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Interface Adaptability for an Industrial Painting Machine

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ABSTRACT

Interfaces play a key role in connection, transformation and interaction of functions between product modules. An adaptable interface supports modules replaceable, upgradeable, and functionally variable abilities in product. This research improves the interface adaptability by increasing interface efficiency in operations using the concept of adaptable design. A quantitive method is developed to evaluate and improve the interface efficiency. The method integrates interface graph representation, criteria matrix, and house of quality. Interface Efficacy is proposed as a measure based on key factors in interface design and operations. The proposed method is used for the interface improvement of an industrial painting machine.

Keywords: adaptable interface, design for assembly/disassembly, product design.

1. INTRODUCTION

Market competition and variable customer requirements have been the driven force of product innovation. Industries have to provide customized products with low cost to survive in the market. A variety of product structures and design methods has been proposed to meet the customer requirements. A product with adaptability can meet requirement varieties using different product functional modules [5,7]. An adaptable product uses adaptable interfaces to adopt functional modules for meeting the changeable requirement of customers in the product life cycle, such as trucks in automobile industry and personal computers in computer industry [8,17,20].

A product with adaptable interfaces allows users to improve or change functions by upgrading or replacing of functional modules of the product [5]. The product can therefore be functionally beyond its designed life cycle. Operation efficiency of interfaces is important for users to update the module. The interface adaptability depends on the operation efficiency of interfaces when functional modules are replaced or updated in a product.

Based on functional requirements, product interfaces transfer power, motion and information using different physical structures or formats, such as mechanical, electrical and software forms. This research investigates techniques to improve mechanical interfaces for an industrial painting machine to increase its adaptability. The purpose is to increase the utilization of the machine. The machine with the adaptability can meet different painting jobs by just replacing its relevant functional modules.

The industrial painting machine is used in the toy industry to paint surfaces of toys made from plastic or metal materials. As shown in Fig. 1, a feeding wheel delivers workpiece into the painting area, robotic manipulators are used for painting and cleaning operations. The completed painting piece is moved out of the machine for following processes. The machine uses two independent manipulators for surface painting and cleaning operations respectively. As a variety of painting colors, areas and processes is required based on different toys' types, sizes and shapes, the size of painting nozzles and motion of painting arms in the manipulator are variable. The existing machine was designed as an integral system. A new machine has to be redesigned for customer if the painting parameter, such as toy's size or shape, changes. It is necessary to have a better product structure to meet the change requirement of toy painting.

Based on the concept of adaptable products, if the modular design method can be applied to

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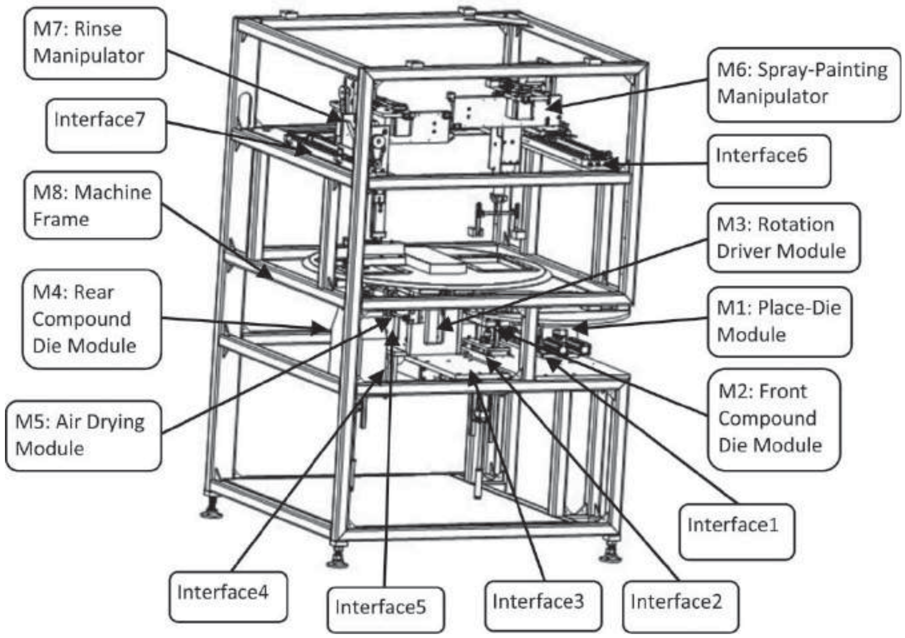


Fig. 1: Painting machine.

the machine, the adaptable interface is used to link different functional modules to meet different painting requirements. The adaptable interface should be designed for the easy operation when functional modules are changed in the machine. The machine can therefore meet different requirements by updating modules of machines through interfaces. This will provide a sustainable solution for the machine manufacturer and users. The manufacturer will produce less types of the machine to meet different needs. The users can use one machine for different painting jobs by changing functional modules of the machine instead of buying new machines.

