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THE IMPLEMENTATION OF AN INDUSTRIAL ROBOT DESIGN TEMPLATE FOR CUSTOMER PARTICIPATION DESIGN

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Abstract

Customer participation design plays an important role in achieving high degree of customization. Complex product such as robot has complicated structure and strong professionalism, the design is hard for users who are lack of professional knowledge. So an industrial robot design template is proposed. Base on composition structure of robot, four elements of the template are analysed. According to relationships and interactions among the four, the design template is established to guide users with a simple design method. This study provides references for the design of other complex products.

Keywords: industrial robot, design template, participatory design, product design, design methods

1. Introduction

Due to the complex work environment and high specialization of industrial robots, the traditional method of configuration engineering by designers cannot completely meet the high degree of customization requirements of different users. According to the characteristic of industrial robots, a user-customized configuration design pattern is put forward to achieve rapid development of industrial robotics (Li et al., 2015). But customers are not professional designers, hence cannot guarantee the manufacturability and rational construction of the product. The vibration, deformation and other issues of industrial robots during operation process are likely to lead to the failure of design. Therefore, it is necessary to develop a design template for industrial robot to make it easy for customers to participate in the design activities. The structure of industrial robot is relatively fixed which offers the possibility for the establishment of customer participation design template.

Customer participation design is actually a design method for mass customization production. Because it is very difficult for customers to design a completely new product, therefore more customers configure the existing components to product. Randall et al. (2005) pointed out that the product customization needs to meet the five principles, including providing different customized interfaces for different users, providing customized starting point, providing modify space, providing design prototypes for customer design reference. The most critical issue is to give customers a product structure template as a basis for the customer participation design. The design template is a generic and abstract product structure composed by components. User instantiates the structure via assigning to the components, then products model with specific features can be obtained. Currently, there are many researches on the design template of complex products in the field of configuration design. Zhang et al. (2010) set the definition of the product template first, then built the ordered tree model of product configuration to support individualized product design. On that basis, the product configuration process was analysed. Rapid product configuration design based on product design template was studied in many literatures (Xu et al., 2011; Lu et al., 2014; Xu, 2016; Chen and

Zhong, 2016). Different methods were used to build a product configuration template in these literatures. For specific industrial robots product, Faiña et al. (2013) provided a heterogeneous modular structure, including a slider module, scalable module, rotation module, hinge module as the basis or toolbox for the industrial robot development. Pacheco et al. (2013) developed a heterogeneous toy robot platform. Customers with non-professional knowledge can configure different toy robots using different modules based on their own interest. In the literature (Ming et al., 2014), a configurable template base method was proposed to solve the problem in multi-dimensional representation of product design knowledge, a software system based on this method is applied in several enterprises in aerospace and shipbuilding industries. Lian (2013) put forward a selection method of design templates, which implements rapid design through reusing the structure of design template based on the layered ordinal relation analysis, and the feasibility of the method was tested by a case of rapid design of metal forming machine. Based on three dimensional models, Zhang et al. (2012) proposed a product modular configuration method. Designers created product configuration models that include configuration template based on product family BOM and 3D information. Driven by customer's individual requirements, the configuration result that met the configuration constraints and requirements was obtained and presented in the form of a BOM structure and a three-dimensional assembly model. Futhermore, a construction method of configurable templates is elaborated, including product structure template, parameter calibration template, BOM template and so on. Through parameter-driven template instantiation, the whole-process product configuration design is realized (Wang and Wang, 2016).

These studies proposed a series of design templates for use in the process of product configuration design. However, there are two problems with existing research about the design templates, on one hand, the majority of templates are designed for designers, lack of support for customers who do not master professional knowledge about industrial robots design. On the other hand, the templates are built from the perspective of structure composition, such as BOM lists and structure trees, lack of the description of connecting relations, constraints, interaction and other aspects of the components.

In view of above problems, this paper does the following research. Firstly, the industrial robot composition structure is introduced. Secondly, the composition of industrial robot design template for customer participation is analysed, including the elements, the external view and the parameters of the template. Finally, an industrial robot design template for customer participation design is established.

2. Industrial robot composition structure

Industrial robot is composed of mechanical system, drive system, control system and sensing system. As shown in Figure 1, the contents of the dark box represent different types of the same layer, and the contents of light-coloured box indicate different constituent parts of the upper layer.

