16th Mitsubishi Electric Cup Automation Contest
(Proposal for the Creative Design Category)

Name of entry: "Blue and White"
— Intelligent Underglaze Porcelain Painting System

Team code: d9y9z5hc

Participating school: Zhejiang University

Supervisors: 昊敏、朱新傑

Team members: 王亦楠、張世琦、王俊傑

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1. Background of the Project Design

"Jingdezhen is an excellent ceramic production center, but it does not produce ceramic craftsmen. Craftsmen come to Jingdezhen from throughout the country and spread ceramics nationwide." China's traditional ceramic craft has always been considered a vital element that speaks of the development and spiritual ethos of the Chinese civilization.

Underglaze porcelain is a type of ceramicware. A painting design is first drawn on the white base surface of a semi-finished product with ink, coated with glaze, and fired in a kiln at high temperatures. The surface is glossy, smooth, and adorned with a poem or painting. Implements that **possess both artistic and material values** have already come to be universally accepted as artworks accompanying the development of large-scale assembly-line productions in the modern pottery and ceramics manufacturing industry. They deserve to be promoted further.

However, as far as traditional crafts go, **the industry as a whole has been forced to undergo a severe internal reorganization** during the period when measures against the COVID-19 pandemic have become the new norm. Due not only to the lack of craftsmen who specialize in underglaze painting, but also to the fact that the completely manual task is costly, time-consuming, physically demanding, and hard to pass down, hopes of its survival are pinned on investments in production based on new generation information technologies such as automation, digitization, and artificial intelligence[1].

Today, the development of culture and tourism is being promoted under the 14th Five-year Plan. Against the backdrop of this era of major cultural development, demand is growing for **"crafts that accord with the times"** in new industries and economic models. Greater emphasis is being placed on the differentiation and integration of diverse resources in the new era "beyond conventional boundaries," and a trend toward customized consumption and atmosphere-driven consumption is also strengthening within the development of underglaze painting.

Mitsubishi Electric automation products boast an advantage particularly with respect to six-axis industrial robots and servo control systems, which are significantly more stable and capable of realizing higher speed control compared to other brands. They also allow flexible configurations and provide strong technical support.

The "Blue and White" Intelligent Underglaze Porcelain Painting System designed by our team is based on the body structure of a Mitsubishi Electric industrial robot and incorporates new science and technology industry resources such as a WeChat mini program and artificial intelligence. By integrating a differentiated design and intelligent painting process, **the system not only promotes the upgrading of the traditional ceramic industry by automation, digitization, and artificial intelligence, but it also contributes to protecting the dignity of the traditional culture and the inheritance of the cultural heritage of the people.** Furthermore, it satisfies needs for the differentiation of ceramic products, enhances the originality of the culture, and **boosts the integration of globalization and localization of China's ceramic arts.**

2. Features of the Project Design

2.1 Realization of traditional brushwork and procedure based on the specialized techniques of private craftsmen

Through careful surveys, research, and design, the "Blue and White" Intelligent Underglaze Porcelain Painting System drew fully upon the experience and techniques of traditional underglaze painting. Using a Mitsubishi Electric industrial robotic arm that delivers high precision and controllability, continuous adjustments were made so that the angles at which the brush is lowered and the thicknesses of the painted lines preserve the fascination of the brushwork, based on users' painting needs. At the same time, the hand-painting technique of using a brush to paint intricate designs, was also incorporated. By stroking the brush tip numerous times, a smooth tip was shaped so the amount of ink absorbed by the brush may be controlled when dipping the brush in ink.

2.2 Customization of traditional painting designs by embedding a mobile WeChat mini program

Based on our system operation scenario and users' differentiation needs, we designed an original WeChat mini program called "Zhejiang Blue and White Painting." The program lets users select the size of the white ceramicware mold and the colors and thicknesses of the painting brush, and when the image to be painted in a specified area is uploaded, it automatically extracts the image data using a background algorithm. By strengthening users' emotional experience and radially expanding the application scenario, the program transforms users from bystanders to participants, and lowers barriers to engaging in ceramic painting.

2.3 Development of an algorithm for image data extraction, intelligent transmission of principal parameters

To acquire the color and line data of an existing image in a network, we performed a series of operations on the image, including edge extraction, rasterizing, connectivity analysis, and color recognition. We then developed an image processing algorithm for extracting image data. With the mini program, image data is extracted via a background algorithm.

2.4 Designing a path planning file algorithm, precise control of the path of lowering the brush

With regard to the planning of fixed paths such as changing brushes, changing colors, and ink dipping, we used a demonstrator to perform a demonstration of rational positions, then executed a path plan using the linear and joint interpolation methods for the robotic arm. When planning the painting path, we processed the image data acquired in the background to generate a series of spline files and imported the spline files into RT ToolBox3 for spline interpolation to control the painting path of the robotic arm. In this process, we realized three types of brush touches—thick, medium, and thin—by using Python to correct the coordinates in the spline files, and we achieved a painting effect resembling a human hand with the robotic arm by meticulously designing the beginning, middle, and end of brushstrokes[2].

2.5 Addition of a servo motor as a user machine, flexible changing of the angle of the ink tray

In the system, we added an axis to the robotic arm and created an intelligent rotary axis painting platform with a servo motor as the user machine. As a result, the host computer runs on a motor via a controller, and the fixing and rotating of the ink tray is controlled via transmission using a helical gear mechanism. This reduced the workload and complex control of the robotic arm and completed the process of changing specific colors.