The purpose of this research is therefore to propose an adaptable painting machine to meet potential different requirements. The machine uses common platforms for a general purpose, and special function modules for the individual need. Interfaces have to be easily operated for adaptable requirements, especially, to allow users to make the module changes in their working place. The adaptable interface is therefore essential in the connection of modular elements for the product functionality. This paper investigates methods for the interface improvement to increase the machine adaptability. The interfaces are evaluated and improved based on measures proposed for the interface efficiency to meet requirements of the adaptable painting machine.

This research focuses on mechanical interfaces as their complex in geometry and operations compared to electrical and information interfaces. Following parts of the paper will first review related research on interfaces. Methods for the interface analysis and improvement are then discussed.

2. RELATED RESEARCH

Market uncertainties increase variables of product and production [18]. A key step in product design is to develop an appropriate structure to transform product specifications into component configurations based on required product functions [2]. Integral product architecture contains a complex structure mapped from product functional requirements to physical components with coupled interfaces between components. A modular product uses the architecture of a one-to-one correspondence between modules with de-coupled interfaces [13]. Modular design has been driving forces to accommodate various requirements in product life cycle [9].

Modular design provides a strategy of using common unites to create a variety of products. It uses individual, standardized and changeable function modules to build products, which widens the diversity of products and shortens time of product development. Modular design methods have been used for ease of product manufacturing and assembly [23]. Product modularity enables platform-based product family design with various modules to achieve a high degree of customization. Moreover, parts or modules carryover and reuse are also possible with modularity. Paralikas et al [13] investigated effects of product modularity in design, configuration and operation of assembly systems.

Varieties of product specifications cause complicated operations in assembly and disassembly of components and modules. Modular design makes the assembly process efficient due to the benefit of commonality in modularity. Interfaces are commonly used in products linking different function modules and components, which is essential to construct a product. The interface decides product compatibility, which is the basis of new products or product function extension. A modular product needs flexible architecture with standard interfaces. A standard interface is important for modularization, which can switch focuses from the module exchange to compatibility of interface [3]. There are different types of interfaces used to link various functional modules in product. Research has been conducted to improve the efficiency and operations of interfaces.

Gu and Slevinsky defined a MechBus for mechanical interfaces to connect product modules and platforms [6]. They discussed Mechbus' functions and linking mechanisms with positioning features. It is claimed that specially designed interfaces are necessary for modular products to make physical connections between modules. Easy assembly and disassembly of interfaces are required for interactive operations of modules. Key features considered in MechBus include functions transferred, connection mechanisms, safety and easy operations. Demoly also emphasized the importance for integration of product assembly knowledge in the early phase of the product development to improve the design feasibility [4].

Pittera and DErrico applied modularity to benefit the rapid assembly of off-the-shelf components in a space system [15]. They used modular design to simplify the product complexity into simpler elements, for the easy operations of repairing or upgrading of the system components. They suggested that the adoption of standard interfaces is crucial to achieve modularity for the interchangeability of components. The plug-and-play features were proposed for implementing self-configuring capabilities of different devices interaction without the external intervention, which can reduce configuration time and problems. They used physical interfaces in connecting sub-modules and bus, data interfaces as transceivers, and power interfaces to feed sub-modules. A controller was used to manage communications, system status and operations.

Interface efficiency can be improved in different areas, such as simplifying interface assembly, or easing connection relations of interface components. The interface representation is important for abstracting interface physical elements and analyzing layout of the interface. Features and graphs are commonly used to represent product structure in design and assembly analysis. Interface design specifies the connection type and geometry of product components and modules. An interface is normally formed by connected components and/or modules. Connections may be surfaces or slots for positioning and limiting degrees of freedoms of the components [1]. Bronsvoort et al used a connection graph to represent the interface and components [1]. The graph uses nodes to represent interface components, and edges for relations of the components. Tseng and Li proposed a representation schemes for different types of connectors [19]. Using the representation scheme, an assembly product can be decomposed into assembly elements. Interface constraints can be identified based on connectors on joined components.

