COMPUTER-AIDED DESIGN & APPLICATIONS, 2017
VOL. 14, NO. 6, 778–788
https://doi.org/10.1080/16864360.2017.1287938

Accessibility analysis of tools in product module interface operations

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ABSTRACT
Open-architecture product (OAP) is designed with the modular structure using personalized modules to meet different customer requirements. Different functional modules are connected to common platform modules through adaptable interfaces. This paper presents a method for the accessible analysis of tools in the interface operation to replace personalized modules of the OAP. The proposed method integrates a box-based method and the global accessibility cone with depth. Interfaces are classed and coded to meet needs of the interface management in the analysis. The tools are classified based on their access angles. An industrial paper-bag folding machine is used in the case study to verify the proposed method.

KEYWORDS
Interface; Assemble/disassembly tool; Accessible analysis

1. Introduction

Product personalization and market globalization require product meeting different needs of users. Open-architecture product (OAP) is proposed using adaptable interfaces and different functional modules to achieve the product adaptability, extendibility and sustainability [14, 23]. The functional modules in an OAP include common platform modules, customized modules and personalized modules. These three types of modules are connected using adaptable interfaces to form an OAP. Adaptable interfaces are used to connect functional modules to ensure that personalized requirements are satisfied through upgrading or replacing of functional modules. The interface affects the operation of functional modules in the replacement, which impacts the product adaptability. The operation efficiency of a product interface is also important for third parties to develop personalized modules for different users. It is therefore important for interfaces to connect modules with the operation efficiency in the module assembly and disassembly [7].

In order to transform product specifications into component configurations based on required product functions, interfaces integrate product modules with a structure mapped from product functional requirements to physical components [1]. Based on the functional requirement, a product interface may transfer power, motion or information using different physical structures or formats. Operability of an interface is decided not only by its function property, but also its attended mode and operation space. Interfaces are essential for development and applications of the OAP. Varieties of interface attributes cause complicated operations in the assembly and disassembly of modules [5]. The interface classification, operational space and tools are important elements for the interface accessibility, which has switched research focuses from the modular design into feasibility analysis of interfaces. It is essential for the tool operability and accessibility of interfaces in the assembly and disassembly of product modules. It is necessary to look at relations between interfaces, and constraints of modules and interface to ensure the adaptability of interfaces. Considering the lack of research on the interface accessibility, product interfaces are analyzed in this paper to evaluate OAP interfaces and tool operations. The proposed method combines a box-based method and the global accessibility cone with depth to analyze the tool accessibility for interface operations. This research also presents an approach to class and code interfaces in order to manage interfaces for the accessibility of operation tools.

Following parts of the paper will first review the related research on the interface representation, classification, standardization, evaluation and improvement. Methods of the classification and coding of interfaces, tools for interface operations, and the feasibility analysis of interface operations are then presented. Conclusions and further work are followed after the discussion of the proposed method application in the accessible analysis of

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interfaces used in a case study of the industrial paper-bag fording machine.

2. Related research

In order to transform product specifications into component configurations based on required product functions, a key step in product design is to construct an appropriate product structure [1]. Interfaces between components are used to connect different elements of a product with a structure mapped from product functional requirements to physical components. An ideal modular product can meet the one-to-one correspondence between modules and functions [16].

There are three types of modules defined in an OAP including common platform modules, customized modules and personalized modules [20]. Interfaces can be divided into three groups based on connections of these three module types: common module interfaces (COI), customized module interfaces (CUI) and personal function interfaces (PFI) [10]. An interface is defined as a common port to connect or combine functional units, exchange energy, transform information, material or media that performs specific functions through linked functional units by the interface. Based on the technique specification, interfaces can be classified into mechanical interface (MI), electrical interface (EI), information interface (II), gas interface (GI), liquid Interface (LI), optical interface (OI), acoustic interface (AI), chemical interface (CI), software interface (SI), man-machine interface (MMI), etc. Based on the purpose of applications, interfaces can also be defined as mechanical connections, electrical connections, liquid pipe connections, gas circuit connections, etc. A mechanical interface is defined as relationships of structure connections including plugging interface (PI), thread interface (TI), flange interface (FI), groove interface (GI), hook interface (HI), pylon interface (PYI), etc [12, 13].

Interfaces are essential for a product to connect different modules and components. Varieties of interface attributes cause complicated operations in the assembly and disassembly of these components and modules [5]. The classification, operational space and tools of interfaces are important for standardization and modularization of the interfaces, which has switched research focuses from modular design to feasibility analysis of interfaces. Operation-embedded analyses for modular design improve the efficiency of module operations to benefit the interface commonality of modular products [20]. Research on the tool operability and accessibility in the interface assembly and disassembly considers relative locations of interfaces and modules, and interface constraints for the module placement to ensure the adaptability and reliability of interfaces [22]. Different methods have been proposed for the analysis of interface operations, such as an expended global accessible cone applied to analyze the space accessibility of operation tools in the product assembly [5]. A bounding box is commonly used for the verification of static interferences of parts [2, 21]. It is necessary to combine the box-based method and global accessibility cone with depth to analyze the tool feasibility for interface operations. The concept of a global accessibility cone can be used in the tool accessibility analysis to reduce the computation complexity [5, 24].

