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Processing of Bars-Converging Joint and Engineering Application

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***Abstract*-The complex structure of the shaped surface formed by a kind of bars-converging single-layer reticulated shell joints is analysed, and the characteristic of higher precision in production is considered, the patter decomposing – patter processing - patter assembling –patter casting joint processing flow is put forward. According to the joint design data, the joint spatial axis model is built, the spatial orientation description method is proposed, the developed SolidWorks 3D drawing software is used to import the design data to visualize the joints in 3D model. According to the joints splitting and assembling principle, the mathematical model of joint processing is derived, based on the mathematical model, the joint processing equipment based on the TriVariant series robots is developed, the real time control of the joint NC machining system is implemented. The results of this research have been verified in the large complex steel structure building of the Sun Valley for Shanghai World Expo and the roof of Star Mall in Shenyang, now the research is being used in the Cell Wall of the new natural museum in Shanghai which is under construction.**

Keywords-reticulated shell joint; 3D model reappearance; splitting and assembling; TriVariant series robots; engineering application

I. INTRODUTION

Spatial reticulated shell structure is a kind of architectural structure connected by spatial bars with multiple joints, in order to adapt to the changing space angles, a type of bars-converging joint for single-layer reticulated shell appeared[1].As shown in Fig. 1,this type of joint has many advantages, such as the shape can be changed with the overall surface of the building, and can be connected easily with bars with various special-shaped sections (such as triangle, rectangle, trapezoid), so it can constitute a variety of fashionable spatial curved surface of architectural modeling, it becomes an important development trend of the highly decorative spatial reticulated shell structure building[2] .

In order to satisfy the whole smooth surface and continuous changes, joints for reticulated shells have different shapes and complex space angles. Through topological mesh the single layer netrack is composed by triangular grids, each grid is mutual restricted, each joint has at least four brackets, each bracket is connected with other components[3]. Any bracket has little error, it will affect the installation of the components, so the joint itself requires high machining precision. At present, at home and abroad the production

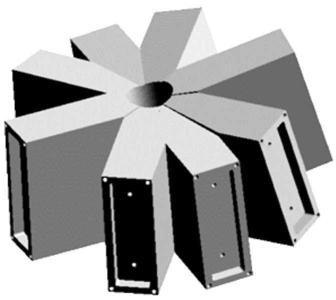

Figure 1. Bars-converging reticulated shell joint

methods of the bars-converging single-layer reticulated shell joint can be put into the following two categories:1）CNC cutting- assembling-processing, this facture process of joints has been applied in the latticed dome of the London Shopping Center called Beispiel Westlife (Fig. 2)by SEELE, a German company. The basic process is firstly steel plate cutting, edge processing and forming different units by pressure,

Figure 2. Beispiel Westlife Shopping Center

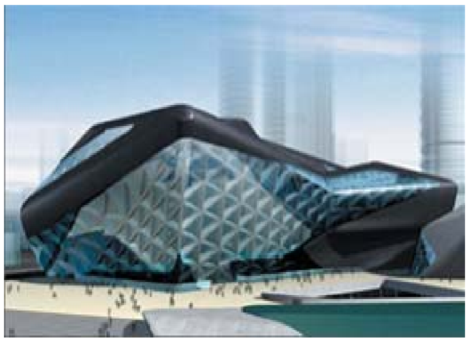

Figure 3. Guangzhou Opera House

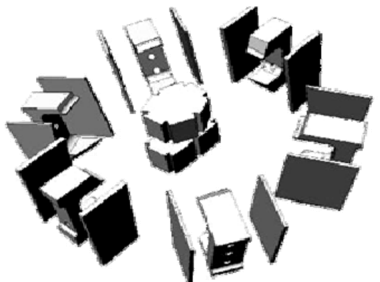

Figure 4. CNC cutting-assembling processing

then the next step is assembling, using clamping fixture for welding, finally the last step is completing the machining of surface / hole combined with bars using 5 axis machining center, as shown in Fig. 4. As the reticulated shell structures often contain thousands of different geometry joints, and each joint is divided into several units, it requires a lot of pressure molding and welding clamping fixture, so it results in high difficulty in joints production, high complexity in information management, high cost, low processing efficiency. In addition, it is difficult to guarantee the manufacturing accuracy.2) Patter processing-casting-processing, this process of joints has been applied in the national stadium Bird's Nest in Beijing for 2008 Olympic Games and Guangzhou Opera House. First the joint mould is made, then the next step is getting the joints semi-finished products by using precision casting, finally the last step is completing the machining of surface / hole combined with bars using 5 axis machining center[4]. Compared with the first method, this process needs mold making for each joint, if there is no quick, low cost molding technology and equipment available, this process can also lead to low efficiency, high cost, poor precision. In the Guangzhou Opera House project (Fig. 3), the sand casting is used in the step of mold making, as it needs a lot of wood patterns, the working efficiency is low and the production cost is high. It also leads to the difficulty in mold making and complex angles formation. So this research adopts the lost foam casting, which can raise the efficiency, lower the cost and guarantee the required precision.