From the figure, it shows that the mechanical body includes base, pillar, upper arm, forearm and end effector. Depending on the task, the end effector is different, such as sucker, gripping fingers, welding gun, spray gun, etc. Drive system includes power system and transmission system. Power systems including drive, motor, and transmission system contains chain transmission, gear transmission, belt transmission, turbo transmission and so on. Control system does not belong in the content of configuration design which is studied in this paper, so it doesn't be researched here. Sensing system includes infrared sensor, force sensor, ultrasonic sensor, etc. The sensor can be selected according to the needs of the robot to make robot have a certain awareness capability.

The existing of some common industrial robots are shown in Figure 2(a). Between the base and the pillar is waist joint; between the pillar and the upper arm is shoulder joint; between the upper arm and forearm is elbow joint; between the forearm and the end effector is wrist joint. Point P is the wrist reference point. Driven by the drive system, the waist joint rotates around the z-axis, and .the shoulder and elbow joint rotates around the y-axis. Waist joint, shoulder joint, and elbow joint form three positions degree of freedom (DOF) of industrial robot, and wrist joint have 0 or more posture DOF. The more DOF the industrial robot has, the more flexible of the industrial robot movement. But it also will lead to the complexity of control. Therefore for the degree of freedom, more is not better. Usually 3 to 6 degrees of freedom can meet most requirements. By pose transformation, industrial robots can move in space and perform different tasks. In the process of moving, the set of point that P can reach constitutes the industrial robots' working space. Work space is closely related to the angular range that industrial robots' joints can reach. With ABB's IRB120 for example, the published work space is shown in Figure 2(b) below.

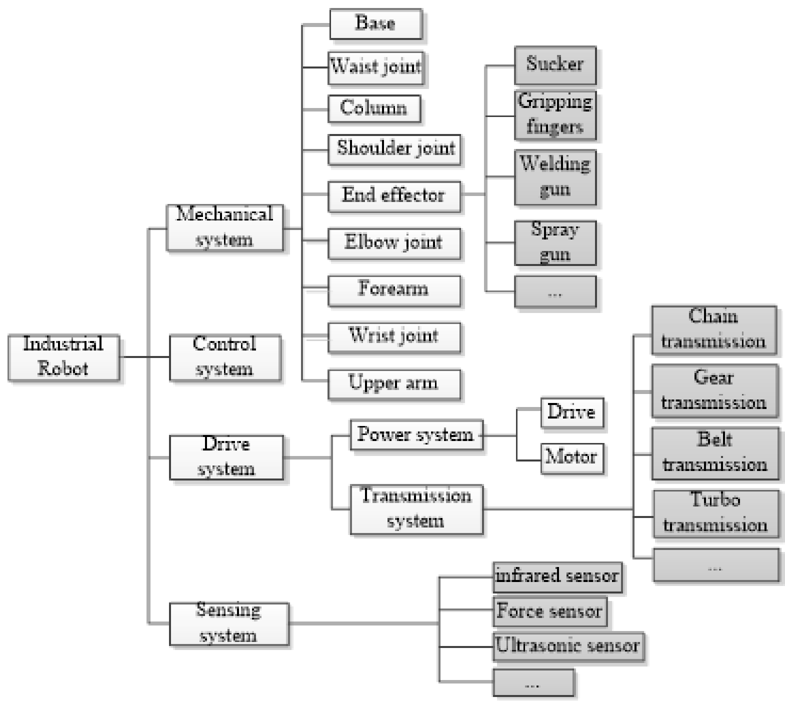
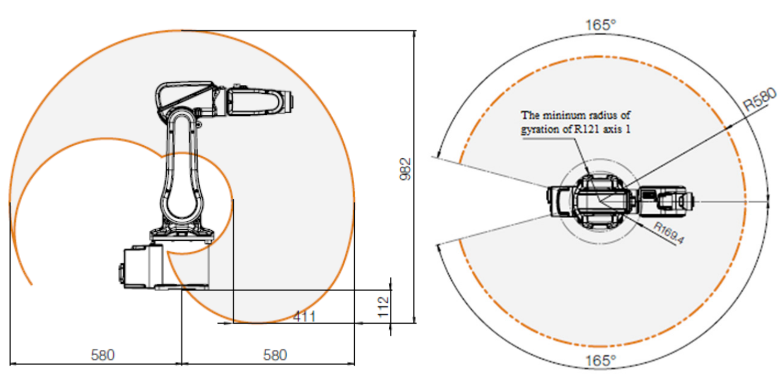