Research on the interface representation, classification, standardization, evaluation and improvement is summarized in Fig. 1. It is found that the most interface research uses the function-behavior-state in the

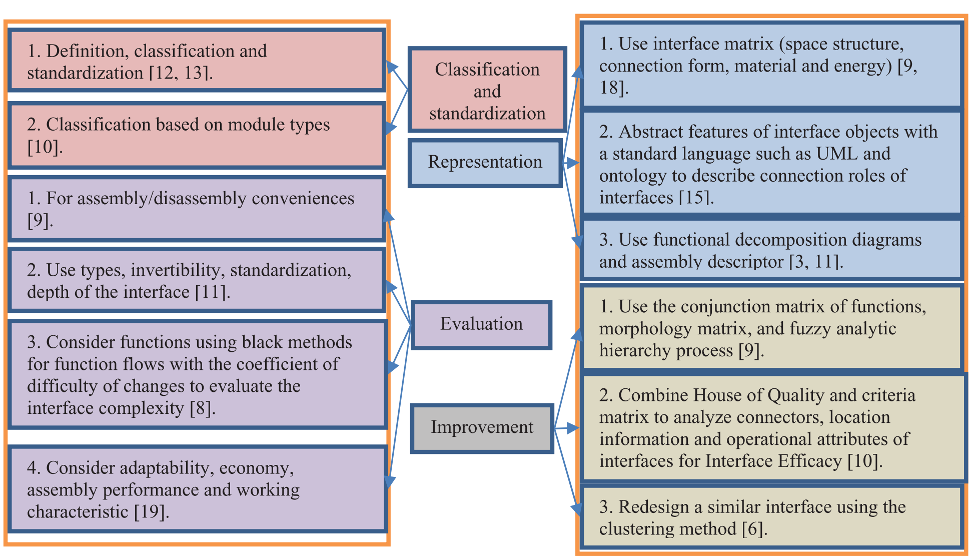

Figure 1. Interface research.

functional design based on the product structure. Analytical models are built to abstract interface details from the physical form. In addition, the research tends to search parameters that may impact interface properties in the evaluation or improvement of the interface.

In summary, although different research actives have been conducted for the representation, classification and standardization, evaluation and improvement of product interfaces and interface operations, these research solutions have limitations. The existing methods are mainly proposed for connections of components in product assembly or disassembly operations. There is a lack of a general method to integrate the interface classification, operational space and tools for the interface feasibility analysis.

The method presented in this paper focuses on the accessible analysis of interfaces with the integration of interface types, operational space constraints and accessibility analysis of operational tools. The method integrates a box-based method and the global accessibility cone with depth (GAC^d). Following sections of the paper introduce details of the method and applications in an industrial paper-bag folding machine.

3. Proposed method

3.1. Classification and coding of interfaces

This research considers interfaces in the modular product. An interface is defined as a connector between product modules. A code of the interface representation is proposed for the classification based on module types, technique specifications, relationships of structure connections and connection forms. The code is a string of characters describing an interface. Similarities and differences of interfaces can be distinguished by the code characters. The detailed information of each character of coding is defined in Fig. 2.

A code of the interface is defined with nine parts. Parts 1 and 3 are two modules connected by the interface I_{ij}. $X = \{G, C, P\}$ represents module types. G is a general module, C is a customized module and P is a personalized module.

Part 2 represents the assembly relationships including $\{\rightarrow, \leftarrow, —\}$, where '$\rightarrow$' represents that there exists a connection relationship between modules M_i and M_j, and module M_i must be assembled before module M_j; '$\leftarrow$' is that there exists a connection relationship between module M_i and module M_j, module M_i must be assembled after module M_j; and '—' represents that there exists a connection relationship between module M_i and module M_j, module M_i and module M_j have no assemble sequence required.

Part 4 is a name of the interface according to its connectors.

Part 5 is the technique specification: M is a mechanical interface, E is an electrical Interface, I is an information interface, G is a gas interface, L is a liquid interface, O is an optical interface, A is an acoustic interface, C is a chemical interface, S is a software interface, MM is a man-machine interface, and OT represents other types of interfaces.

Part 6 is the module type: CO is a common module, CU is a customized module, and PE is a personalized module.

Part 7 is decided by the connection structure: P is a plugging interface, T is a thread interface, F is a flange interface, G is a groove interface, H is a hook interface, P is a Pylon interface and O represents other type interfaces.

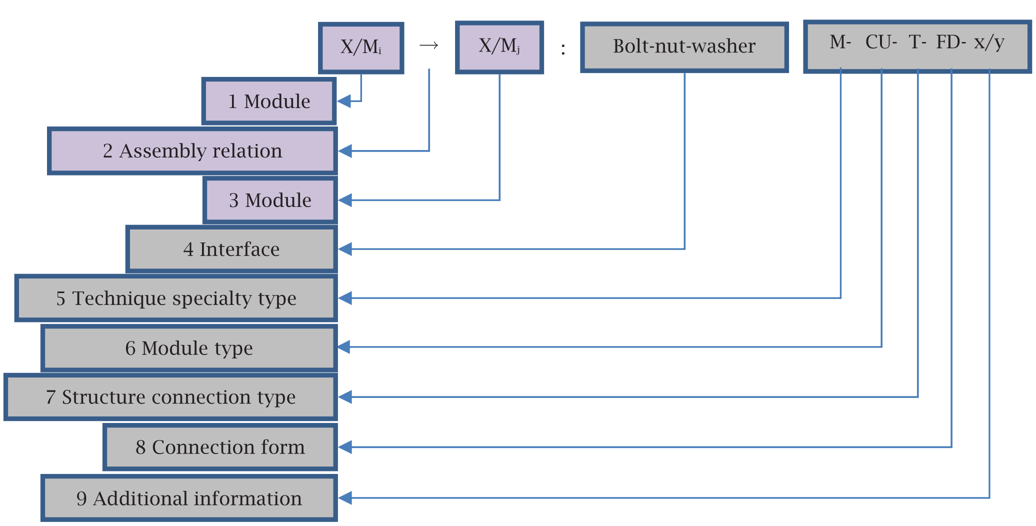

Figure 2. Interface coding definition.