In order to solve the engineering difficulties and make up for the previous study defects, this paper presents a joint processing method which includes deepen design- patter decomposing – patter processing - patter assembling–patter

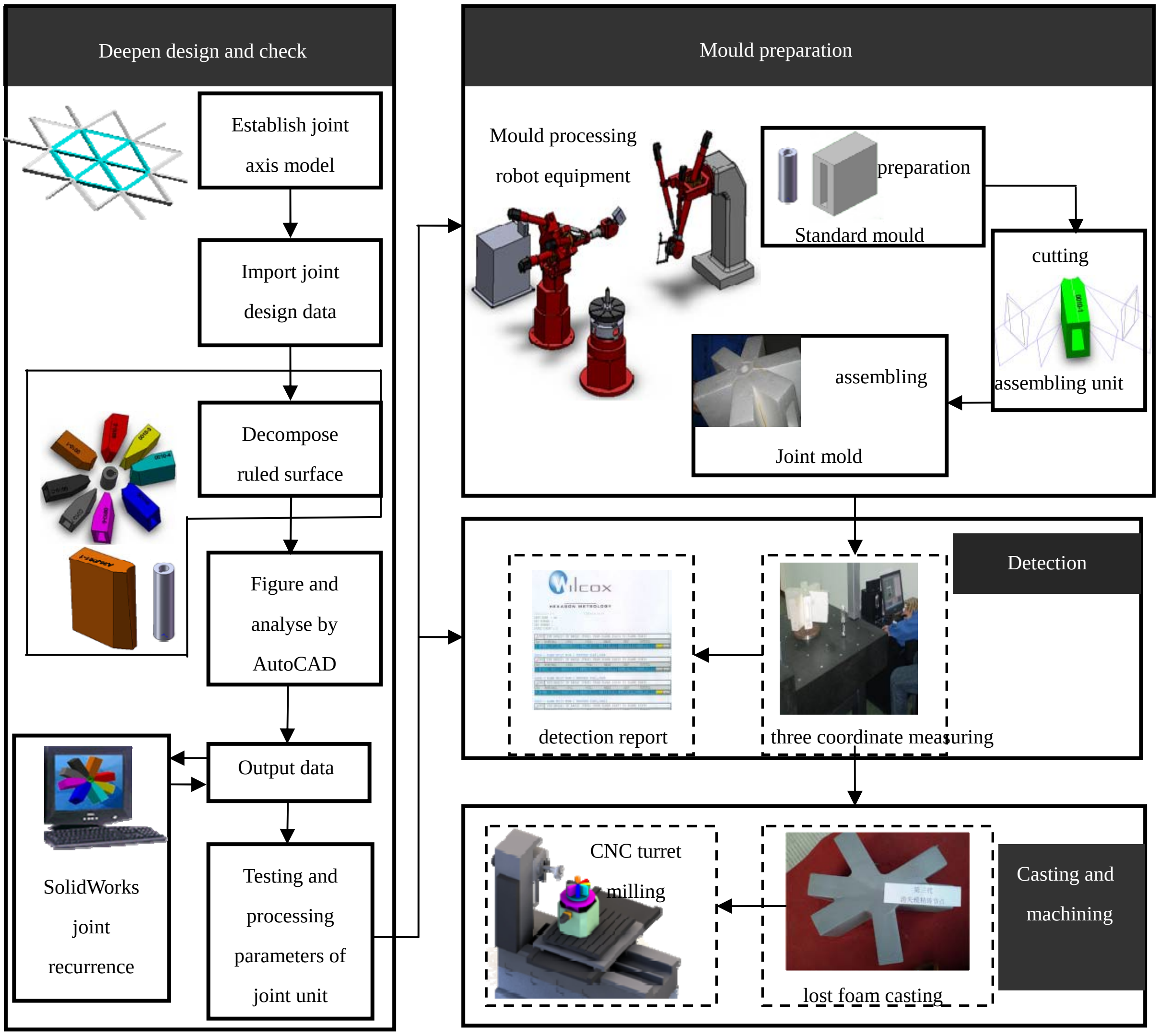

Figure 5. Joint CNC processing flow

casting- machining. At first the key point coordinates of the bracket is extracted from reticulated shell structure axis model, based on the developed SolidWorks software the joints are visualized in 3D model and virtual preassembled to verify the joint deepen data, then according to the principle of joint splitting - assembling, the method of ruled surface for parting and positioning is used, with the 5 degree of freedom TriVariant series hybrid robots as the joint mold processing equipment, the cutting and assembling of joint mould is completed.