Criteria of the interface evaluation can be decided based on the operation cost of product module assembly, disassembly, or life cycle management. Tseng and Li considered operation constraints of interface connectors for fixing, motion, and force [19]. They defined a representation of the connector and associated assembly components as Ci [component 1, component 2, component n], where connector Ci is for fixing component 1, component2, and component n.

Commonality and compatibility are critical issues in product manufacturing and applications. Interfaces contribute commonality and compatibility by adopting various functional modules [3]. Rahmani and Thomson proposed the port ontology for interface design and control [16]. They used interface rule sets to describe product interfaces for the product development. The ontology provides a common vocabulary for interface definitions to overcome the lack of commonality in interface terminologies.

Peng and Chung introduced an analytical method for the component accessibility in product disassembly [14]. Space around a connector is considered for evaluation of connector's accessibility in product disassembly analysis. Manzini et al suggested criteria for assembly-oriented product structure to reduce the number of elements, variety of components and interfaces [12]. Bottlenecks and developmental tendencies were indicated for the flexible assembly. They suggest looking at details of complex relationships between various assembly variables, supporting techniques and tools for product end-of-life disassembly [12].

Zhou et al proposed a function to evaluate the quality of product assembly [23]. The geometric feasibility and assembly cost related to assembly directions and tools of components were used to determine the quality of the assembly sequences. An evaluation function was defined including the number of components in product, the length of the longest feasible sub-sequence, the number of orientation changes of the assembly, the number of gripper changes and the maximum number of similar assembling operations grouped together [23].

Li et al used a method based on design for assembly (DFA) to analyze and improve the design of a bioreactor [10]. Product difficulty levels were introduced to the DFA analysis to ease operation, save time and increase the application efficiency. The assembly complex is classified into two groups: the part complex based on product design, and the process complex based on assembly operations. Luo and Peng [11] discussed product disassembly efficiency for product maintenance and recycling. They introduced a method for the calculation of total disassembly time by adding the total moving time of parts and removal time of fasteners.

In summary, although different research activities have be conducted for representations and improvements of product interfaces and interface operations, these research solutions have limitations. Most of them were proposed for the connection of components in product assembly and disassembly operations, not for the interface linked to product modules which contains more components with more complicated factors. There is not a general method that can abstract interface information from the product design for the interface analysis. Especially, there are limited methods for the quantitive evaluation of interfaces. Most of the methods were proposed for the analysis of product components assembly or disassembly, without enough factors considered for the modular product interface evaluation.

We propose a comprehensive method for the analysis and improvement of the modular interface. The method integrates the graph representation, criteria matrix, and House of Quality (HOQ). A qualitative evaluation is designed for the calculation of Interface Efficacy (IE). IE considers interface factors of connectors, positioning and operation attributes for the analysis and improvement of interfaces. Following parts of the paper introduce details of the proposed method and applications in the painting machine for the interface evaluation and improvement.

3. PROPOSED METHODS

Proposed steps for the interface analysis and improvement are shown in Fig. 2. A bill of materials (BOM) is first built for understanding of details of the machine structure to abstract functional modules and interfaces based on the machine design. A representation of the interface is developed to analyze interface factors that affect the efficiency of interface operations. Interface Efficacy (IE) is then proposed to evaluate the effectiveness of interfaces for connecting modules, considering the machine structure, interface connection and module handling in the operation based on principles of design for manufacturing, design for assembly, and design for disassembly. In order to prioritize improvement alternatives of interfaces identified in the IE calculation, House of Quality (HOQ) is used to rank alternatives of improvement areas to avoid conflicting for cost-effective improvement solutions [21]. Assumptions and rules are suggested for the interface improvement based on the simplification of structures and