Part 8 is decided by the connection form: MD is a movable and disassembled fastener, FD is a fixed and disassembled fastener, MND is a movable but not disassembled fastener, and FND is a fixed but not disassembled fastener based on the definition of Tseng et al. [19].

Part 9 is the addition of an interface. When a pair of functional units connects to each other with more than one interface, the extension is added to distinguish their types. x represents the sum of interfaces, y represents a specified interface in x.

3.2. Tools for interface operations

Tools are used for implementing operations, measurements and modifications of interfaces. Tools include manual tools, power tools, fitter tools, explosion-proof tools, pneumatic tools, hydraulic tools, measuring and weighing tools, cutting tools and grinding tools, etc. The tools details are based on manuals of hardware tools and website sources [2, 17]. For the convenient analysis, two geometric parameters α and β are defined. Where α is an angle between the fastener y-axis and axial direction of the tool rotation ranging from 0° to 180° while β is the rotation angle of tools, as shown in Fig. 3. While n_f is the rotation axis of a fastener, n_t is the motion axis of a tool. Some of manual operation tools are shown in Fig. 4.

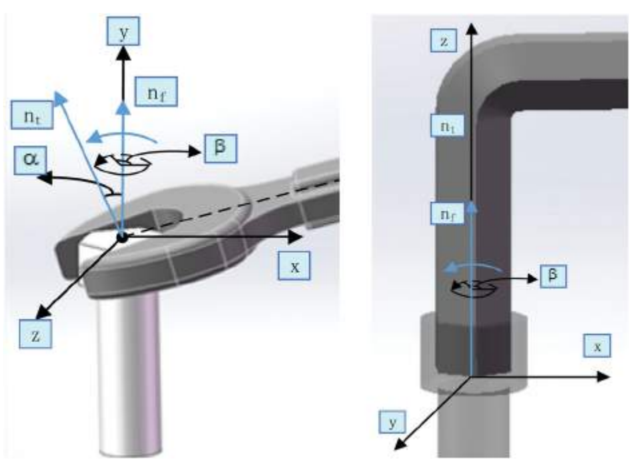

Figure 3. Classification of tools: (a). Tool rotation not around the fastener axis. (b). Tool rotation around the fastener axis.

Figure 4. Manual operation tools: (a). Tools rotation not around the fastener axis (b). Tools rotation around the fastener axis.

3.3. Box-based methods

Bounding box can be a bounding sphere, axis-aligned bounding box (AABB), oriented bounding box (OBB), or a fixed direction hull (K-dops) that provides an envelope surrounding geometry features of a part to test the collision in complex product operational environments. AABB is the smallest six-sided enveloping of a part based on its coordinate axis. Sides and surfaces are parallel or perpendicular to the axis. OBB is a surrounding box of geometry features of a part in a direction to achieve the smallest hexahedron. In a complex environment, OBB and K-dops are complex in the calculation [2]. AABB is used in this research to represent a tool for the accessibility analysis. An AABB for an amphibious wrench in Fig. 4(a) is shown in Fig. 5.

3.4. Global accessibility cone with depth (GAC^d)

GAC^d consists of 180×360 pixels with total 64800 directions on a discrete unit sphere. The number of pixels is exactly matched with 180 colatitude angles (φ) and 360 longitude angles (θ) in a spherical coordinate. There is a one-to-one mapping between directions in the GAC^d and unit vectors in the 3D space, which are defined by angles φ_s and θ_s. φ and θ are used to calculate a unit vector and to represent the operation direction using an equivalent pixel(φ, θ). A GAC^d is formed as follows [5].

- The center point is the initial position of a fastener.
- Y-axis is the fastener removal direction.

Figure 5. Axis-aligned bounding box of the head of an amphibious wrench model.

- The depth information is determined for each direction on a GAC^d by projecting a unit vector onto a face of a surrounding part or obstacle. A triangle patch is used to represent a product part for the ease of calculating the depth with the shortest distance from the center point of a GAC^d. The triangle patch is mapped into a spherical triangle. In a special condition, the spherical triangle is formed by connecting three points mapped on the surface of the GAC^d with great circles passing through the points.
- Based on six points (three vertices and midpoints at three sides of the formed spherical spherical), four pixel boundaries on the GAC^d are defined.
- Every unit vector within the pixel boundaries is projected onto the triangle patch in the 3D space.
- An intersection point is found. If the intersection point is inside the triangle patch, the direction at a pixel within the pixel boundaries is not accessible from the outside.

In this way, the feasibility can be concluded. The depth between the intersection point and center point is found.

3.5. Feasibility analysis of interfaces

An operational tool analyzed in this research is composed of four parts including a head that interacts with interface, a handle used by an operator, a cervix linked to the head and handle, and an extension. Sizes and shapes of the four parts can be different. Each part of a tool is regarded as the independent unit to analyze its accessibility by combining the bounding box and GAC^d. Based on the description shown in Fig. 6, sixteen geometric parameters are defined to represent an operational tool, they are $\alpha, \beta, \alpha_{min}, \alpha_{max}, r_e, h_e, a_a, b_a, c_a, b_c, c_c, a_x, b_x, c_x, d_f$, and L.