3. Overall Draft Design of the Project

3.1 System architecture

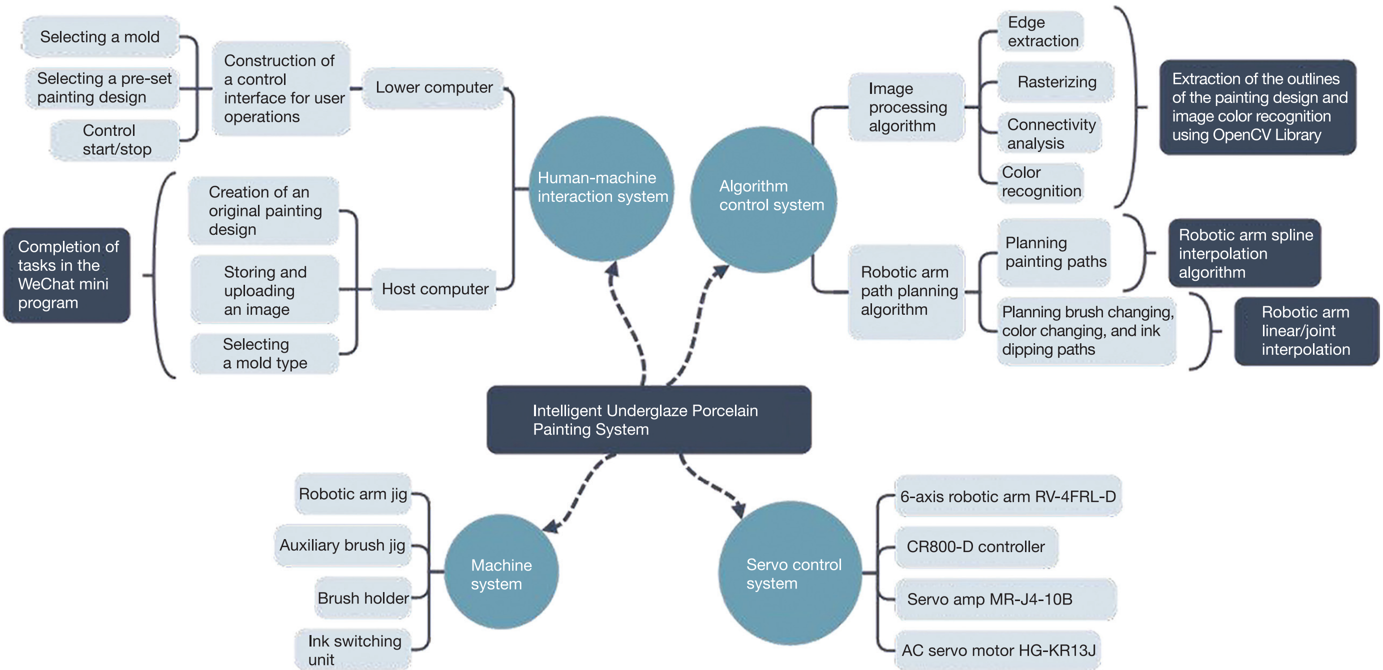


Fig. 1 System architecture

The Intelligent Underglaze Porcelain Painting System is composed of four sub-systems, a human-machine interaction system, servo control system, algorithm control system, and machine system.

The human-machine interaction system contains two main components: a host computer and a WeChat mini program. Through the WeChat mini program "Zhejiang Blue and White Painting," users can select the type and size of the mold and the colors and thicknesses of brushes, create a differentiated painting design, and import that design into a host computer. The host computer component includes a control interface that can control the start and end of the painting process in real time and monitor the program's execution process.

The servo control system comprises the RV-4FRL-D six-axis robotic arm, CR800-D robot controller, MRJ4-10B servo amp, and HG-KR13J AC servo motor. It allows for simultaneous and flexible control of the movements of the robotic arm and motor via a robot controller, making it possible to simulate manual painting and production scenarios[3].

The algorithm control system is mainly composed of an image data extraction algorithm and a robotic arm path planning algorithm. The image data extraction algorithm is used to extract data on the position of each brushstroke within an image, and the path planning algorithm is used to design and generate spline files based on the extracted image data. By importing the generated spline files into RT ToolBox3, appropriate robotic arm paths are generated.

The machine system includes a robotic arm jig, auxiliary brush jig, brush holder, ink switching unit, and a porcelain plate holder. The robotic arm jig and auxiliary brush jig maintain the brush in proper position. The brush holder mainly facilitates the changing of the robotic arm brush, and the ink switching unit is central to changing brush colors. The porcelain holder helps to paint each mold in the same position.