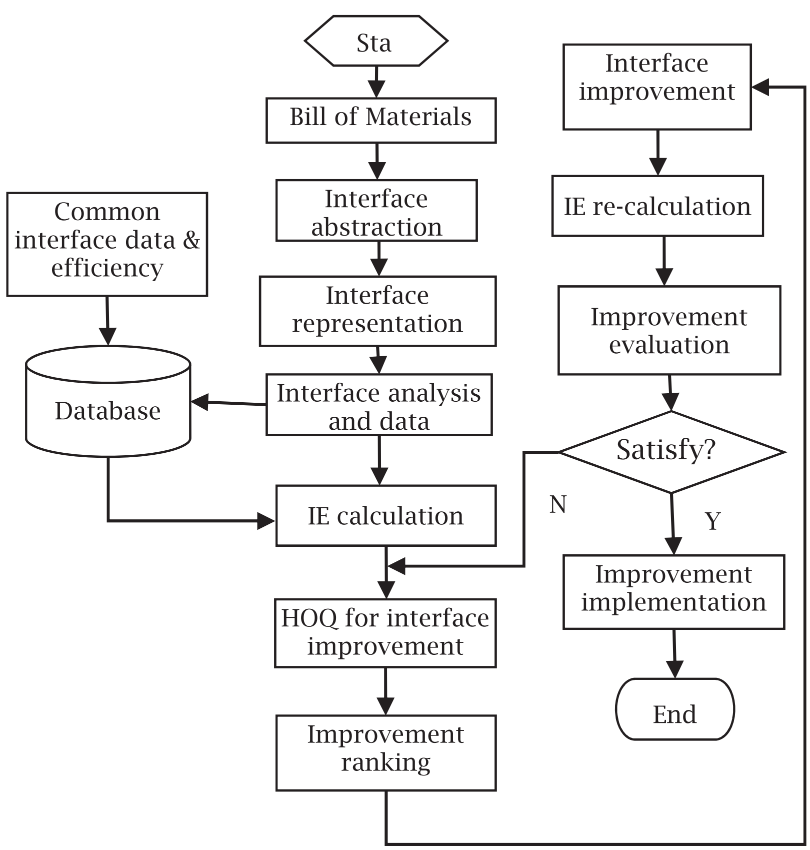


Fig. 2: Interface analysis and improvement.

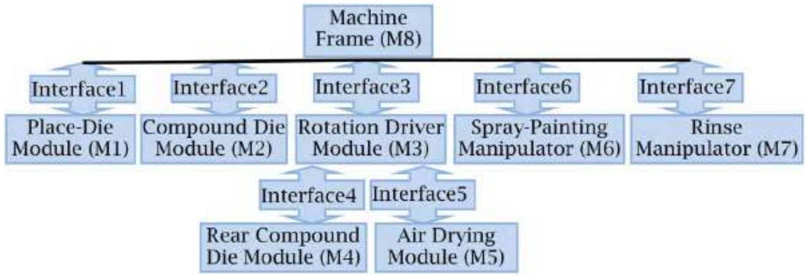


Fig. 3: Modules and interfaces.

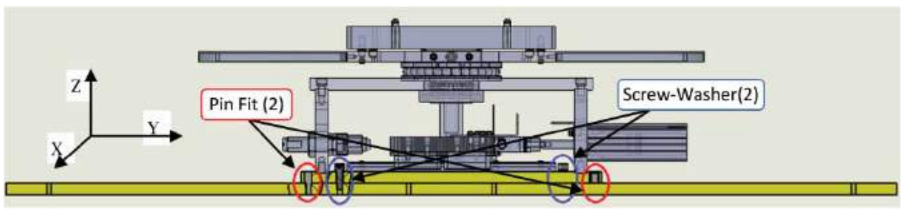


Fig. 4: Interface1 and Module 1.

easy operations without loss of the machine function and reliability. IE is re-calculated for the comparison of solutions using an iteration search processing until reaching satisfaction of the improvement. The new structure can finally be implemented for the interface improvement in the machine design.

The module details and interfaces required are identified based on BOM of the painting machine. The modules are decided based on the machine functional requirements and design parameters. The machine is divided into 8 functional modules using modular design methods. Interfaces are used for the connection of these modules. There are 7 interfaces linking 8 modules of the painting machine, their locations are indicated in Fig. 1. The machine frame (M8) is a base used to install other modules through the interfaces as shown in Fig. 3.

Like the common structure of mechanical interfaces, these interfaces consist of fasteners and connected parts. Fasteners include bolts, screws, and pins to connect modules through the connected parts, or interfaces. The interfaces are made by different mechanical structures to transfer force, torque, or motion between functional modules. As the different shape and size of the functional modules, there are various structures used for the module connections which result in the complexity of interfaces.

Factors to affect the interface complexity include the number of fasteners used, shape and size of connected parts, tools and equipment required in the interface operation, space available for the interface manipulation, etc. Therefore, in order to simplify structures to improve efficiency of interface operations, the interface structure used in the machine has to be evaluated for the improvement. A quantitative measure is essential for the comparison of different structures of interfaces. Based on concepts of mechanical design, design for assembly, and design for disassembly, following assumptions are used for quantitative modeling of the interface analysis.