II. JOINT PROCESSSING FLOW

According to the bars-converging single-layer reticulated shell joint processing project, this paper proposed a joint NC machining process based on the multi functional robot.

Steps are as follows: At first the joints are deepen designed, the axis model of bars-converging single-layer reticulated shell structure is set up, the initial designed coordinate parameters and dimension parameters of all joints and bars are input into the computer, and each joint is divided into a number of tectonic units, AutoCAD is used to figure and analyse, the size data and processing parameters of each unit are gotten, by the programming language VC++ , Solidworks 3D drawing software is developed, every joint in 3D model is visualized based on the size data and processing parameters, the correctness of joint deepen data is verified. Then the size data and its processing parameters after testing of each joint structure unit are input into the joint processing robot CNC equipment, the robot is controlled to complete the cutting and assembling of joint mold units, three coordinate measuring instrument is utilized to detect the size and accuracy of the joint mold, the detection report is gained. Finally the qualified joint mold after measuring and testing is obtained, through the lost foam casting process, the molten steel is casted, through machinery processing the prepared products are obtained by using the CNC turret milling.

The process for joint products has many advantages, such as good mechanical properties, low production cost, and it can guarantee the required precision, the joint processing flow is shown in Fig. 5.

III. JOINT SPACE ATTITUDE

In order to unified describe the spatial different joints, the characteristic that a large number of joints are similar but not identical is used. For every different joint, the joint number of

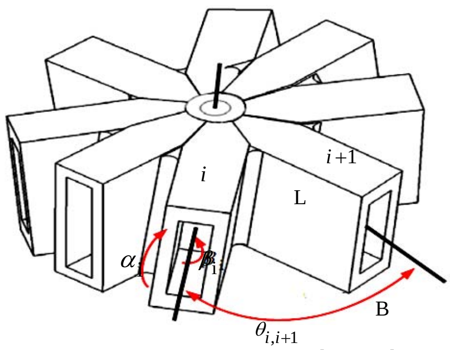

Figure 6. Joint space angle attitude

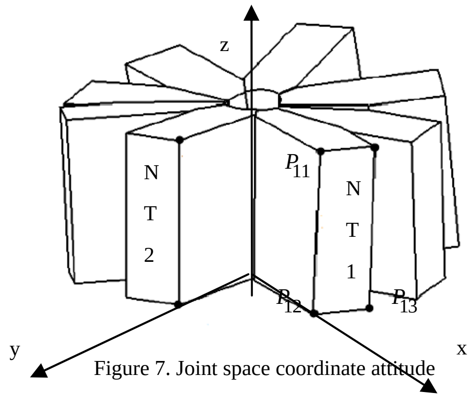

Figure 7. Joint space coordinate attitude

unit N and the pitch angle α_i 、the torsion angle β_i and the angle of circumference between units $\theta_{i,i+1}$ (Where i is the joint unit number)and bracket unit length L and width B are used to describe the joint spatial attitude, as shown in Fig. 6, But in actual machining, in order to be measured and expressed easily, this study uses joint end face point coordinates to describe the spatial attitude. According to the joint spatial attitude, the coordinate system $O-xyz$ is established ,the point O is the point of intersection in the theory diagram model, as O is the origin, the axis of the center column is axis z, upward is positive, according to the clockwise direction (z upward direction) to define each joint unit NT-1、NT-2、……、NT-i（determined by the unit quantity）,the bottom center line of the numbered NT-1 unit is the axis x, the direction departs from the central cylindrical axis and points outwards. In accordance with the right-hand rule in Cartesian coordinate system to determine the y axis direction, the joint model is shown in Fig. 7. According to the joint initial designed space attitude angles and the bracket unit parameter data, the three vertices coordinates on every rectangular cross section of the numbered joint in the coordinate system $O-xyz$ are figured out(as P_{11}, P_{12}, P_{13} in NT-1）,a total of 3i vertices coordinates can express the positional relationship between each unit and the space angle relation in the same joint.