3.2 Process design

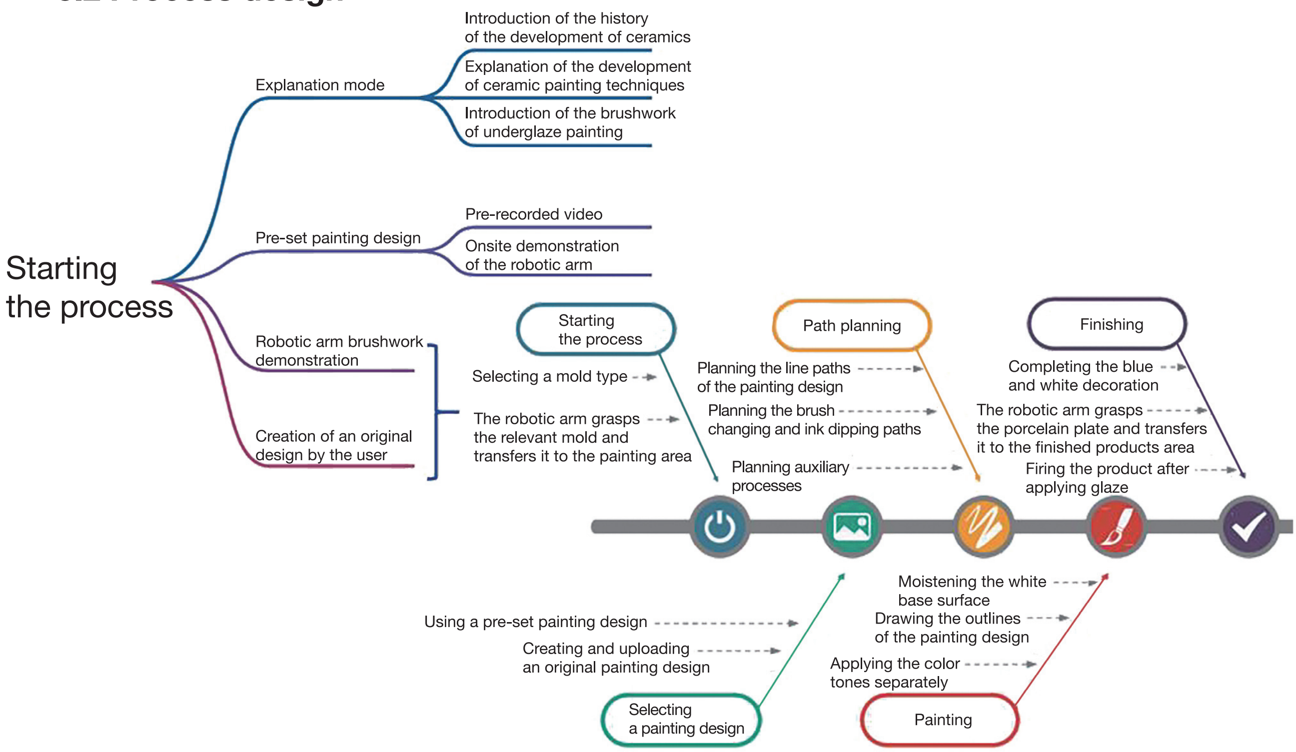


Fig. 2 Block diagram of the entire process

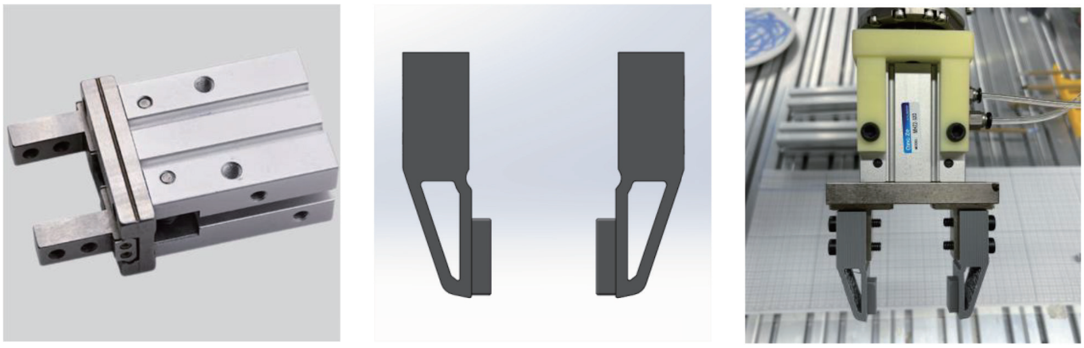
The entire process of the project: As shown in the figure, the Intelligent Underglaze Porcelain Painting System offers a selection of multiple models. Here, we focus on the model in which the user creates an original drawing. The user opens the WeChat mini program, selects the mold size and the colors and thicknesses of the paint brushes according to the usage instructions, and designs and uploads an original painting design. When painting preparations are completed, the host computer calls up the image data extraction algorithm and robotic arm path planning algorithm to extract parameters, optimize paths, perform spline interpolation, and plan the paths for the painting design uploaded by the user. Ultimately, a prg file that is recognizable by the robotic arm is generated and sent to the robotic arm. Thereafter, the robotic arm follows the planned path and paints the user's design stroke by stroke in the order drawn by the user.

The system provides three types of molds and multiple pre-set painting designs to choose from. When creating the system, 3D modeling was performed for the three mold types, and the paths for the pre-set painting designs were planned and stored in a lower computer.

3.3 Machine design

3.3.1 Robotic arm jig and brush jig

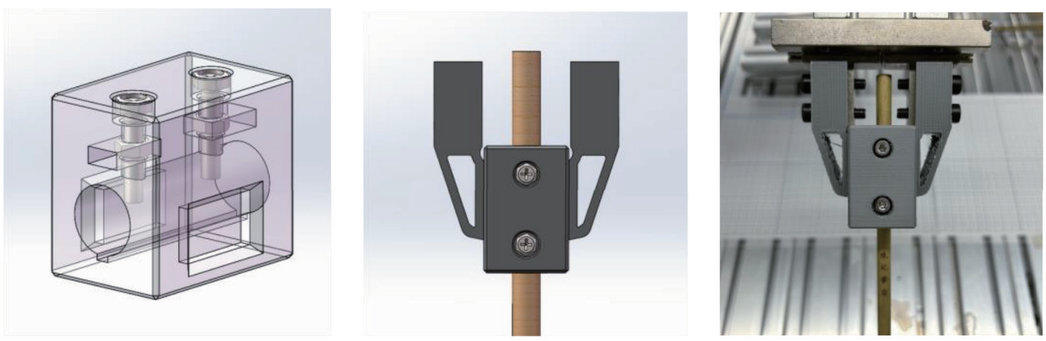
In this project, an MHZ2-32D finger cylinder was used as the work end of the robotic arm, and a corresponding extension gripper was designed and 3D-printed. The tip of the gripper features a rectangular protrusion for precise positioning and secure gripping by the robotic arm[4].