- Interfaces contain connection parts linked by fasteners.
- Interface assembly or disassembly is manually operated using assembly tools.
- Commonly used fasteners require same or different operations.
- Space around interfaces will affect the interface efficiency.
- Identical tools will increase the interface efficiency.
- Identical fasteners will increase the interface efficiency.
- Number of parts used, parts' size, shape and weight in an interface will affect the interface efficiency.

Based on above discussions and assumptions, a graph is proposed to represent the interface for efficient elements in the operation. The indicated elements are then included into a matrix for data required in the IE calculation. The graph representation shows details of an interface used in the machine with information of connected parts and fasteners, functions to transfer force, torque or motion, and surrounds in the operation. Based on the structure of Interface1 shown in Fig. 4, the interface graph is accordingly represented as shown in Fig. 5. Other interfaces can be depicted using the same process.

Where: represents the module, represents connection methods, represents mating surface couples, \ represents operation space, determines the module center of gravity. (x_g, y_g) is the center of gravity of connected modules. The table

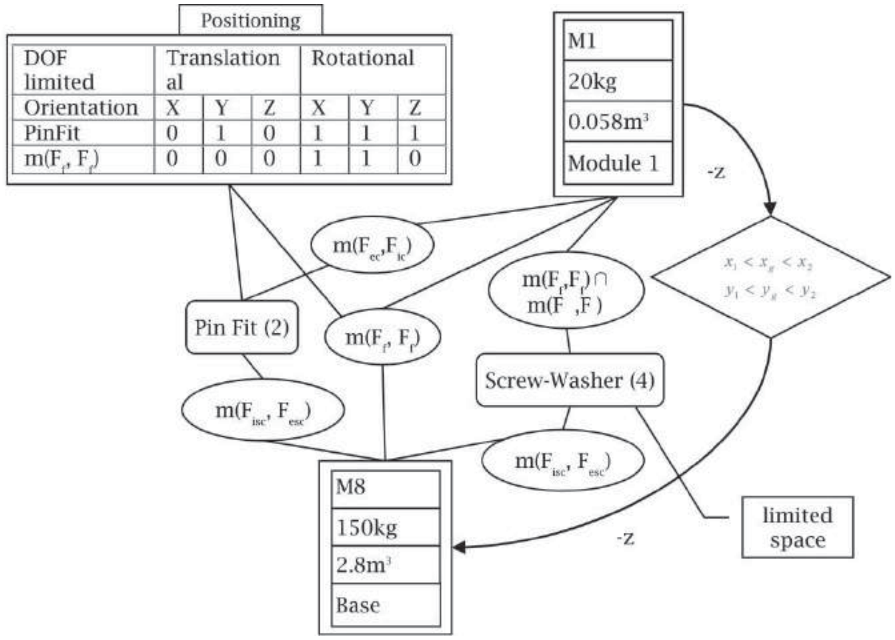


Fig. 5: Representation of Interface1.

includes DOF of modules positioning. x_1 and x_2 are max and min values of the connection between M8 and M1 along X direction, respectively. $y_1$and y_2 are max and min values of the connection between M8 and M1 along Y direction, respectively. The connection sequence and directions can be obtained based on Fig. 4 and Fig. 5 as Screw → Washer → M1 →M8.

4. INTERFACE EFFICACY (IE)

Interface efficacy (IE) is defined for the operation efficiency of interfaces in this research. IE is an interface measure proposed based on solutions from product design for assembly and disassembly. Evaluation criteria of the interface efficiency are proposed based on the geometrical and operational complex of the connection operation for modules and interfaces. The factors and data are collected based on the common measures used for the evaluation of product assembly and disassembly [10,11]. The criteria used are based on assumptions including connector attributes (e.g, number, size, weight, etc.), positioning attributes (e.g, ease of position, easy of handling, etc.), and operation attributes (e.g, accessibility, ease of assembly, tool applications, etc.). The interface efficacy is proposed as follows:

$$IE = f(V_P, V_C, V_G, V_O, V_T, V_A) \tag{4.1}$$

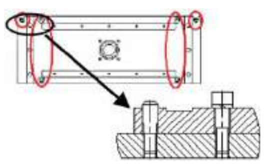
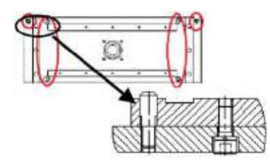
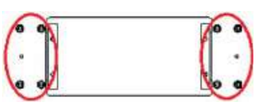
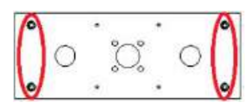
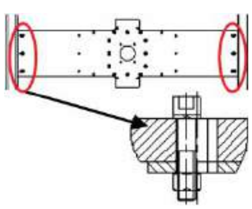
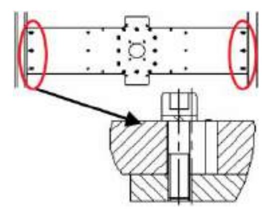
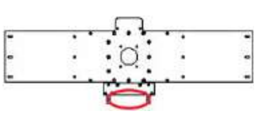
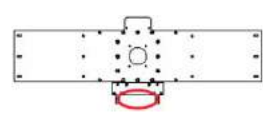
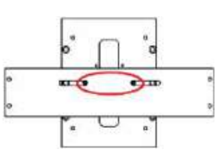
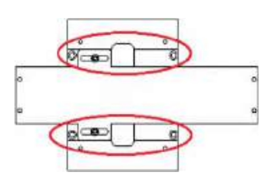
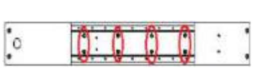
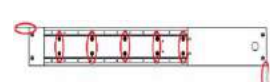
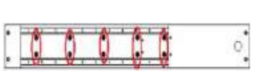
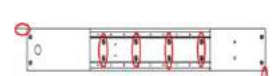
Where, variables are index values. V_P is an index value related to parts or modules connected, Vc is index value related to connectors used, V_G is related to geometry complexity, Vo is for operation complexity, V_T is for tools used in the operation, and V_A is for spatial accessibility. Geometry complexity includes parts' size, shapes, weight, etc. Operation complexity considers fasteners' operations and positions. Index values are described using the coefficient, a number between 0 to 1. Values of these elements are assigned by weighting factors for their importance in the interface operation. Therefore, the weighted IE is

Vc						V_P		V_G					
Types ($V_{species}$)		Connection (V_{type})		Number (V_{number})				Shape (V_{shape})		Module size (V_{size})		Module Kg (V_{weight})	
N_S	w	type	w	N_C	w	No. of Modules	w	couple	w	mm^3	w	Kg	w
0	1	Various fasteners		0	1	2	1	Various couples		$\leq 10^2$	0.5	≤ 20	1
1	0.8			1–4	0.8	3	0.6			10^2–10^8	1	20–80	0.5
2	0.6			5–10	0.5	$\geq$4	0.2			$\geq 10^8$	0.3	≥ 80	0.3
$\geq$3	0.3			$\geq$11	0.3								

Tab. 1: Index values of V_c, V_p and V_G.

Operation complexity (Vo)				Spatial accessibility (V_A)		Tools used (V_T)	
Position ($V_{position}$)		Operator ($V_{operator}$)					
Limited DOF	w	N_O	w	Space	w	N_T	w
<3	0.3	1	1	enough	1	0	1
3	0.7	2	0.5			1	0.8
4	0.8						
5	0.9	≥3	0.2	limited	0.4	2	0.5
6	1					≥3	0.2

Tab. 2: Index values of V_o, V_A and V_T.

