released with large time steps. When iteration reaches the condition of convergence, the surface flattening with minimum energy can be obtained; the context is described as follows:

A. Mass-Spring Model

Mass-spring model is the critical foundation that makes parametric method could be applied to surface flattening, this cause deforming degree of mesh have revising reference. A 3D surface is regarded as a spring structure composed of mass and spring, and adjacent masses are connected by springs, the structure is shown as Fig. 1, including two types of spring:

1. Structural Spring: Structural spring presents the edges of quadrilateral mesh which maintains the connecting distance between each two masses in a reasonable range, to avoid the model being over stretched or compressed, as shown as the solid line in Fig. 1.
2. Shear Spring: Shear spring presents inner connection of each quadrilateral mesh; this maintains the structure of mesh after the force has impact on mesh, as shown as the dotted line in Fig. 1.

When this model is applied to the target 3D surface for flattening, the type of spring and length of spring which are ready to be constructed can be recognized and obtained from geometric information. When a 3D surface is flattened on a 2D platform, the deformation generated by mesh will lead the stretch of spring and the strain energy will then be generated. Through the effect of spring, the deformation of patterns can be revised, and accuracy of calculation can be enhanced with the release of energy.

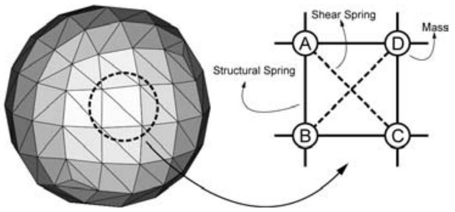


Fig. 1 The mass-spring model

B. Strain Energy

When 3D surface is flatten into a 2D pattern, strain energy and shear strain energy would be generated by the transforming of mesh, this corresponds to real situation. As shown in Fig. 2, when a quadrangle with length ℓ is stretched by the force F_x and generate the flexible displacement δ (Fig. 2 (b)), and the elastomer then generate strain energy. The energy U_x could be calculated by (1), where tensile stress presents as $\sigma_x = F_x/\ell^2$, strain presents as $e_x = \delta/\ell$, and strain energy density dU_x could be calculated.

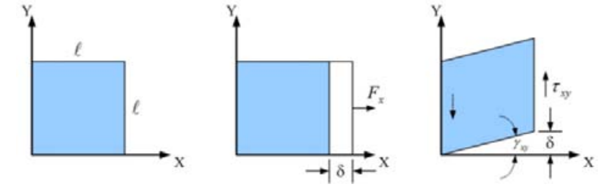
$$\begin{aligned} U_x &= \frac{1}{2}\sigma_x e_x \ell^2 \\ dU_x &= \frac{1}{2}\sigma_x e_x dxdy \end{aligned} \tag{1}$$

In addition, if elastomer generates a flexible shear strain γ_{xy} (Fig. 2 (c)) by the influence of an upper shear stress, shear strain energy U_s and strain energy density dU_s could then be calculated by (2).

$$\begin{aligned} U_s &= \frac{1}{2}\tau_{xy}\gamma_{xy}\ell^2 \\ dU_s &= \frac{1}{2}\tau_{xy}\gamma_{xy} dxdy \end{aligned} \tag{2}$$

During the process of surface flatten, the whole elastomer might be affected by tensile stress and shear stress simultaneously, thus (3) presents the unit strain energy bore by masses, and 1N·m=1J is adopted as the unit system.

$$dU = dU_x + dU_y + dU_s = \frac{1}{2}\left(\sigma_x e_x + \sigma_y e_y + \tau_{xy}\gamma_{xy}\right) dxdy \tag{3}$$



(a) Without the effect of stress
(b) With the effect of tensile stress
(c) With the effect of shear stress

Fig. 2 Transformation of elastomer

C. Approximate Implicit Integration

Approximate implicit integration is an effective solution for unstable problem of iteration, the state of masses on mesh could be continually and stably renewed by using implicit Euler method in (4).

$$v_i^{t+h} = v_i^t + F_i^{t+h}\frac{h}{m_i}$$
$$x_i^{t+h} = x_i^t + v_i^{t+h}h \tag{4}$$