(a) MHZ2-32D finger cylinder (b) Extension gripper (c) Actual assembly

Fig. 3 Robotic arm jig

The brush jig and robotic arm extension gripper must interlock with each other, so an auxiliary brush jig was designed as shown in design drawing 2(a). It is rectangular and has a circular through-hole in the center to accommodate diverse brushes. A recessed groove at the bottom of the hole restricts the rotation of the brush and contributes to holding it in position. Above the hole are bolt holes and nut holes for thread locking, to strictly restrict the position of the brush. On both sides of the jig, there are indentations that perfectly match the protrusions on the robotic arm extension gripper to prevent slight misalignments caused by positioning errors. The protrusions on the extension gripper are filleted and the edges around the indentations on the auxiliary jig are chamfered to increase positioning fault tolerance when gripping and securing the brush.

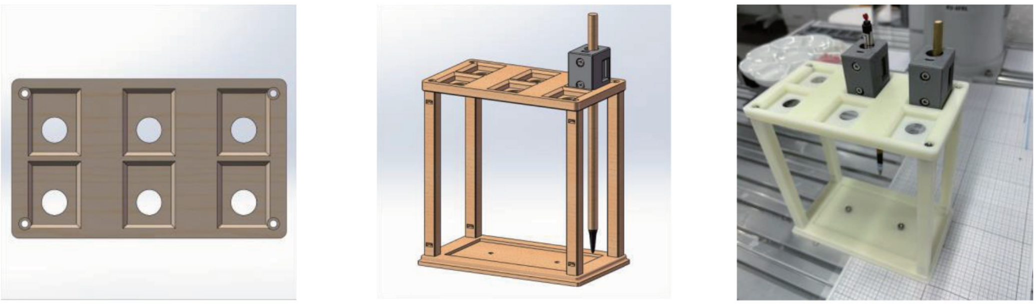


(a) Auxiliary brush jig (b) Securing simulation (c) Actual assembly

Fig. 4 Brush jig

3.3.2 Brush holder

To easily secure the brush to the robotic arm, we designed a dedicated brush holder. As shown in Fig. 3, the holder has six positions, each designed to accommodate brushes of different standards. To prevent positioning errors, the grooves are similarly chamfered.

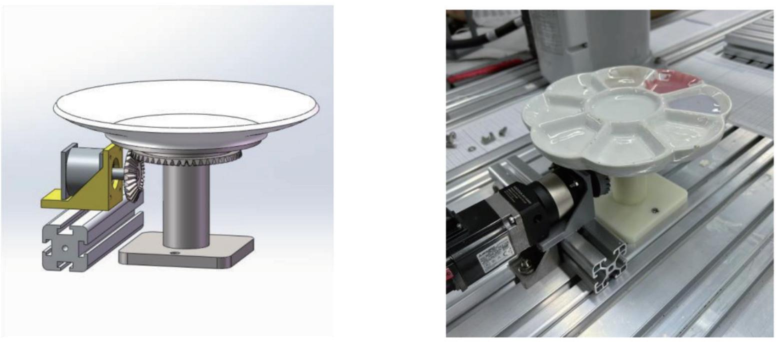


(a) Brush holder seen from above (b) Brush holding simulation (c) Actual assembly

Fig. 5 Brush holder

3.3.3 Ink switching unit

When the robotic arm is moved between many areas for ink dipping according to the path planning method, the operational load of the path planning process increases on one hand, and the range of motion of the robotic arm expands on the other, causing uncertain movements to increase significantly. For this reason, the Mitsubishi Electric HG-KR13J AC servo motor was introduced as an additional axis for the robotic arm, and color changing was made possible by designing a gear mechanism that transmits the rotation of the motor to the ink tray. The high control precision of the servo motor ensures precise color changes, and the gear transmission mechanism significantly increases the spatial utilization rate, leading to the overall compactness of the system.



(a) Simulation model (b) Actual assembly

Fig. 6 Ink switching unit

3.4 Electrical design

The system is centered on the Mitsubishi Electric RV-4FRL-D industrial robot. It also employs servo controller CR800-D as the main control device, a personal computer as the host computer, and the WeChat mini program “Blue and White Painting” as the interactive interface. It also incorporates a servo motor module to ensure outstanding control.

The electrical design demonstrated the high precision and high-speed control of the Mitsubishi Electric robot and drive unit, in addition to Mitsubishi Electric’s comprehensive services.