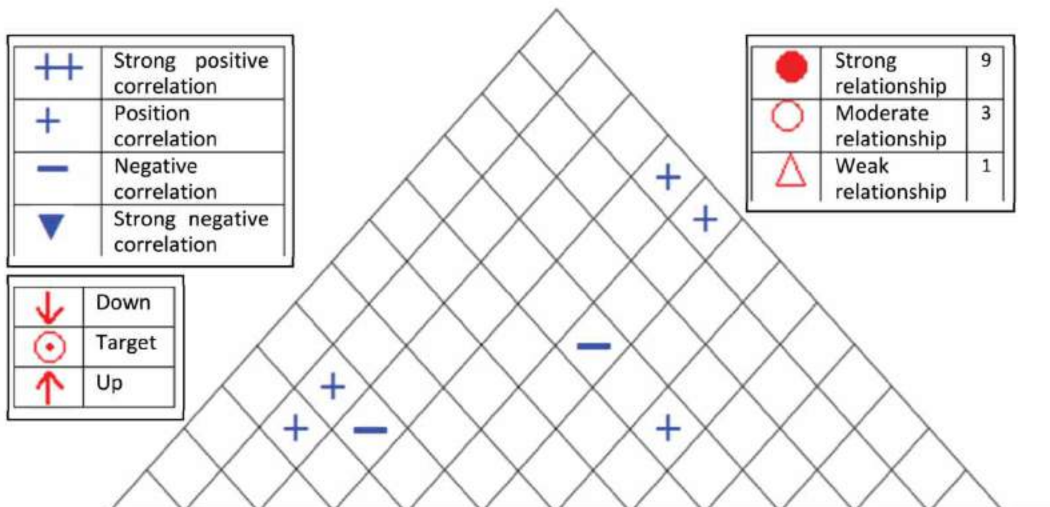
	Original	Changes made	IE before	IE After	Improv	After improvement
1		Change fastener types; Change installation directions from up to down into from down to up.	72.6%	84.8%	12.2%	
2		Combining fasteners; Simply connection parts; Add positioning area; Extending M2 connecting area; Change installation direction.	70.3%	86.7%	16.4%	
3		Change fastener types for easy operation.	72.3%	78.1%	5.8%	
4		Combining fasteners; Extending M4 connecting areas; Moving center of gravity into connection area.	75.3%	85.7%	10.4%	
5		Add positioning area in connection areas Change M5 connection area shape for easy operation.	72.1%	89.1%	17.0%	
6		Combining fasteners; Add positioning area; Change screw installation directions.	53.7%	74.1%	20.4%	
7		Combining fasteners; Add positioning area; Change screw installation directions.	53.7%	74.1%	20.4%	

Tab. 3: Comparison of interfaces improvement.

formulated as:

$$IE = (W_P V_P + W_C V_C + W_G V_G + W_O V_O + W_T V_T + W_A V_A) {}^* 100\% \quad (4.2)$$

Where Wp, Wc, W_G, Wo, W_T, W_A are weighting factors of items in the calculation equation, including parts connected, connectors used, geometry complexity, operation complexity, tools used in the operation,



	Use the same connections	Choose maneuverable connections	Merger connections	Use geometrical shape of interface to replace connections	Use standard connections	One interface connected only two modules	Add locating surface	Module partition to medium size and weight	Add locating element	Change installation direction of modules	Change installation direction of connections	Choose less tools used connection type	Importance Weight
Less connection species	●		△	●	△				○				7
Simple connection mode		●	○	○	△				△			○	6
Less number of connections	△	△	●	●	△				△				7
Less modules connected by the same connections						●							10
Easily connection interface shape							●						8
Medium sized module								●					6
Medium weight module								●					6
Module easy to positioning							●		●				10
Less operator								○		○			10
Enough operating space				△						○	○	△	20
Less tools used	○	△		○	○				○			●	10
Importance Weight Total	100	71	88	194	50	90	162	138	154	90	60	128	
Relative Weight Total	8	5	7	15	4	7	12	10	12	7	5	10	
Priority	4	6	5	1	7	5	2	3	2	5	6	3	
Ideal Value		↓	↓					⊙	↓			↓	

Fig. 6: HOQ for the interface improvement.

and operation accessibility. In this research, these weighting factors are set as the value of 0.1, 0.2, 0.2, 0.2, 0.1, 0.2, respectively, representing the importance of these evaluation aspects based on the assumption. The total of weighting factors equals 1. The details of items of $V_{C,}$ $V_{G,}$ and V_O are listed in Tab. 1. The values of them are calculated as follows.

$$
\begin{aligned}
&Vc = (V_{species}.V_{type} + V_{number})/2,\\
&V_G = (V_{shape} + V_{size} + V_{weight})/3,\\
&Vo = (V_{position} + V_{operator})/2 \qquad (4.3)
\end{aligned}
$$

Details of index values of V_o, V_A and V_T are listed in Tab. 2. w is the weight of each items in Tables.

For commonly used various fasteners, including Bolt-Nut-Washer, Screw, Screw-Washer, Pin Fit, Taper Fit, Key-Key Way, and Spline Fit [19], their weighting factors are assigned as 0.7, 0.8, 0.75, 0.9, 0.9, 0.9 and 0.8, respectively, considering the number of parts and tools used in the operation.

For various surface couples [22], representations are used as F_f – flat surface, F_{ic} - internal cylinder , F_{ec}- external cylinder, F_{ip} - internal conical surface, F_{ep} - external conical surface, F_{is}- internal spherical surface, F_{es} - external spherical surface, F_{isc}- internal screw and F_{esc} - external screw. The mating surface couples are used to indicate the surface connection of interfaces, such as $m(F_{f,}\ F_{ec})$ is the connection of a flat and external cylinder. The weighting factors are assigned based on the DOF limited. The mating information is also indicated in the graph represetation of interfaces shown in Fig. 5.