Figure 1. Industrial robot composition

KUKA spot welding robot KR180-2 KUKA small scale robot KR5 ABB robot IRB120

(a) the examples of common industrial robots



(b) industrial robots' working space

Figure 2. The examples of some common industrial robots and working space

3. Compositions of the industrial robot template for customer participation design

3.1. The elements of the template

The design template is a product model composed of components under certain constraints, which can be expressed as follows:

$$T=\left\{\sum_{i=1}^{n} S_i\ ,\ \sum_{i=1}^{m} Con_j\ ,\ \sum_{x=1}^{o} C_x\ ,\ \sum_{v=1}^{q} Ipar_y\right\} \tag{1}$$

$\sum_{i=1}^{n} S_i$ is the set of components that make up the template, n is the number of components; $\sum_{i=1}^{m} Con_j$ is the relationships that connect the components, m is the number of associations; $\sum_{x=1}^{o} C_x$ is the set of constraints, o is the number of constraints; $\sum_{v=1}^{q} Ipar_y$ is a collection of template parameter interfaces, q is the number of parameter interfaces. The parameter interface defines the types of input/output parameters of the template and the interface type that the template connects with other models. The specific contents of each component are as follows:

(1) The structure tree view of the template. The design template can be divided into product structure trees by layers of components, as shown in Figure 3. S_p represents a product model composed of components. The structure tree shows clearly the composition of the template, and the set of all components that can't be decomposed at the bottom is $\sum_{i=1}^{n} S_i$.

(2) The external view of the template. The design template connects components to the external view of the template, which is similar to the appearance of actual product. Different kinds of products have different types of external views, which can be quickly understood and used by customers.

(3) The internal constraint set of the template. The components of the design template need to be in accordance with certain constraints in the instantiation process. For example, when the two gears mesh, the required transmission ratio determines the choice of gears' teeth number; when the sensor and controller connects, not only the interfaces must be the same, communication standards must be consistent too. Internal constraints of template are the basic constrained which must be met between the components. They guarantee the feasibility of the final design result.

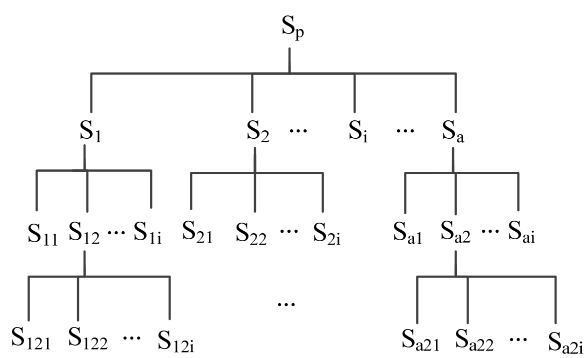


Figure 3. The decomposition tree of design template

(4) The external parameter interface set of the template. The parameter interface of the template mainly interacts with two parts: customers and technical models. The customer inputs the parameters required by the template through the parameter interface, then obtains the calculation result parameters from the template. The technical model provides parameter calculation and simulation analysis for the template, generally established with simulation softwares such as Matlab and Pro/e. The template transfers parameters required by the simulation analysis to the technical model through parameter interface. And the analysis result will be fed back to the template after the accomplishment of technical model analysis through parameter interface too. Figure 4 shows the interaction process of the parameter interface.

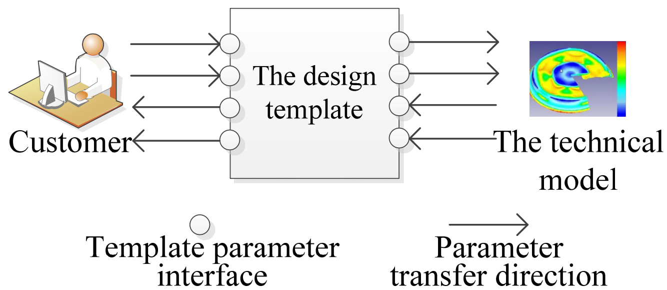


Figure 4. Interaction process of the parameter interface

The design template supports the customer participation design through the above two views and two sets. The relationships and interactions between the four are shown in Figure 5. The components in the external view and the structure tree view are constrained by the internal constraint set of the template. The customer inputs demand parameters and obtains the final product performance parameters through the external view, obtains the BOM list of the final product through the structure tree view as well.