Where α is an access angle between y-axis and the rotation direction of a tool head ranging from 0° to 180° while β is the rotation angle of the tool. Based on α, tools are classified into two types: Tool rotation around the fastener axle when α is zero, and Tool rotation not around the fastener axle when α is not necessary zero. When α is zero, the tools are classified into two types: the projection of bounding boxes about all parts of the tool onto X-Z plane is symmetrical about the origin, and the projection of bounding boxes about all parts of the tool onto X-Z plane is not symmetrical about the origin.

An operational tool rotates about y-axis with variations in the access angle α and the fastener removal displacement d_f. In order to analyze its accessibility, a searching range based on these variations is defined along the φ direction at the longitude angle θ. The defined searching range at the angle θ is used for the interference check of the effective handle with a GAC^d including depth information. The check is executed until the required minimum tool-application angle β is found within the GAC^d. As shown in Fig. 7, the searching range for an effective handle at a longitude angle θ is defined via four angles φ_{*1}, φ_{*2}, δ_{*1} and δ_{*2}, where $* = \{e, a, x, c\}$ representing four parts of the tool [5].

Angle β of a tool is transformed into $\Delta\theta$. The calculation process is as follows.

When α is not necessary zero:

$$R_{\max} = \sqrt{(L - r_e)^2 + (b_x/2)^2} + d_f + h_e/2,$$
$$R_{\min} = L - r_e \quad (1)$$

$$Y_1 = Y - (b_*/2)\cos\alpha,\ X_1 = X - e_{*1}\sin\beta,$$
$$Z_1 = Z + e_{*1}\cos\beta, R_1 = \sqrt{X_1^2 + Y_1^2 + Z_1^2} \quad (2)$$

$$Y_2 = Y + (b_*/2)\sin\alpha, X_2 = X + e_{*2}\sin\beta,$$
$$Z_2 = Z - e_{*2}\cos\beta, R_2 = \sqrt{X_2^2 + Y_2^2 + Z_2^2} \quad (3)$$

$$\Delta\varphi = \cos^{-1}\left(\frac{R_1^2 + R_2^2 - b_*^2}{2R_1R_2}\right) \quad (4)$$

$$\varphi_1 = \sin(Y/R), \varphi_2 = \varphi_1 + \Delta\varphi \quad (5)$$

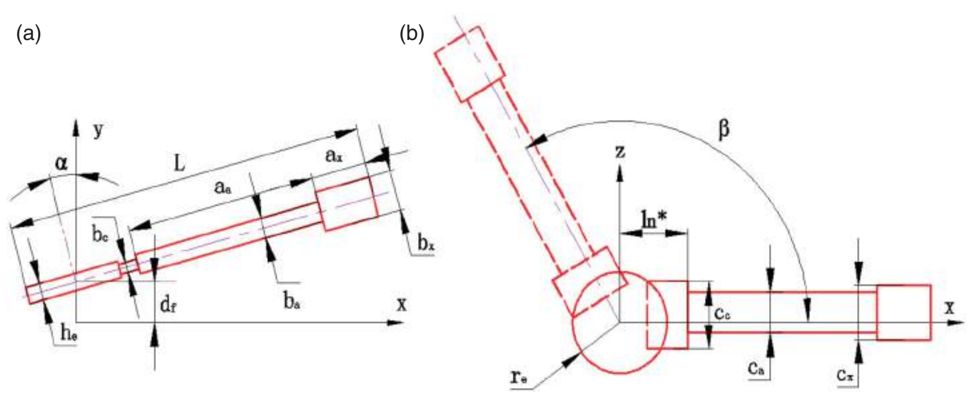

Figure 6. Parameters of a tool: (a) Projection on the x-y plane, (b) Projection on the x-z plane.

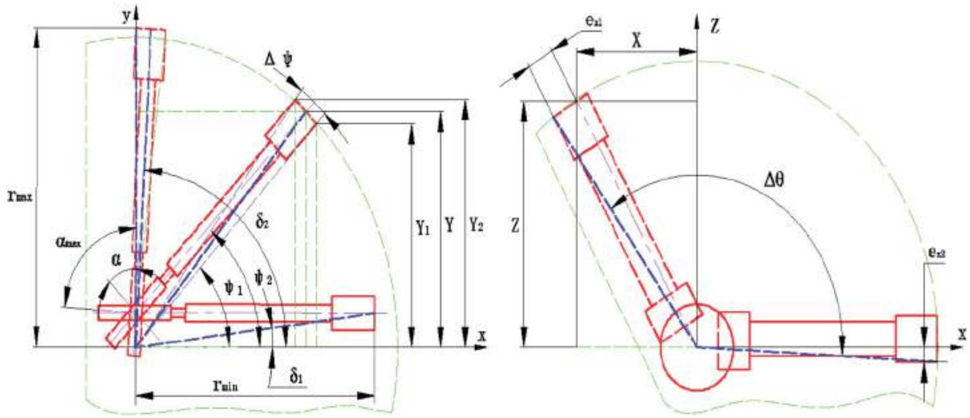

Figure 7. Accessibility analysis of the tool.