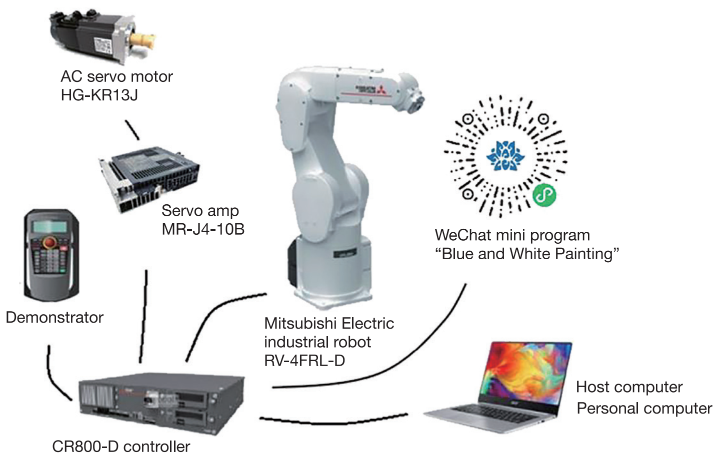


Fig. 7 Electrical diagram

3.5 Algorithm design

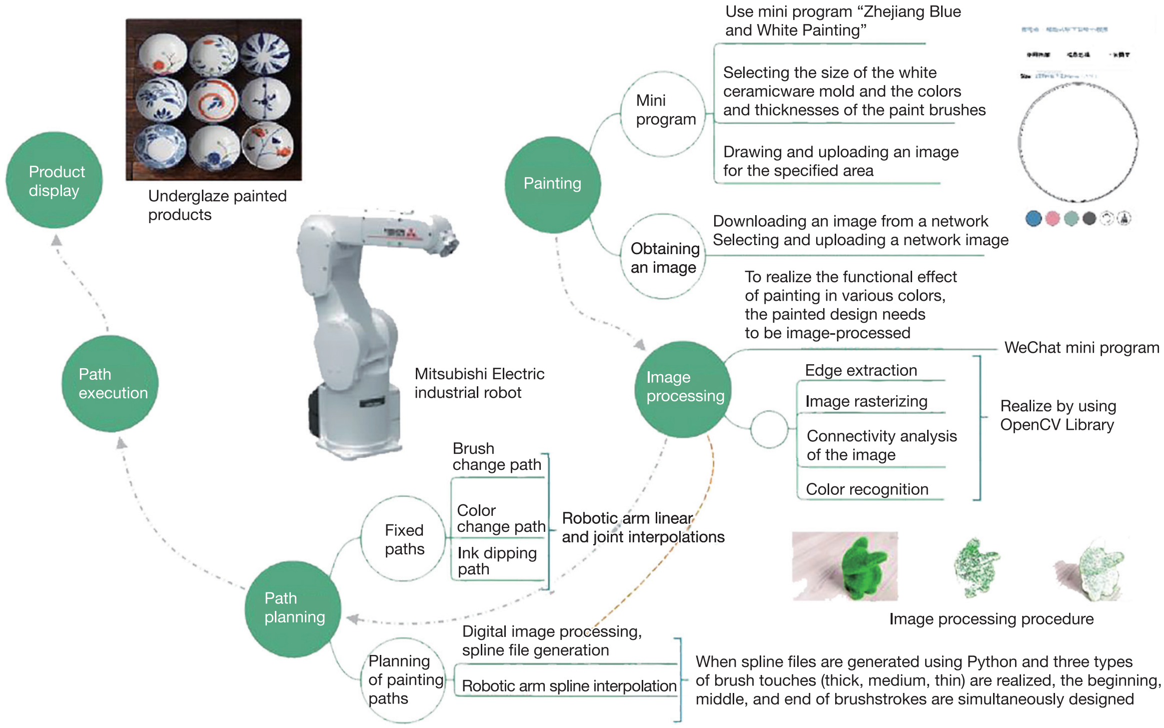


Fig. 8 Design drawing of the algorithm process

To achieve lines of three different thicknesses (thick, medium, thin) with a brush, it is insufficient to merely adjust the raising and lowering of the brush. It is also necessary to minimize the inclination angle and increase the contact surface of the brush and plate. Therefore, we continuously varied the angle and height of the brushwork based on the distribution of line thicknesses in the drawing to achieve a satisfying painting effect[5].

In addition to the above, the beginning and end of each brushstroke are also extremely important. There are two types of stroke beginnings: “forward stroke” and “backward stroke.” The forward stroke begins at a higher position with a sharper stroke, while the backward stroke begins by pressing the brush downward to create a thick beginning. There are also two types of stroke ends: a “concealed tip” and an “exposed tip.” For a concealed tip, the brush must be lifted straight up, and for an exposed tip, it must be lifted at a certain angle. We added points of differing heights and positions at appropriate positions at the beginning and end of the spline file and realized various stroke beginnings and ends by adding and deleting these points[6].

The specific process is as follows. First, the brushwork path of a brushstroke is sought based on the coordinate data of a certain single brushstroke, and the orientation of the brush tip at certain points in the drawing is calculated in relation to the height and angle of the given brush tip at the beginning of the stroke. The Euler angle representation of that orientation is then converted to a fixed-angle representation and aligned with the posture representation of the robotic arm in the RT ToolBox software. Lastly, the other parameters of the relevant point are established. By repeating the above process, a spline file for all discrete points constituting the relevant brushstroke is obtained and processed. Processing the stroke beginning: Points are accordingly added to the beginning of the spline file to achieve forward and backward stroke beginnings.[7] Processing the brush touch during painting: The brush touch while painting is realized by correcting the brush orientation at intermediate points. Brush touch is therefore controlled by correcting the height and angle of the brush at intermediate points according to a certain rule, allowing the pressing and inclination of the brush to be realized during the painting process. Processing the stroke end: The end of the spline file is processed, and points are reasonably increased, decreased, or corrected, to realize stroke ends with either a concealed or exposed tip. After processing the spline file, spline interpolation is performed by importing the RT ToolBox and generating a path that conforms to the requirements.