In addition, *t* is the whole operating time for iteration, and *h* is the required time step. m_i presents the mass of mass *i*; F_i, v_i^t and x_i^t present force, velocity and position respectively. Nevertheless, this method involve in the thorny problem of the calculation for F_i^{t+h}, thus first-order differential (1) is adopted to simulate the problem.

$$F^{t+h} = F^t + \frac{\partial F}{\partial x}\Delta x^{t+h} \tag{5}$$

In the mentioned equation, Δx is distance among masses with connected relation. Due to partial differential $\partial F/\partial x$ is a Hessian matrix, $\partial F/\partial x$ is presented as *H* here. Because of $\Delta x^{t+h} = x^{t+h} - x^t = (v^t + \Delta v^{t+h})h$, (4) could be revised as (6).

$$\left(I - \frac{h^2}{m}H\right)\Delta v^{t+h} = \left(F^t + hHv^t\right)\frac{h}{m} \tag{6}$$

hHv^t presents viscosity forces which could be calculate by (7), and E is the set of spring connected all masses.

$$\left(hHv^t\right)_i = h\sum_{(i,j)\in E} k_{ij}\left(v_j^t - v_i^t\right) \tag{7}$$

Next, in every turn of iteration, how to acquire Δv^{t+h} and $I - (h^2/m)H$ are the two main problem of this method. Even though implicit integration is stable, the matrix involved in calculation is very time consuming. Therefore, Desbrun et al. [18] proposed an effective method to presents every determinant value in matrix H. And then, (6) could be deduced as (8).

$$\Delta v_i^{t+h} = \frac{\tilde{F}_i^t h + h^2 k \sum_{(i,j)\in E} \Delta v_j^{t+h}}{m_i + kh^2 n_i} \tag{8}$$

$\tilde{F}^t$ is the sum of spring force and viscosity forces, that means $\tilde{F}^t = F^t + hHv^t$. Although (5) has unknown velocity difference Δv_j^{t+h} which connects the related masses. Calculate Δv_j^{t+h} by (8), and after the calculation of continuous coefficient h^2k, viscosity difference for related mass of mass j has rarely effect on viscosity difference of mass i, so that could be omitted and approximation of Δv_j^{t+h} could be:

$$\Delta v_j^{t+h} \cong \frac{\tilde{F}_j^t h}{m_j + h^2 \sum_{(j,l)\in E} k_{jl}} \tag{9}$$

Finally, after stiffness constant is adopted the acquired equation is as follows:

$$\Delta v_i^{t+h} = \frac{\tilde{F}_i^t h + h^2 k \sum_{(i,j)\in E} \tilde{F}_j^t h \Big/ (m_j + h^2 k n_j)}{m_j + h^2 k n_i} \tag{10}$$

In the equation, n is the spring number among connected and related masses, which also relates to the adopted physical model.

Through the mentioned method, after every turn of iteration, the mass position in pattern could be simultaneously renewed to revise the error of primary surface flatten. Meanwhile, in order to effectively judge if simulating calculation is stable, (11) is adopted to be the reference for judgment of convergence. When iteration of surface flatten reach the condition of convergence, the result of surface flatten with minimum energy could be obtained.

$$\frac{\left|\Delta\mu_{t+h} - \Delta\mu_t\right|}{\Delta\mu_t} \le \varepsilon \tag{11}$$

Besides, $\Delta\mu$ is difference of total energy for mesh in iteration, and ε is defined threshold of convergence.

IV. CASE STUDIES

Surface flattening is a quite important research issue in the field of computer aided fashion design, the application of 3D mannequin aided fashion design for surface flattening based on minimum energy is proposed in the study, the context is illustrated as following:

A. Form Design Mainly Based On 3D Mannequin

In fashion design, mannequin is an important medium for realizing design concept. Mannequin not only makes fashion design be directly operated on the model but also the basic patterns for design requirement be measured. The various forms can be further generated to obtain platforms of patterns that correspond to the design concept. When a 3D mannequin based on feature lines is reconstructed (Fig. 3 (a)), the 3D form required to design task is available from each brick on 3D mannequin. When the developed products is dress, the 3D forms compose of related bricks can be selected as shown in Fig. 3 (b); if the case is T-shirt, the 3D form and related bricks set can only be selected as shown in Fig. 3 (c). Various different 3D forms can be generated by further shape blending that based on a brick-piling data structure; Fig. 3 (d) presents a new form blended by each feature profile on 3D form. Through this mode, different form designs can be processed by the basement of original form.