$$\delta_{*1} = \tan^{-1}\left(\frac{(L - r_e - a_*)\cos\alpha - (b_*/2)\cos\alpha + \left(d_f + \dfrac{h_e}{2\cos\alpha}\right)\cos\alpha}{(L - r_e - a_*)\cos\alpha + (b_*/2)\sin\alpha}\right) \quad (6)$$

$$\delta_{*2} = \tan^{-1}\left(\frac{(L - r_e - a_*)\cos\alpha + (b_*/2)\cos\alpha + \left(d_f + \dfrac{h_e}{2\cos\alpha}\right)\cos\alpha}{(L - r_e - a_*)\cos\alpha - (b_*/2)\sin\alpha}\right) \quad (7)$$

$$X = (L - r_e)\cos\alpha\cos\beta,$$
$$Y = d_f + h_e/2 + (L - r_e)\sin\alpha,$$
$$Z = (L - r_e)\cos\alpha\sin\beta,\ R = \sqrt{X^2 + Y^2 + Z^2}, \quad (8)$$

$$e_{*1} \cong \frac{c_*}{2} + \left(\frac{b_f}{2} + b_f cos\frac{360^\circ}{n}\right)\sin\alpha_t,$$
$$e_{*2} \cong \frac{c_*}{2} - \left(\frac{b_f}{2} + b_f cos\frac{360^\circ}{n}\right)\sin\alpha_t \quad (9)$$

$$\Delta\theta = \beta + \tan^{-1}\left\{\frac{e_{*1}\cos\beta}{X}\right\} + \tan^{-1}\left\{\frac{e_{*2}\cos\beta}{X}\right\} \quad (10)$$

This process does not include the tool with the zero access angle. If the projection of bounding boxes about all parts of a tool onto X-Z plane is symmetrical about

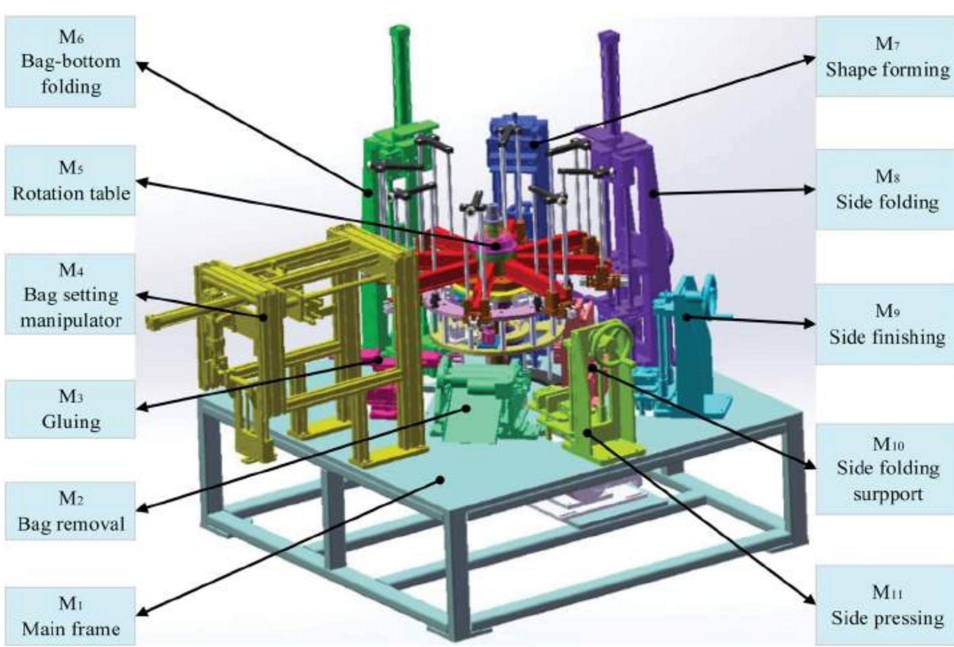

Figure 8. Functional modules of the paper-bag folding machine.

the origin, the analysis process is relatively simple. If the projection of bounding boxes about all parts of the tool onto X-Z plane is not symmetrical about the origin, the analysis is same as those tools with the non-zero α. $\Delta\theta$ is the tool application angle. Following formulas are for the tool analysis when $\alpha = 0$ and the projection onto X-Z plane is not symmetrical about the origin.

$$\delta_2 = 90^\circ + \tan^{-1}\left(\frac{b_x/2}{d_f + h_e + a_x}\right),$$
$$\delta_1 = 90^\circ - \tan^{-1}\left(\frac{b_x/2}{d_f + h_e + a_x}\right) \quad (11)$$

$$\varphi_2 = 90^\circ + \tan^{-1}\left(\frac{b_x/2}{d_f + h_e}\right),$$
$$\varphi_1 = 90^\circ - \tan^{-1}\left(\frac{b_x/2}{d_f + h_e}\right) \quad (12)$$

Every part of a tool has corresponding four parameters: φ_{*1}, φ_{*2}, δ_{*1} and δ_{*2}. The minimum distance between parts or obstacles around the interface and the center of a GAC[d] in an operational tool working state is used to decide accessibility of the tool to see if the intersection point between the direction of the pixel (φ, θ) and the tool is in the area of the tool. There are three