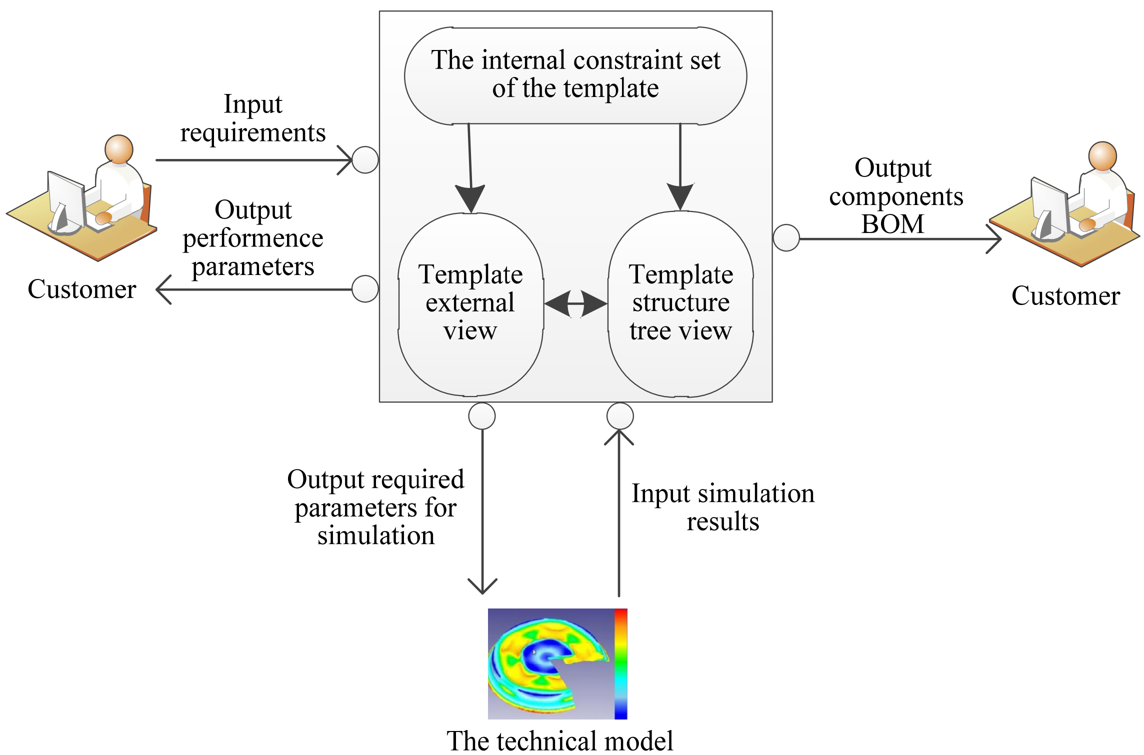


Figure 5. The relationships and interactions between the design template elements

3.2. The external view of the template

The external view of the industrial robot needs to provide customers with an easy-to-understand view, so it should be able to directly reflect the structure of the industrial robot. Zhang et al. (2000) introduced a representation method with six types of modular joints to represent industrial robots. Although the method is intuitive, the representation view is too complicated.

From a mechanical point of view, industrial robot is an open chain structure composed by rod-shaped parts which are connected by kinematic pair. In the customer participation design process, customers only configure the whole structure and the movement pattern of kinematic pair, and not design the specific structural of components. Therefore, the mechanical schematic which ignores the specific structure of component is taken to establish the template. The mechanical schematic symbols used by the template are shown in Tables 1 and 2. In Table 1, the symbols are taken from ISO3952/1-1981, ISO3952/2-1981, ISO3952/3-1979. And the symbols in Table 2 are needed here but not taken from ISO.