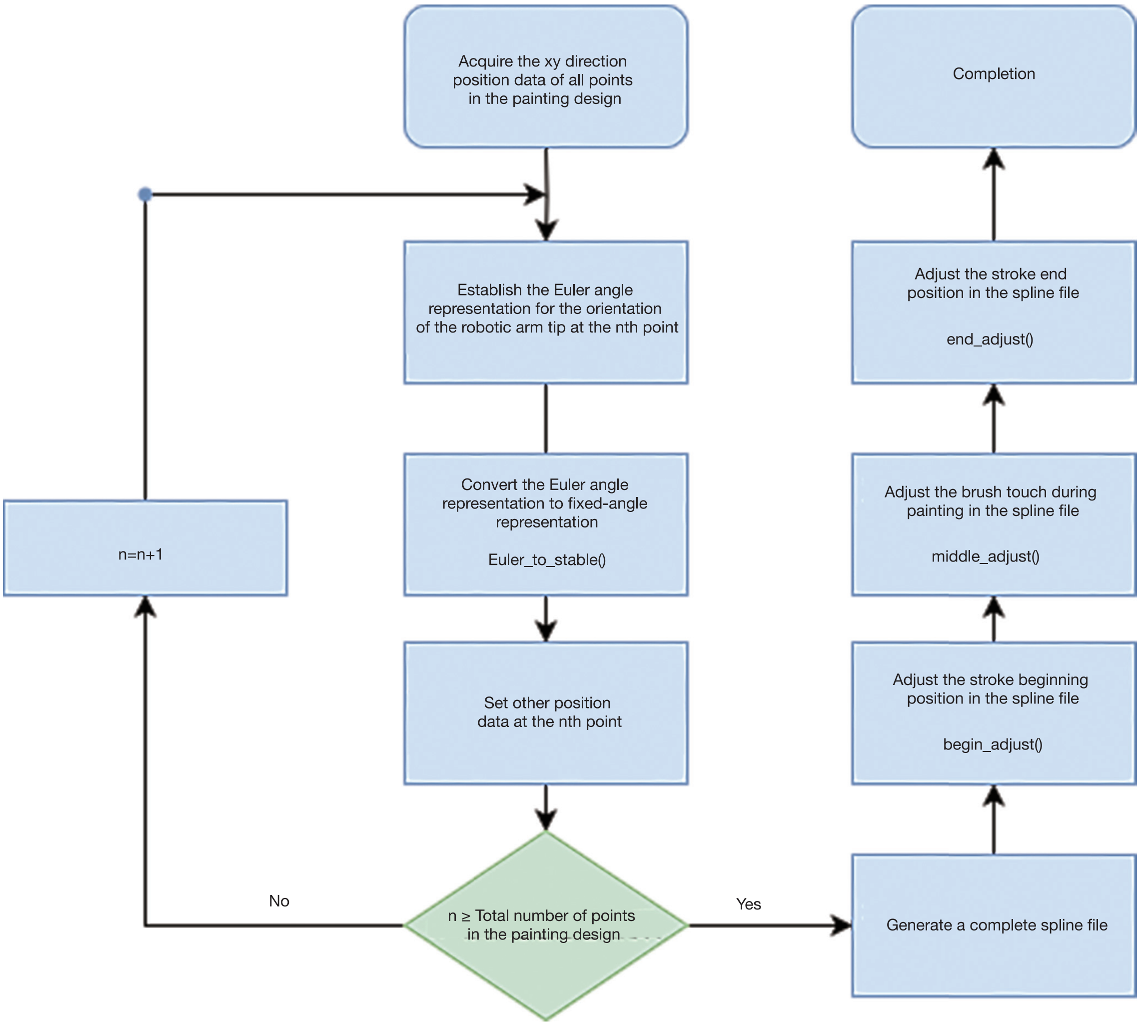


Fig. 9 Software process diagram

3.6 Interactive design

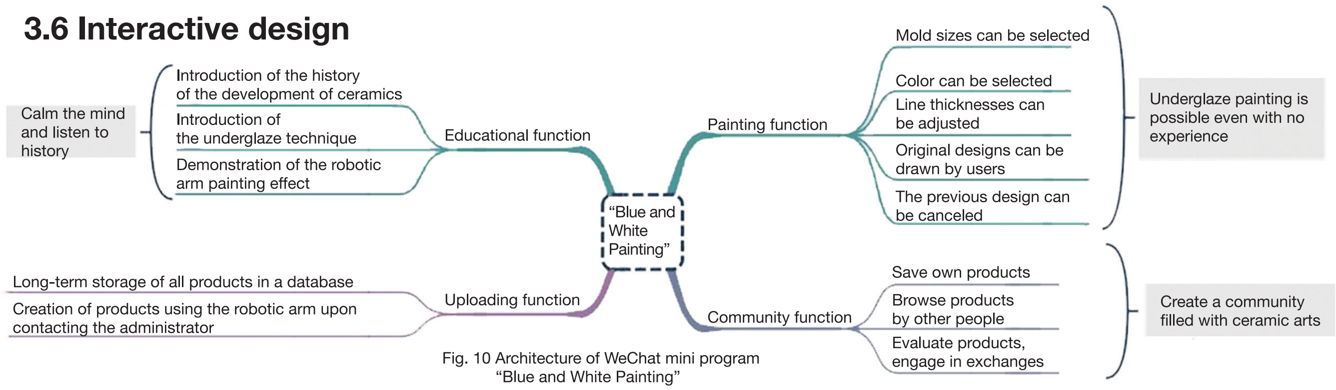


Fig. 10 Architecture of WeChat mini program "Blue and White Painting"

The interactive system of this project mainly employs the WeChat mini program "Zhejiang Blue and White Painting" that we have developed independently. The overall architecture of the functions of this mini program is as shown in the chart. The most important function is painting. Users can freely create painting designs on a circular canvas and arbitrarily change the size of the mold and colors and thicknesses as they wish. It is a program that could transform the challenging underglaze painting into a project that allows the general public to experience it anytime, anywhere[8].