5. INTERFACE EVALUATION AND IMPROVEMENT

Take Interface1 as example, IE is calculated using following steps:

1) Identify Interface1 as the connection between M1 and M8 from Fig. 1 and Fig. 3.
2) Obtain the interface connection information from Fig. 4. M1 and M8 are connected by Screw-Washer (2) and Pin Fit (2), positioning limits 4 DOF. There is a limited space for the operation.
3) Based on the data in Tab. 1 and Tab. 2, V_{type}= (0.75+0.9)/2 = 0.825, number of connectors: N_C = 4*2+2 =10, number of tools: N_T = 1+0 =1.
4) Index values of IE can then be obtained from Tab. 1 and Tab. 2, IE of Interface1 can then be calculated using Eqn. 4.3 and Eqn. 4.2 as follows:

$$
\begin{aligned}
&V_P = 1, Vc = (0.6^*0.825 + 0.5)/2 = 0.498,\\
&V_G = (0.8 + 1 + 1)/3 = 0.933,\\
&Vo = (0.8 + 1)/2 = 0.9, V_T = 0.8, V_A = 0.4,
\end{aligned}
$$

$$
\begin{aligned}
IE = &(0.1^*1 + 0.2^*0.498 + 0.2^*0.933\\
&+ 0.2^*0.9 + 0.1^*0.8 + 0.2^*0.4)^*100\%\\
= &72.6\%.
\end{aligned}
$$

Similarly, IE of all seven interfaces can be obtained as those shown in Column 4 of Tab. 3.

Based on the proposed IE, the machine interface efficiency is evaluated. The solutions of IE are listed in Column 4 of Tab. 3. It can be observed that IE values are from 53.7% for Interfaces 6 and 7 to 75.3% for Interface4 based on initial design of the machine.

Following strategies are proposed for the interface improvement based on our knowledge and assumptions:

- Reduce numbers of connectors if possible,
- Reshape structure into symmetric if allowed,
- Use same connectors in interfaces,
- Add positioning area,
- Adjust installation directions if possible,
- Adjust fastener installation directions if allowed,
- Use less or identical tools in the operation.

In order to analyze factors that affect the interface IE, House of Quality (HOQ) is used for strategies planning to improve interfaces based on the possible solutions listed in Fig. 6. Conflicts of these possible solutions are also analyzed. The solutions are then ranked in HOQ to decide the priority of change areas of interfaces among the effect factors to improve IE.

Based on improvement solutions analyzed in HOQ shown in Fig. 6, the interface structures and connection methods are revised to improve IE of the machine. Column 5 in Tab. 3 lists improved IE values after the changes are made. The change details are listed in Column 3 of Tab. 3. Percentages in Column 6 show the interface improvement using the IE comparison of interfaces before and after the improvement. It can be observed from the results that the range of improvement is from 5.8 % for Interface3 to 20.4 % for Interface6 and Interface7. The improvement so far only considers the connection parts of interfaces without changing design of modules, which limits the further improvement of the interface efficacy.

6. CONCLUSIONS

Mechanical interfaces of product realize function interactions of components and modules. Adaptable products promise that products' function upgrading or changing can be performed by either product developers or users by adding or replacing functional modules in the product. Adaptable products depend on adaptable interfaces to upgrade or replace function modules of the products. The interface of adaptable products therefore should be designed for easy operations of assembly and disassembly when the product modules are changed.

This research suggested IE to measure the interface efficiency. The measure provides a direction to improve the design of interfaces for an adaptable painting machine. An initial result shows the improvement of interface operations with the reduced time and efforts to change functional modules for different user requirements. After the general method is developed for the interface evaluation, the focus will be moved on the modules and related interfaces that have the frequent change requirement. Further work will analyze the entire structure of the machine from top to bottom using the adaptable design method to improve adaptability of the machine completely. The index values will be validated in the machine operation environment. Training data will be tested for some experience-based coefficients using machine learning methods.

ACKNOWLEDGEMENTS

The authors wish to acknowledge that this research has been supported by Guangdong Province of China through the Leading Talent Project to Peihua Gu and by the Natural Sciences and Engineering Research Council (NSERC) of Canada through the Discovery Grants to Qingjin Peng.

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