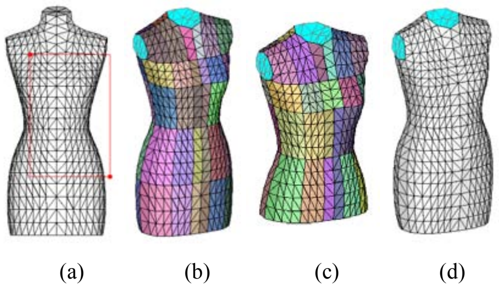

(a) (b) (c) (d)

Fig. 2 The generation of required 3D forms based on 3D mannequin (a) a 3D mannequin based on feature line (b) required 3D forms for dress design (c) required 3D forms for T-shirt design (d) a new form blended based on each feature profile

B. The Flattening for 3D Surface to 2D Patterns

When 3D form design is achieved (Fig. 4 (a)), the 3D surface that allowed surface flattening can be selected again from the 3D model (Fig. 4 (b)). Even though cloth is sewed by various 2D patterns, the process contains basic mode for pattern cutting to attain standard pattern. Then 3D surface can be flattened to 2D platform by geodesic method, because form is normally constructed by feature profiles along one direction. The surface is derived from 3D mannequin based on feature lines, selecting the original feature line as the datum line for surface developing from the processing direction of feature profiles are a solution corresponding to real requirement of design task. This leads points on profiles develop from the two sides of datum line to the parallel outsides, as shown in Fig. 4 (c). In addition, this is an initial result of surface flattening in an unnatural condition, the strain energy of mesh has to be released through numerical method, and 2D pattern with minimum energy can further be calculated by iteration (Fig. 4 (d)). In this study, the iteration of an approximate implicit integration can be calculated real-time with a large time step. This can also release the strain energy that has accumulated in mesh and revise the transforming degree to obtain surface flattening, as shown in Fig. 5.The strain energy of mesh can still be released when inputting the larger time step into the iteration. Through this mode, the surface on 3D mannequin can be completely flattened to 4 basic patterns (Fig. 6). These patterns can be applied to design method of plane cutting, and the mesh line on patterns can further offer related information of coordinate for 3D surface and 2D pattern, this makes the application of fashion design method quite practical.

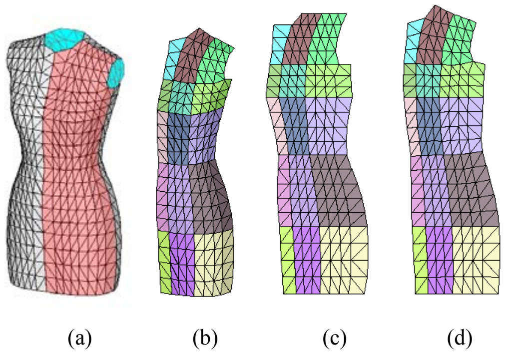

(a) (b) (c) (d)

Fig. 3 The process of 3D surface flattening to 2D pattern (a) The acquired 3D form (b) 3D surface for flattening (c)Primary development of 2D pattern (d)2D pattern with minimum energy