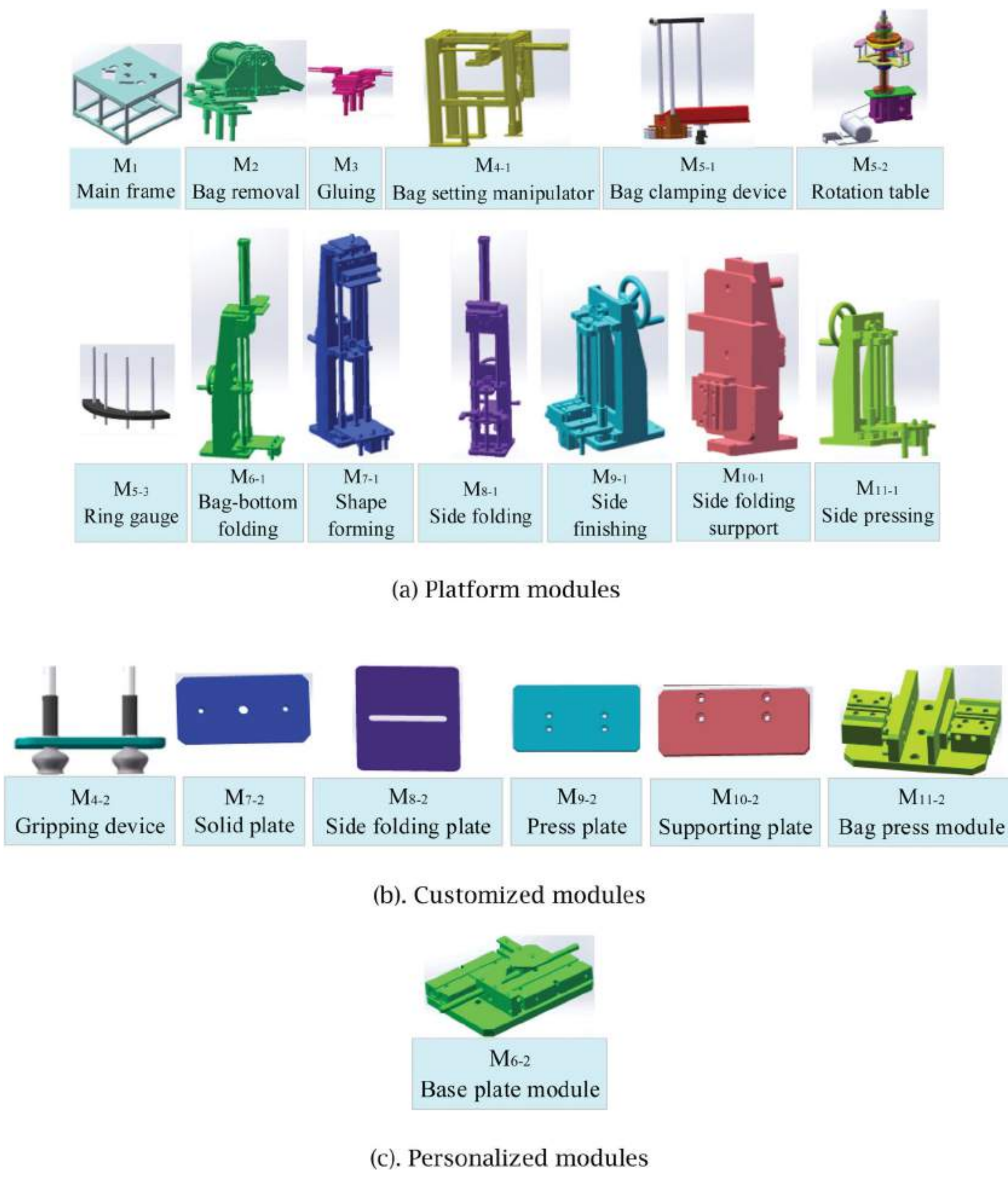

Figure 9. Different modules of the paper-bag folding machine.

different criteria examined for three different angle configurations: (a) $\varphi_{*1} < \delta_{*1} \wedge \varphi_{*2} < \delta_{*2}$, (b) $\varphi_{*1} < \delta_{*1} \wedge \varphi_{*2} > \delta_{*2}$, (c) $\varphi_{*1} > \delta_{*1} \wedge \varphi_{*2} > \delta_{*2}$.

φ is found by searching the point in the GAC^d surface that has the minimum distance between parts or obstacles around an interface and the center point of the GAC^d. Formula 13 is used to examine the feasibility ($\Re$) of configuration (a), Formula 14 is used to examine feasibility ($\Re$) of the configuration (b), and Formula 15 is used to examine feasibility ($\Re$) of the configuration (c) [5].

$$\Re = \begin{cases} 1 & r(\varphi) \le R(\varphi,\theta) \vee r(\varphi) \ge R(\varphi,\theta) \\ 0 & \min(\varphi,\varphi) \le \varphi \\ & \quad \le \max(\delta,\delta) \vee \theta \le \beta \end{cases} \tag{13}$$

$$\Re = \begin{cases} 1 & r^{\varphi_{*1}}(\varphi) \le R(\varphi,\ \theta) \vee r^{\varphi_{*2}}(\varphi) \ge R(\varphi,\theta) \\ 0 & \min(\varphi_{*1},\ \delta_{*2}) \le \varphi \\ & \quad \le \max(\delta_{*1},\ \varphi_{*2}) \vee \theta \le \beta_{\min} \end{cases} \tag{14}$$

$$\Re = \begin{cases} 1 & r^{\varphi_{*1}}(\varphi) \le R(\varphi,\ \theta) \vee r^{\varphi_{*2}}(\varphi) \ge R(\varphi,\ \theta) \\ 0 & \min(\delta_{*1},\delta_{*2}) \le \varphi \\ & \quad \le \max(\varphi_{*1},\varphi_{*2}) \vee \theta \le \beta_{\min} \end{cases} \tag{15}$$

$$r^{\varphi_{*1}}(\varphi) = \frac{L\sin(90^\circ - \alpha - \varphi_{*1})}{\sin(90^\circ - \alpha - \varphi)}, \quad r^{\varphi_{*2}}(\varphi) = \frac{L\sin(90^\circ - \alpha - \varphi_{*2})}{\sin(90^\circ - \alpha - \varphi)} \tag{16}$$