IV. JOINT THREE-DIMENSIONAL REAPPEARANCE

In order to meet the requirement of high precision of joints, it needs to test and check the deepen design data, the programming language VC++ is used to develop SolidWorks 3D drawing software. According to the characteristics that the joints are similar but not identical, by dimension driving method, the joint model structure is maintained unchanged, all the dimension which affect the model structure are defined as the dimension variables, by means of giving these dimensions variables with different values, it is able to obtain a series of a different sort of junction joints with identical structure and different sizes.

The concrete steps are as followed: In Visual C++ 6 integrated developed environment for programming, through the dynamic link library DLL and SolidWorks API functions

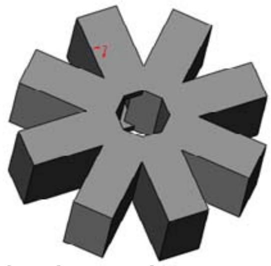

Figure 8. Three-dimensional reappearance results

to develop SolidWorks software, then the data tables which contain batch joint features are imported into the 3D drawing software automatically, automatic batch drawing is carried out, the joint model is reconstructed, at last virtually the reticulated shell structure model is assembled in advance, the initial visual inspection of joint and structure is realized. Because of the visualization and intuitionism of the model, the joint data with obvious errors can be found, reappearance results are shown in Fig. 8.

V. JOINT SPLITTING-ASSEMBLING PRINCIPLE

Joint splitting - assembling principle which is adopted in this paper is that the joint are split into assembling units and the cylinder which is connected to each unit, the split surface between the unit is the angle bisector plane, the robot is used to cut the standard module into the assembling units, and with circular arc and plane surface to position each unit and the units are combined into complete joint mold.

The processing of each unit of joints is the cutting of the angle bisector plane and cylindrical ruled surface of the standard foam mold, the key technology is the transformation from the ruled surface mathematical expression in space to the trajectory data of the processing equipment. The overall principle of robotic cutting: Through the geometric relationship, the space equation of processing ruled surface in the joint coordinate system can be obtained, the conversion between joint coordinate system, workpiece coordinate system and processing device coordinate system is created, equipment's trajectory control data is gotten by post processing ,the end-effector space pose when cutting ruled surface can be obtained, the track pulse is input into the servo control system, the robot servo control is realized.

Standard module cutting mathematical principle: the center cylindrical surface equation and each unit's two plane equations are united, two arc α and β equations can be obtained. Similarly the space plane equations are united, the angle bisector planes λ_1 and λ_2 equations can be obtained. Considering that the joint cutting data is easy to use and express, in each unit corresponding vertex the coordinate system $O'-x'y'z'$ is established, as shown in Fig. 9. According to the coordinate system conversion, the rotation matrix can be expressed as ***R***=

$$\begin{bmatrix} \sin\theta_1 \sin\theta_2 & -\cos\theta_2 & \cos\theta_1 \sin\theta_2 \\ \cos\theta_1 & 0 & -\sin\theta_1 \\ \sin\theta_1 \cos\theta_2 & \sin\theta_2 & \cos\theta_1 \cos\theta_2 \end{bmatrix}$$

The θ_1 and θ_2 are the attitude angle of the joint unit. Coordinate translation vector $P = \overrightarrow{OP_{4-2}} = \left[x_0, y_0, z_0\right]^T$ .The coordinate transformation equation is T

$$T = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix}$$

So the relation is $T^{-1}\left[x \quad y \quad z\right]^T = \left[x' \quad y' \quad z'\right]^T$

Similarly, with the intersection method the equation of cylindrical surface and each unit plane in a new coordinate system $O'-x'y'z'$ can be obtained, then the equation of intersecting lines between upside and downside section and the cylinder surface α' and β' can be obtained, and the equation of $\lambda_1{}'$ and $\lambda_2{}'$ which is the angle bisector planes by adjacent bracket units intersecting in the new coordinate system $O'-x'y'z'$ are achieved. Thus the spatial vector and the position which the robot end effector needs to arrive at in the unit coordinate system $O'-x'y'z'$ can be expressed.