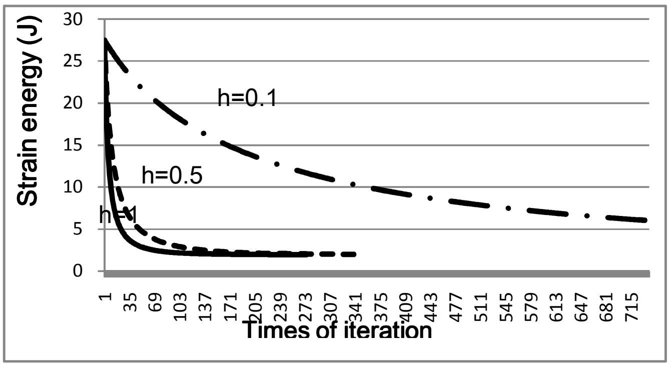


Fig. 4 An approximate implicit method with stability

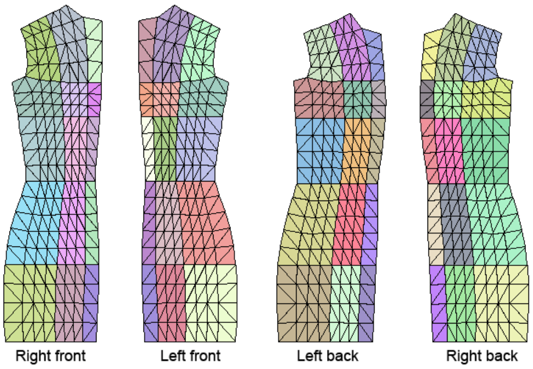


Fig. 5 Four basic patterns on 3D mannequin

C. Surface Cutting

In some cases, cutting mesh to further release the energy is a common way to fix the situation and enhance the accuracy of the surface flattening, and this makes the obtained 2D pattern naturally generate significant cracks. In this study, in order to make the result of surface flattening corresponds to the requirement of real design task, each feature line on 3D surface is an important reference for selection of cutting position, because 3D surface is derived from 3D mannequin based on feature line, this leads common cutting position be presented on the flattened 2D pattern. When implementing surface cutting, the distribution of strain energy can offer the strongest reference for mesh revision (Fig. 6 (a)). Through information of energy distribution, form of chest is the mainly and highly deforming section in the pattern. Therefore, selecting the features line related to chest as cutting line is a better solution for this situation. In Fig. 6 (b), the energy release after surface flattening is conducted based on cutting line A and B separately in the study. Through the iteration of energy release, the 2D patterns as Figs. 6 (c) and (d) are separately acquired; crack in pattern is naturally generated due to the energy release of mesh. At meanwhile, the strain energy is decreased from initial 1.66(J) to 1.32(J) and 1.16(J) separately. Although the degree of energy release is not the only solution for this issue, the information that presented on distribution of strain energy benefits decision making for surface cutting, especially when cloth design contains curves that fitted human body.

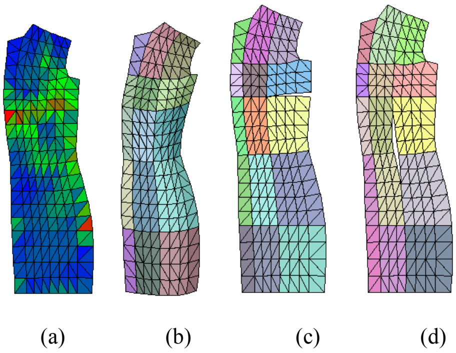


Fig. 6 The mode of surface cutting (a) Energy distribution of pattern (b) Cutting on 3D surface (c) Cutting line based on feature line of chest (d) Cutting line based on segment of princess line

V. CONCLUSION

Surface of 3D mannequin is directly developed to 2D patterns, and the adopted parametric method can steadily release strain energy that has accumulated in mesh. This can not only enhance the accuracy of surface flattening but also acquire different platform of patterns with fabric behavior. The specialty is the coordination of energy distribution, the interactive relation between 2D pattern and 3D surface can be realized which determines the wearing tightness for pattern manufacturing. When operating the mesh cutting, the distribution offers strong reference. Through the application of 3D mannequin, the cracks generated due to cutting will obtain the result corresponding to the factual fashion design. Meanwhile, the further consideration for the effect of material properties on surface flattening is a quite important issue which can lead 2D patterns corresponding to design requirements to be developed. This benefits the development of cloth products; especially the accuracy of flattening in fashion design is not the only concern. This makes designed form can be directly developed into practical 2D pattern in a 3D simulation system.

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