Table 1. Template symbols from ISO (a)

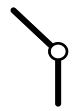
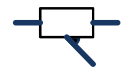
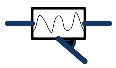
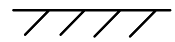
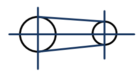
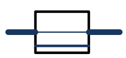
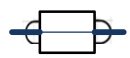
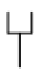
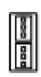
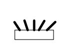
Components of industrial robot	ISO3952 standard symbol	Components of industrial robot	ISO3952 standard symbol	Components of industrial robot	ISO3952 standard symbol
Rotation pair		Plane rotation pair		Translation pair	
Screw pair		Shaft		Rack(fixed rack)	
Coupler		Belt/chain transmission		Gear transmission	
prime motor (universal)		Electric motor		Bearing	

Table 2. Template symbols (b)

Components of industrial robot	Symbol	Components of industrial robot	Symbol	Components of industrial robot	Symbol
End effector		Actuator		Sensor	

The industrial robot design template is shown in Figure 6. The template contains basic elements of building an industrial robot. Each joint of the robot contains a prime motor, a reducer and an actuator corresponding to the prime motor. Actuator is usually installed outside of the robot, and is connected to the motor by control line. The contents in the dotted box represent undetermined elements, and they will be determined by customers, then the dotted line will become solid line. For example, the undetermined transmission way can be belt transmission, gear transmission, chain transmission and so on. The undetermined DOF is wrist joint DOF. The sensor can be in installed in some part of the robot as needed. L_1~L_4 represent the lengths of base, pillar, upper arm, forearm respectively. O_0-X_0-Y_0-Z_0 is the absolute coordinate system. It takes the earth as a fixed reference, and it is regardless of the position and orientation of the robot. O_1-X_1-Y_1-Z_1 is the base coordinate system. It takes the base surface o of the robot as reference, and the default is generally the same as the absolute coordinate system. O_t-X_t-Y_t-Z_t is the tool coordinate system. It takes the end effector as reference, and it provides a reference for the end effector relative to the robot body. θ_1~θ_3 represent the angles of the three position DOF. The base coordinate system is adopted to the three angles, and the positive rotation is counter-clockwise.