Where $* = \{e,\ a,\ x,\ c\}$including the head, cervix, handle and extension of a tool during analysis. The accessibility of all parts of a tool is analyzed independently based on access angle α, the moving distance of the interface, and features of a GAC^d. The axis-aligned bounding boxes of all tool parts are embedded into the proposed method to solve problems such as any irregular shape and great size difference of the head and the handle. A searching process is repeatedly executed on a constructed GAC^d. The process includes the four individual feasibility analyses for an assembly tool, which continues until an interface is completely assembled or disassembled (i.e., $d_f \ge l_f$, where l_f is the contact length of the interface and connected modules) without any collision with surroundings.

The proposed method combines parameterized axis-aligned bounding boxes of assembly tools and a non-homogeneous global accessibility cone that approximates obstacles of an interface being assembled. It avoids the use of complex collision-detection methods. The method can simply deal with complex variations in an interface movement and a tool access angle. It is a relative fast reasoning method.

4. Case study

4.1. 3D models and module types of a paper-bag folding machine

An industrial paper-bag folding machine is used as a case study to verify the proposed method. 3D machine models, module connections and module types of the machine are shown in Figs. 8 and 9 [24].

4.2. Accessibility analysis

Fig. 10 shows details of interface connections. Types and codes of interfaces, module connections and operation tools of interfaces are listed in Tab. 1 based on the description and definition in Section 3.1. Single-headed wrench stay, hexagon wrench and two different specifications of Philips screwdrivers are four tools used for interface operations in the paper-bag folding machine. A common feature of these four tools is that the handle and head are connected directly, i.e. $b_c = c_c = a_x = b_x = 0$. The difference is that the access angle of a single-headed wrench is variable although it is set to zero in this analysis for the convenience in the calculation.

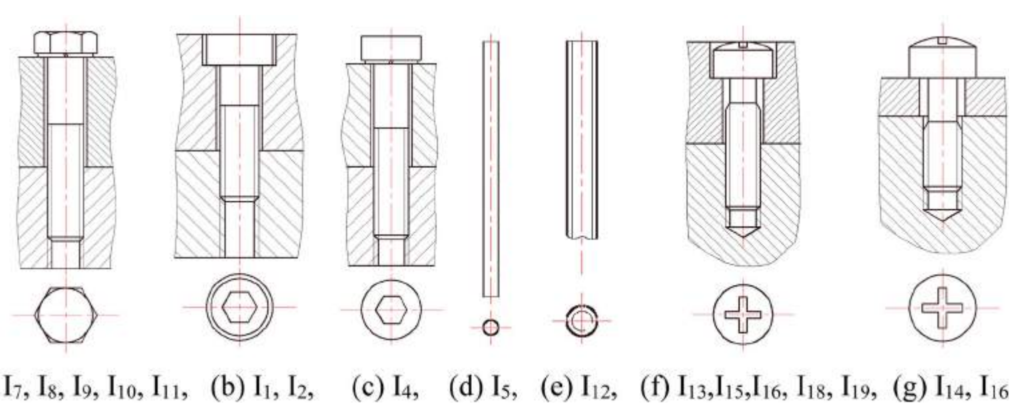

Figure 10. Details of the interface connections.

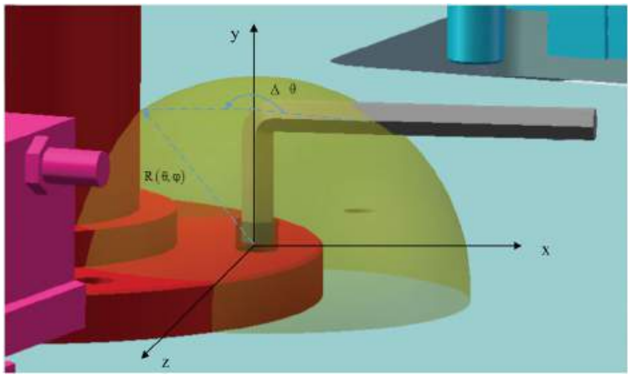

Figure 11. The GAC^d and initial position of the hexagon wrench for the operation of I_4

Due to the space limitation, a hexagon wrench is selected to explain the analysis process for the accessibility of interface I_4. The GAC^d and initial position of the hexagon wrench in the operation of I_4 is shown in Fig. 11. The type and code of the interface, connected modules, and the operation tool of the interface are listed in Tab. 1. The projection of bounding boxes about the hexagon wrench onto the X-Z plane is not symmetrical about the origin, $\alpha = 0$. The initial position of the hexagon socket head cap screws becomes the center point of the GAC^d, and the removal direction of the hexagon socket head cap screws is aligned to its y-axis. Tool parameters and calculation results are shown in Tab. 2. Based on the analysis, the minimum application angle

Table 1. Interfaces and operational tools of the modules.