Furthermore, the mini program has a community function that allows users to not only save their painting history but also to browse works shared by others and thereby create a ceramic painting community. Additionally, it has a certain educational function, with a section that includes contents on a vast collection of ceramic works and the history of the development of underglaze painting techniques. Lastly, if there are users who wish to create a product using the robotic arm, they simply need to contact the administrator, and the robotic arm will complete the painting after we post-process the painting design uploaded by the user and send it to the robotic arm.

The post-processing is performed via a Python script that includes such contents as coordinate mapping, Bezier curve fitting, sampling, and brushstroke processing.

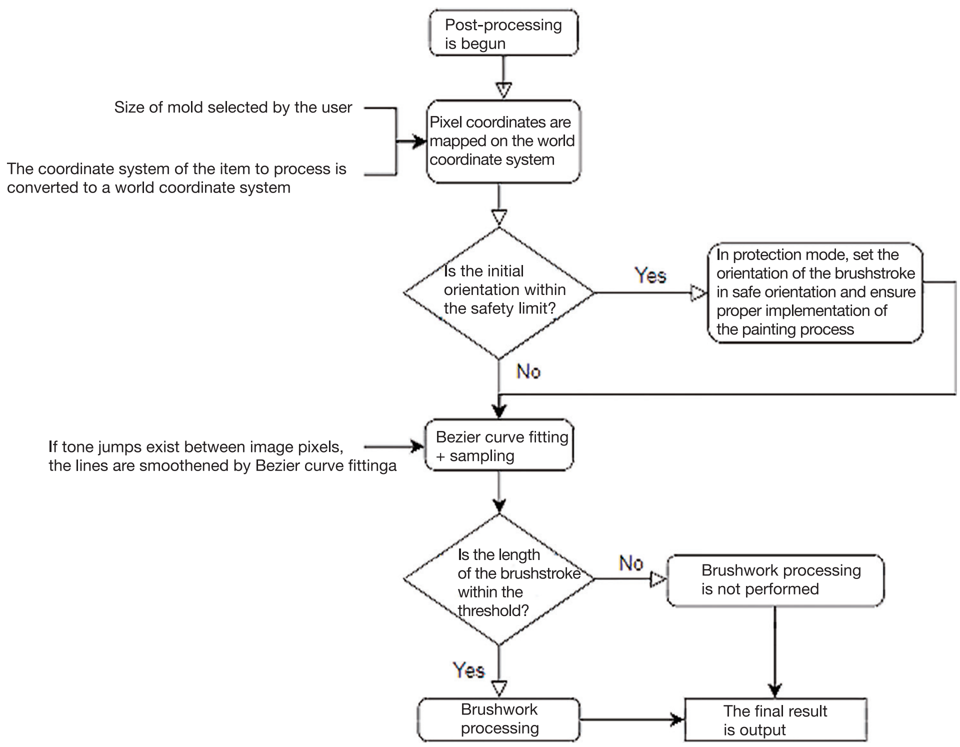


Fig. 11 Post-processing algorithm process

4. Expected Achievement of the Project

As the Intelligent Underglaze Porcelain Painting System can be incorporated into assembly-line production processes, it is primarily intended for **small and medium-sized custom underglaze manufacturing workshops.** The main painting methods that it can currently perform are the **industrial gold leaf pressing manufacturing method and the traditional hand-painting technique.** These methods are suited to products with a high repetition rate of patterns and low novelty. The system can reduce costs, shorten work time, and enhance the service level in the ceramics industry.

Additionally, because the system exhibits a Chinese-style appearance, a variety of application scenarios, including diverse types of exhibition venues, can be envisioned. Compared to small scenarios such as retail stores, museums, and farmers' markets, for example, exhibition venues can attractively showcase the system's features such as its intelligent and flexible human-machine interactive design, uniqueness, and antique appearance, and the manufacturing process of the traditional craft for exhibition purposes.

4.1 Intelligent underglaze painting with a focus on the "hotspot" of medium and small-scale custom ceramic production[9]

The system will allow the ceramics industry to emerge from its unstructured state and achieve standardized, high-quality development. This also translates into improving the financial standing of medium and small-sized ceramics businesses. Based on the boom in custom manufacturing services, it will effectively solve the resource redundancy issue in the industry. Furthermore, as an intelligent and flexible industrial system that responds to customization needs, it will actively promote the transformation and upgrading of service-oriented manufacturing.

4.2 The revival of Chinese-style original ceramics will reinvigorate the new era of traditional ceramic handicrafts

Methods of transmission driven by high technology provide ideal opportunities for the development of "new craftsmen" and the integration of resources beyond conventional boundaries. The system aims to bridge the distance between the general public and intangible cultural heritage, reinvigorate the exhibition and sales of handicrafts, arouse strong interest in traditional Chinese crafts and arts in and outside the country, and promote self-initiatives and creativity in the transmission of traditional ceramic culture.