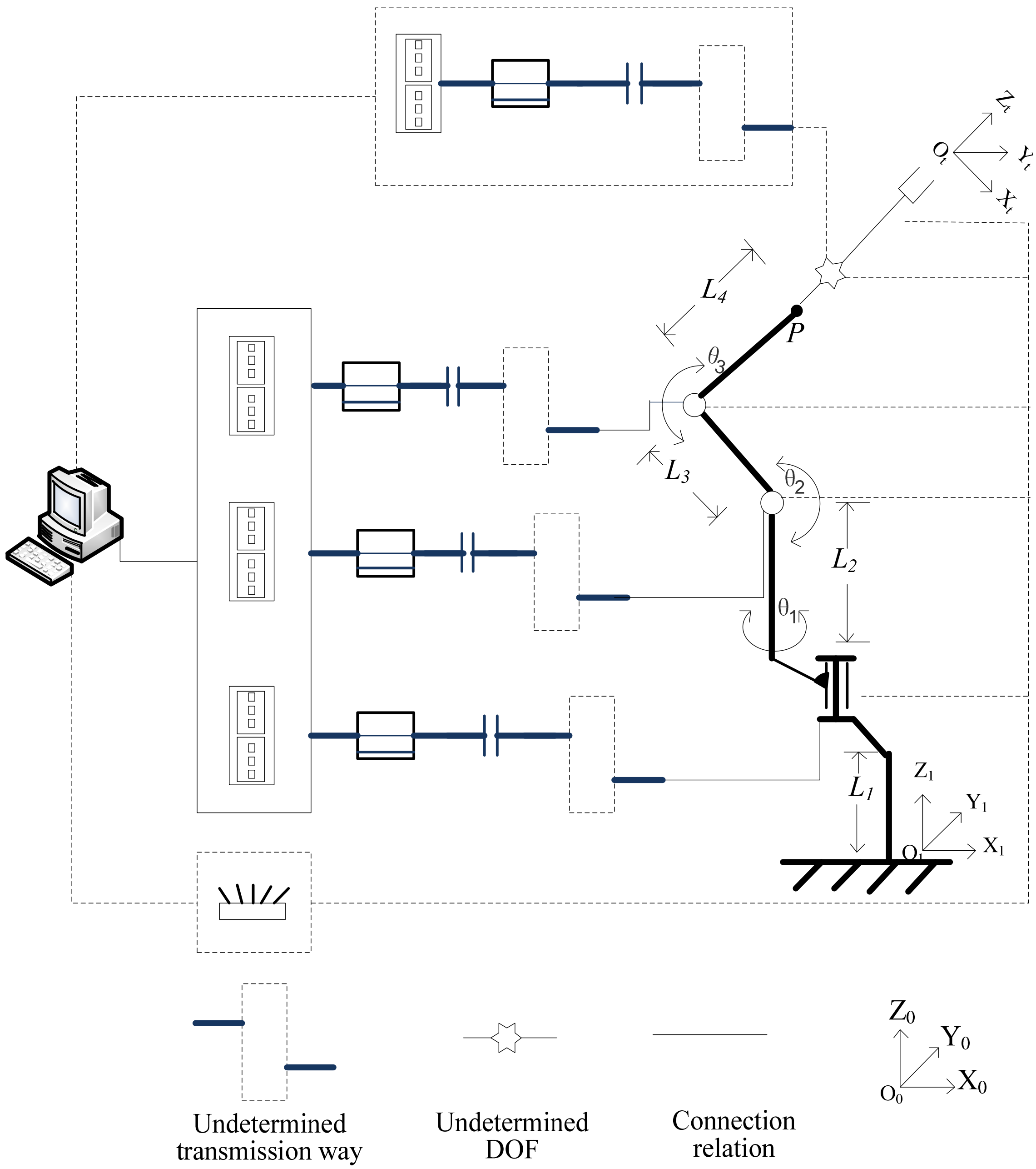


Figure 6. The external view of the industrial robot design template

The internal parameter constraints of the industrial robot design template are derived from the interaction with Simscape through the kinematics and dynamics analysis of the external view. The specific calculation of the parameters has been given in the article (Li et al., 2017), which will not be described in detail here.

3.3. The external parameter interfaces of the template

3.3.1. Input-output parameter interfaces

According to the content of the dotted box in Figure 6, the parameters of template needed to be determined by the users are as follows:

$$P_s = \{N_{DOF}, T_{KP}, T_{DS}, T_{Tr}, T_{Se}, T_{EE}, W_{EE}, L_a\} \tag{2}$$

N_{DOF} is the number of DOF;

$$T_{KP} = \{T_{KP1}, T_{KP2}, \dots, T_{KPn}\} \tag{3}$$

T_{KPi} is the kinematic pair type of the *i*th DOF, *n* is the number of DOF;

$$T_{DS} = \{T_{DS1}, T_{DS2}, \dots, T_{DSn}\} \tag{4}$$

T_{DSi} represents the prime motor type which provides motive for T_{KPi}. It is usually a motor except under exceptional circumstances;

$$T_{Tr} = \{T_{Tr1}, T_{Tr2}, \dots, T_{Trn}\} \tag{5}$$

T_{Tri} represents the transmission way used by T_{KPi}. It is usually a gear reducer except under exceptional circumstances;

$$T_{Se} = \{T_{Se1}, T_{Se2}, \dots, T_{Sem}\} \tag{6}$$

T_{Sei} represents the type of the *i*th sensor, *m* is the number of sensor used in the template;
T_{EE} is the end effector type, and it is determined by the robot task;
W_{EE} is the maximum load imposed on the end effector;
L_a is the minimum length of the robot arm, and it determines the work space of the robot。
P_s represents the static parameters needed to be determined in Figure 6. In addition to these, some dynamic parameters need to be input to the template. The dynamic parameters P_d are represented as follows:

$$P_d = \{\omega_p, A_p, \omega_{ee}, A_{ee}\} \tag{7}$$

ω_p represents the velocity of point *P*;
A_p represents the accelerated velocity of point *P*;
ω_{ee} represents the velocity of end effector;
A_{ee} represents the accelerated velocity of end effector.
After determining the template parameters, it will become an industrial robot template composed by components. Through value assignment to the components, the template will become a specific product composed by component objects.
The parameters that the external view outputs are mainly performance parameters of the final product designed the customer, including the workspace, the vibration response, the stress-strain scope, kinematic velocity, etc. obtained through the finite element analysis, and the workspace, kinematic velocity analysed by the Simscape model, as well as a list of components composed of the final product obtained from the product structure tree.