In actual production, in order to control the cutting trajectory of the cutting robot, it needs to transform the measurement of joint mold unit ruled surface for processing (two spatial surfaces and a cylindrical surface) in the unit coordinate system $O'-x'y'z'$ to the same reference coordinate system with the cutting robot, the space relation between the two coordinate systems is shown in Fig. 10, the rotation matrix is R,

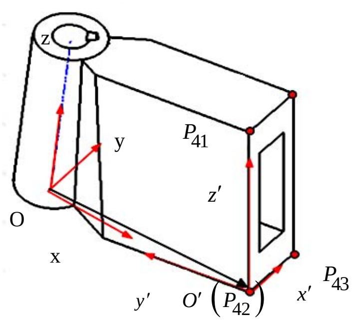

Figure 9. Joint coordinate system conversion

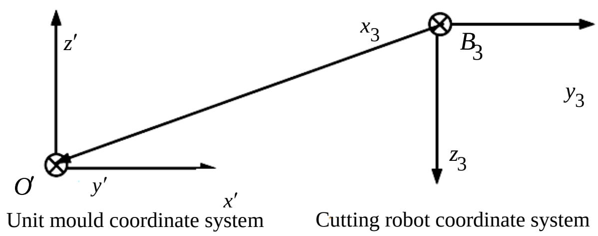

Figure 10. Relation between unit mould coordinate system and cutting robot reference coordinate system

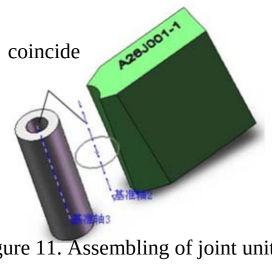

Figure 11. Assembling of joint unit mold

$$R = R(x_3, 180^\circ)R(z_{3'}, -90^\circ) = \begin{bmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

Translation vector $P = \overrightarrow{B_3O'} BO$, the space vector L_i and position E_i which the end executor needs to reach in the cutting robot reference coordinate system $B_3 - x_3y_3z_3$ respectively are $L_i = RL_i{}', E_i = RE_i{}' + P, (i = 1, 2 \ldots n)$

Where n is the number of sampling points, $L_i{}'$ and $E_i{}'$ respectively are the space vector and the end position of the end-effector needs to arrive at in the unit coordinate system $O' - x'y'z'$.

Through this two quantities and the robot inverse kinematics model, the relevant parameters of the branched chains and the joint angle values of TriVariant-A cutting robot can be obtained for completing processing, thereby the robot control during the cutting process is realized[8] .

Unit assembling process is essentially the process that the TriVariant-B robot module terminal control unit axis is coincident with the center cylinder axis by means of the rotary with the single degree of freedom platform to the assembling area, as is shown in Fig. 11. When the center cylinder axis of joint mold is expressed as $S = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$ in the coordinate system O - xyz ,the vector $\overrightarrow{P_{42}P_{41}}$ is the robot target vector, point P_{42} namely is the target point. Similar with the cutting process of mold unit, in the assembling process, each vector is required to be measured in the robot coordinate system, in order to convert to the robot recognizable data, through the inverse kinematics solution for assembling robot, as is similar with the coordinate system transformation in the cutting process, so is not discussed here.

The joints splitting -cutting - assembling process method not only realizes joint batch production, but also transfers the processing difficulty to the digital cutting of various unit's bisecting planes and curved surfaces, the arc and planes are used for positioning to ensure the precision of the joint shape. Finally through the lost foam casting the joint processing is finished.

VI. CONCLUSION

This paper presents a method based on the basic idea of joint NC processing process flow which includes deepen design- patter decomposing – patter processing - patter assembling –patter casting- machining, the developed SolidWorks software is used to carry out the batch joints three-dimensional reappearance, and to test the correctness of the deepen data, the joint mold cutting- assembling model is established, on the basis of the mathematical model the

Figure 12. Robot equipment for processing joint mold

Figure 13. Shanghai World Expo Sun Valley

Figure 14. Star Mall in Shenyang

Figure 15. The design sketch of natural museum in Shanghai

control of the robot end-effector pose is realized. The robot NC equipment(Fig. 12) for processing the joint mold is used to complete cutting and assembling. The novelties of this method are as followed:1)The application of the TriVariant series robots in the mold cutting and assembling; 2)The utilization of lost foam casting in producing joints;3)The proposal of the whole process flow for bars-converging joints. Based on the multi functional robot, the digital joint manufacturing process has been successfully applied in the Sun Valley in 2010 [8] (Fig. 13)and the roof structure of Star Mall in Shenyang in 2011(Fig. 14). In addition now the Cell Wall of the new natural museum in Shanghai is under construction by using the results of this research (Fig. 15). It proves that this joint processing method not only reduces the joint production cost, but also improves the production efficiency, and it creates favorable conditions for the development of spatial reticulated shell structure technology.

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