InF	Modules and assembly relationship			Name	Encoding	identity	Corresponding tools	criterion
I_1	G/M_1	←	G/M_2	Hexagon socket head cap screws	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×25	Hexagon wrench	GB/T 5356-2008
I_2	G/M_1	←	G/M_3	Hexagon socket head cap screws	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×25	Hexagon wrench	GB/T 5356-2008
I_3	G/M_1	←	G/M_{4-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_4	G/M_1	←	G/M_{5-2}	Hexagon socket head cap screws	M-S-T-FD-1/2-6	GB 70-85 M8×30	Hexagon wrench	GB/T 5356-2008
I_5	G/M_1	←	G/M_{5-3}	adjusting rod of ring gauge	M-S-T-MD-1/1-4	12 Φ	hand	
I_6	G/M_1	←	G/M_{6-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_7	G/M_1	←	G/M_{7-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_8	G/M_1	←	G/M_{8-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_9	G/M_1	←	G/M_{9-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_{10}	G/M_1	←	G/M_{10-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_{11}	G/M_1	←	G/M_{11-1}	Outer hexagon bolt	M-S-T-FD-1/1-4	Hexagon bolts GB /T 5782-2000 M8×38	single-headed wrench stay	GB/T 4388-2008
I_{12}	G/M_{4-1}	←	C/M_{4-2}	threaded rod	M-HO-T-FD-1/1-2	M8	hand	
I_{13}	G/M_{4-1}	←	C/M_{4-3}	Cheese head screws with cross recess	M-O-T-FD-1/1-2	GB 65-85 M4×12	Philips screwdrivers PH2×	GB/T 10640-1989
I_{14}	G/M_{6-1}	←	P/P_{6-2}	Cheese head screws with cross recess	M-O-T-FD-1/1-4	GB 65-85 M5×12	Philips screwdrivers PH2×	GB/T 10640-1991
I_{15}	G/M_{7-1}	←	C/P_{7-2}	Cheese head screws with cross recess	M-HO-T-FD-1/1-2	GB 65-85 M5×16	Philips screwdrivers PH2×	GB/T 10640-1992
I_{16}	G/M_{8-1}	←	G/P_{8-2}	Cheese head screws with cross recess	M-HO-T-FD-1/1-2	GB 65-85 M5×16	Philips screwdrivers PH2×	GB/T 10640-1993
I_{17}	G/M_{9-1}	←	G/P_{9-2}	Cheese head screws with cross recess	M-HO-T-FD-1/1-4	GB 65-85 M5×16	Philips screwdrivers PH2×	GB/T 10640-1994
I_{18}	G/M_{10-1}	←	G/9_{10-2}	Cheese head screws with cross recess	M-HO-T-FD-1/1-4	GB 65-85 M4×14	Philips screwdrivers PH2×	GB/T 10640-1995
I_{19}	G/M_{11-1}	←	G/M_{11-2}	Cheese head screws with cross recess	M-HO-T-FD-1/1-4	GB 65-85 M6×22	Philips screwdrivers PH3×	GB/T 10640-1989

Table 2. Tool parameters and calculation results.

Classification of tools	Name of tools	L	α	$\beta(^\circ)$	r_e	h_e	a_a	b_a	c_a	d_f	Y	X	Z	R
$\alpha = 0$	Hexagon wrench	96.82	0	30	3.41	38	90	6	6.82	30	80.09	158.0	46.71	183.55

$\Delta\theta$	Y_1	X_1	Z_1	R_1	Y_2	X_2	Z_2	R_2	$\varphi*1$	$\Delta\varphi$	$\varphi*2$	d*	l*	$\sigma*1$	$\sigma*2$
34.18	77.94	158.00	48.41	182.71	83.85	158.00	45.00	184.44	59.86	1.79	61.65	68.00	68.09	87.13	88.12

$\beta_{\min}$ of the hexagon wrench is 30°. According to Tab. 2, $\varphi_{*1} = 59.86$, $\varphi_{*2} = 61.65$, $\delta_{*1} = 87.13$, $\delta_{*2} = 88.12$, $\varphi_{*1} < \delta_{*1} \wedge \varphi_{*2} < \delta_{*2}$, which meet the condition (a), Formulas 13 and 16 are available to calculate feasibility of the hexagon wrench. For the condition: $\beta \geq \beta_{\min}$, that is $\theta \geq \beta_{\min} = 30^\circ$, while there is: $\varphi \approx \tan^{-1}\frac{Y}{36.5} \approx 66^\circ$, 36.5 is an approximate distance based on the GAC^d method. In this case:

$$r^{59.6^\circ}(66^\circ) = \frac{96.82 \sin 30.4^\circ}{\sin 24^\circ} \approx 119.7,$$

$$r^{61.65^\circ}(66^\circ) = \frac{96.82 \sin 28.35^\circ}{\sin 24^\circ} \approx 119.7 \qquad (17)$$

$$R(\varphi, \theta) \approx \sqrt{36.5^2 + Y^2} \approx 87.62 \qquad (18)$$

Therefore, $\Re = 1$ is achieved based on Formulas 17, 18 and 13. The hexagon wrench is accessible to operate interface I_4.

5. Conclusions

Product interfaces support connections and interactions of functional modules in an OAP. The interfaces should be operable and feasible to meet the OAP need in upgrading function modules. This paper analyzes the interface feasibility based on interface types, module connections and operation tools. The tools are divided into two types based on the access angle defined during the operation. GAC^d is combined with the box-based representation to simplify the analysis of the complex structure for operation tools in the interface accessibility. The proposed tool accessibility reasoning method is based on parameterized operational tools and the global accessibility cone with depth that approximates obstacles of the interfaces. It avoids detecting the complex collision for a relative easy analysis method. Further work of this research will consider the interface improvement and the assembly sequence optimization with the interface feasibility.

Acknowledgements

The authors wish to acknowledge that this research has been supported by the National Natural Science Foundation of China (No.51375287), and Discovery Grants (RGPIN-2015-04173) of the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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