3.3.2. Technical model interaction parameter interfaces

The interactions between the external view and the technical model begin from the interaction with the Simscape model. The external view inputs the length *l*, weight *W*, joint angular acceleration *ω*, etc. of each rigid body *L* to the Simscape model and the Simscape model inputs the calculated T_i (The maximum torque of the *i*th DOF) value to the external view, so as to provide parameter constraints for external view. At the same time, the Simscape model can also input the product workspace, kinematic velocity and other parameters to the external view for the customer to view.
In addition, since the external view needs to output the final product performance parameters to the customer, it also needs to interact with the product performance simulation model to acquire the

simulation results. This interaction with the product performance simulation model is performed after all the parameters input by the customer have been determined and instantiated into a specific product. The purpose is to extract the related product parameters after the design accomplishment and then carry out performance analysis for the design result, thus providing a basis for the improvement of designing, which is also an analysis of the design template.

Generally, we make the performance analysis of industrial robots with finite element analysis. Finite Element Analysis (FEA) refers to decompose the physical structure into a finite number of elements interacting on each other, set an approximate mathematical solution for each element, and based on this, obtain the solution of the whole mechanical structure. FEA can achieve the simulation of real mechanical structure under different loads, working conditions, constraints and other conditions.

The industrial robot finite element analysis includes statics analysis and modal analysis. Statics analysis researches the balance condition (including stationary and uniform linear motion) of the mechanical structure under stress. The condition generally refers to the mechanical structure stress and strain in the equilibrium state. Through applying load to mechanical structures, the mechanical structure stress and strain analysis is taken. When the stress and strain of mechanical structure is too large, an appropriate interpolation value can be provided in the control system, or improving the mechanical structure to improve structural strength, thereby improving the motion accuracy of industrial robot. Modal is a basic concept of structural dynamics. It refers to the natural vibration characteristics of the mechanical structure (including frequencies and vibration mode). Mechanical structures have different modals, and each modal has a corresponding frequency and vibration mode. The process of analysing and calculating the modal of mechanical structure is modal analysis. The natural frequencies and vibration mode belonging to each modal can be determined through modal analysis, so the actual vibration response of mechanical structure in the role of a vibration source can be known. The industrial robot finite element analysis is generally aimed at the main structural components including base, pillar, upper arm and forearm (Zhan, 2016).

The finite element analysis software commonly used includes ANSYS, Pro/MECHANICA, ABAQUS, etc. In this paper, the ANSYS is chosen to establish the technical model of industrial robot product, and the product's finite element analysis is completed by transferring the product parameters to the technical model.

4. Industrial robot design template establishment

Through a series of processing to the parameters inputted, the customer participation design template outputs the components list of industrial robot and performance parameters meeting the needs. Final establishment of industrial robot template with the flow and analysis process of parameters is shown in Figure 7.

According to the needs of the task, the customer inputs the required parameters to template, including the DOF of wrist joint, the kinematic pair type of each DOF, the workload weight, the end effector type, the minimum arm length, velocity and other parameters. Simscape model obtains parameters such as load weight, arm length, joint angle from the design template, simultaneously query the weight estimate table, calculate the parameters of the work space, joint torque and then output them to the template. In the constraint of the Simscape calculation results and design template internal constraint, the component objects meeting the constraints can be retrieved from the database to compose the design result. When all components of the design template have become into component objects, the corresponding three-dimensional models of objects and the calculated load data will be input to ANSYS. The ANSYS is used in statics analysis and modal analysis of the design result. The analysis results include stress-strain data and vibration frequency data. These data is output to template. Finally, the template will send the design result and ANSYS analysis result to customer.