4.3 Creating aesthetic lifestyles that can be expressed as "ubiquitous utopia" by delivering both utility and visual appreciation

Today, the problem with craftworks circulating in the market is that they lack design and creativity and are excessively commercial. In the business process, it is difficult to strike a good balance between cultural significance and sales profitability. Immersive PR and experience-based models increase the share of differentiated consumption in the post-pandemic cultural tourism market economy and match the leisure style of modern people in the post-pandemic era.

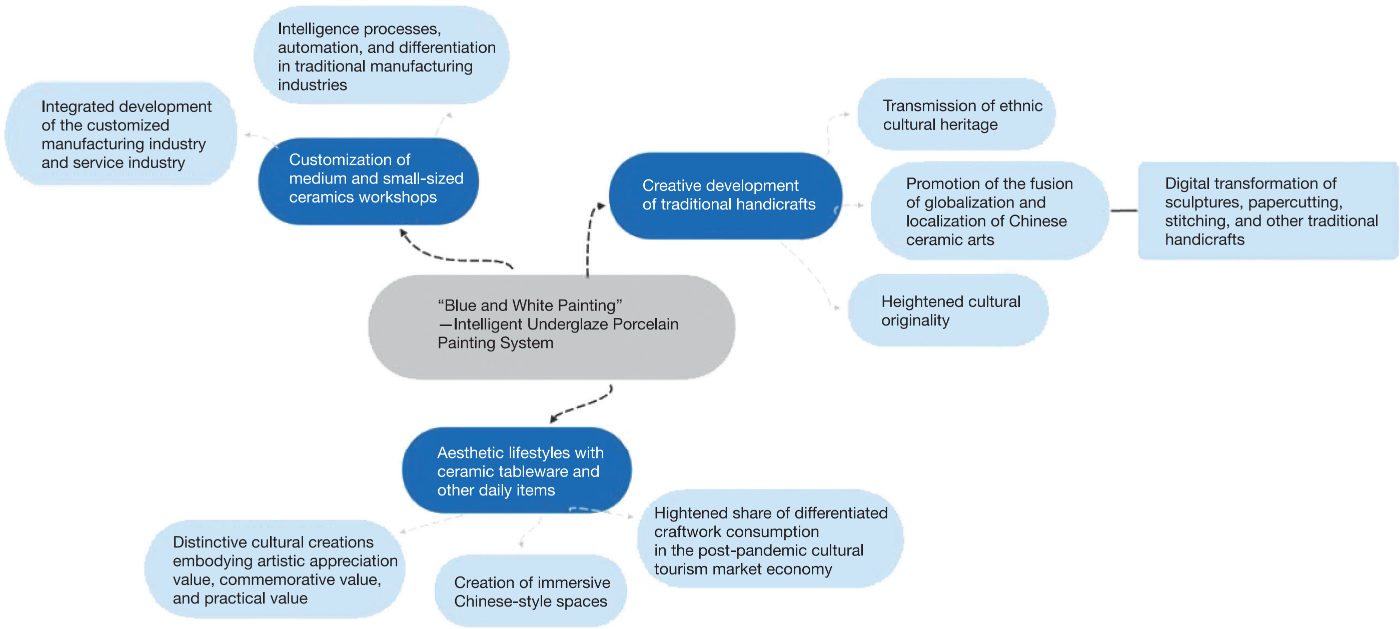
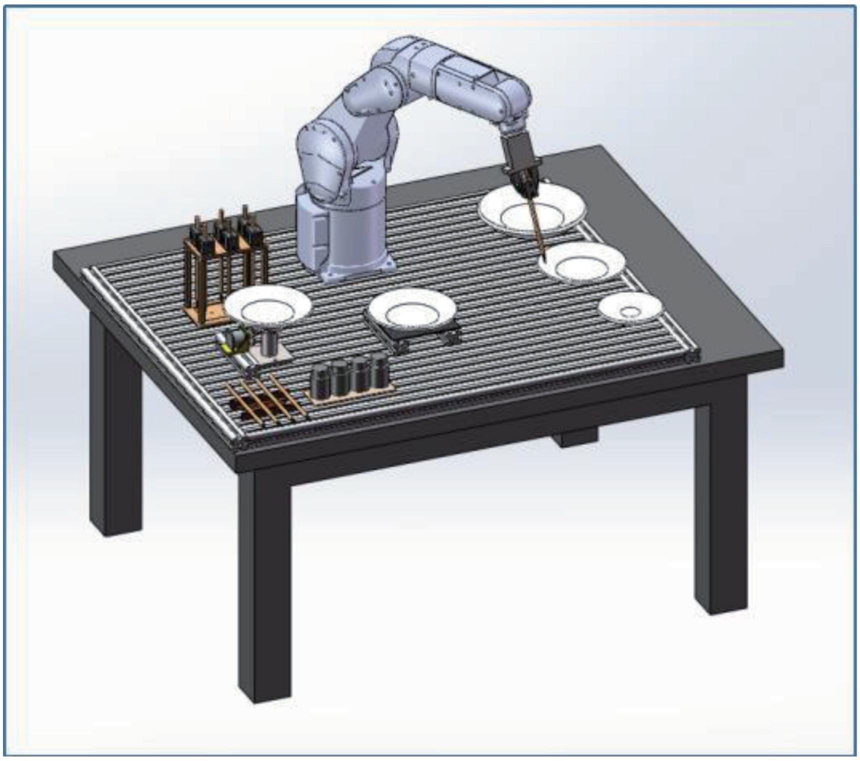


Fig. 12 Radial expansion of the project

Exterior design of the entire system



Simulated setup drawing

Actual setup

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