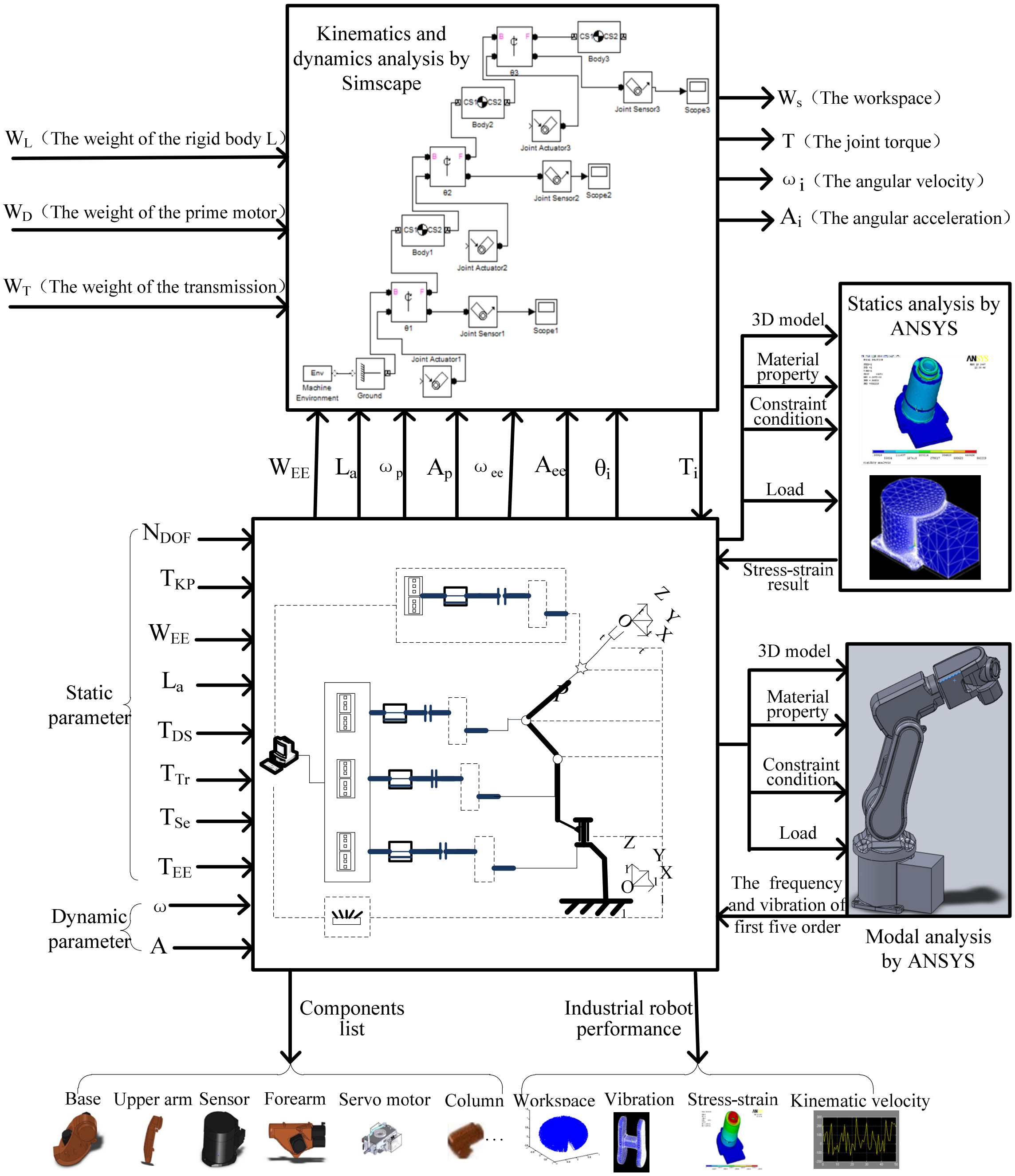


Figure 7. The industrial robot design template

5. Conclusion

To achieve high degree of customization, customer participation design gains more and more attention and has become the inevitable trend of product development. As a complex mechatronic product, it is complex for industrial robots to take customer participation design because it is not possible for the customer to understand the underlying relationships between components composed of the product. To implement customer participation design, an industrial robot design template is given in this paper. Contribution of the article mainly includes the following three parts: Firstly, the industrial robot composition structure is constructed, which is the basis for design template implementation. Secondly, the customer participation design template elements for industrial robot are analysed, including the structure tree view, the external view, the internal constraint set and the external parameter interface set. At the same time the relationships and interactions between the four are made clear. Finally, the industrial robot design template establishment is proposed through the specific flow and analysis process of parameters. The design template provides non-professional customers with a simple design method and design process, and ensures the feasibility of the design result. The study has certain reference value to the implementation of customer participation design of other complex mechatronic products.

Acknowledgement

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