

Intelligent approaches for generating assembly drawings from 3-D computer models of mechanical products

Ke-Zhang Chen^{a,*}, Xin-An Feng^b, Lan Ding^b

^a*Department of Mechanical Engineering, The University of Hong Kong, Hong Kong*

^b*Faculty of Mechanical Engineering, Dalian University of Technology, Dalian 116024, China*

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Abstract

In order to reduce the time of mechanical product design and ensure the high quality of their assembly drawings, this paper develops an intelligent approach for generating assembly drawings automatically from three-dimensional (3-D) computer assembly models of mechanical products by simulating the experienced human designer's thinking mode with the aid of computer graphics and knowledge-based expert system. The key issues include the strategies and methods for selecting the necessary views in an assembly drawing, determining necessary sectional views in each view, eliminating the unreasonable projective overlap of the components in each view, and minimizing the numbers of both the views in an assembly drawing and the sectional views in each view. Based on the approach, corresponding software prototype was developed. Finally, it is demonstrated, from an example of the fixture in a modularized drilling machine, that its assembly drawing was generated successfully using this intelligent software prototype. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Any product that has more than one component must have an assembly drawing. The primary functions of assembly drawing of a product are to show the product in its completed shape, to indicate the relationship of its various components, and to designate these components by labels. Assembly drawings are the important documents for assembly, inspection, installation, maintenance, and even disassembly and recycling of the product at the end of product lifecycle. A high-quality assembly drawing should contain minimum numbers of both views in it and sectional views in each view, and clearly illustrate product configuration and working principle along with overall dimensions, installation dimensions, capacity dimensions, relationship dimensions and fits between components, operating instructions, and data on design characteristics.

Since a mechanical product involves many components, it is always time-consuming to create its assembly drawing. For the same mechanical product, it is also possible for different designers to select different views in an assembly drawing and to determine different sectional views in each

view. The quality of assembly drawings would thus depend on the designer's technical competence and experience.

Currently, the assembly modeling system [1] in existing CAD graphic software has enabled a designer to create three-dimensional (3-D) product assembly models, which can be used to generate the exploded views of the product and bill-of-materials (BOM) automatically, and used as a digital mock-up for further analysis, such as kinematic analysis, packaging studies, interference checks etc. Although the two-dimensional (2-D) orthographic projections of the product can also be generated from the assembly model directly, there is a need for a lot of interactive operations to obtain an effective assembly drawing, such as determining which view is the front view, which views are the other necessary views, which sectional views are needed in each view, which components are needed to be illustrated in each sectional view, etc. Therefore, the operation is still very complicated and time-consuming. Furthermore, the quality of assembly drawings would still depend on the designer's technical competence and experience.

To reduce the time of product design and ensure the high quality of assembly drawings, this paper develops an intelligent approach for generating mechanical product assembly drawings automatically, from their 3-D assembly model made with existing CAD systems, by simulating the experienced human designer's thinking mode with the aid of

* Corresponding author. Tel.: +852-2859-2630; fax: +852-2858-5415.
E-mail address: kzchen@hkucc.hku.hk (K.-Z. Chen).

computer graphics and knowledge-based expert system [2,3]. The key issues include the strategies and methods for selecting the necessary views in an assembly drawing, determining necessary sectional views in each view, eliminating the unreasonable projective overlap of the components in each view, and minimizing the numbers of both the views in an assembly drawing and the sectional views in each view. Based on the approach, corresponding software prototype was developed. Finally, it is demonstrated, from an example of the fixture in a modularized drilling machine, that its assembly drawing was generated successfully using this intelligent software prototype.

2. Elements and workflow of the intelligent approach

At the beginning of creating a mechanical product assembly drawing, an experienced human designer has to sketch the product assembly model in his/her mind or on paper. The assembly model is usually three-dimensional. The designer will then determine which view is the front view, which views are the other necessary views, which sectional views are needed in each view, which components are needed to be illustrated in each sectional view, etc. according to the configuration of mechanical product designed. Based on this layout of assembly drawing, the designer starts to draw the assembly drawing step by step. By simulating the experienced human designer's thinking mode mentioned above, an intelligent approach of generating assembly drawings from 3-D computer models of mechanical products was developed with the aid of computer graphics and knowledge-based expert system. The elements and work flow of the intelligent approach are shown in Fig. 1, and illustrated as follows:

2.1. Assembly model of the mechanical product designed

Currently, the assembly modeling systems in some commercial CAD graphic software have enabled a designer to create 3-D product assembly models. The designer may use one of them to build up a 3-D model of each component in the product on computer screen interactively and to mate these component models into the 3-D assembly model of the mechanical product designed. Relevant design parameters are collected while building the assembly model and form the data files for expressing the product.

2.2. Intelligent layout of the assembly drawing

According to relevant design parameters provided by the assembly model, the intelligent approach will determine which views are needed in the assembly drawing, which sectional views are needed in each view, which components are needed to be illustrated in each view and sectional view, etc.

2.3. Automatic generation of 2-D product assembly drawings

According to the intelligent layout, the assembly drawing will be generated automatically by computer with the aid of a graphic base. The other tasks, such as the improvement of assembly drawing, dimensioning, labeling, etc. are required to be fulfilled interactively. After that, a high quality assembly drawing is then finished.

3. Technical strategies of expert system for the layout of assembly drawings

The technical strategies of expert system for determining the layout of an assembly drawing are shown in Fig. 2, and described as follows:

3.1. Preliminary data input

The orientation of the product assembly model and its front view are designated interactively according to the

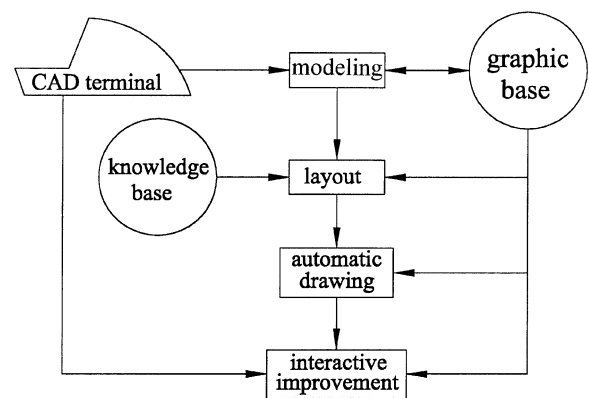


Fig. 1. Elements and work flow of the intelligent approach.

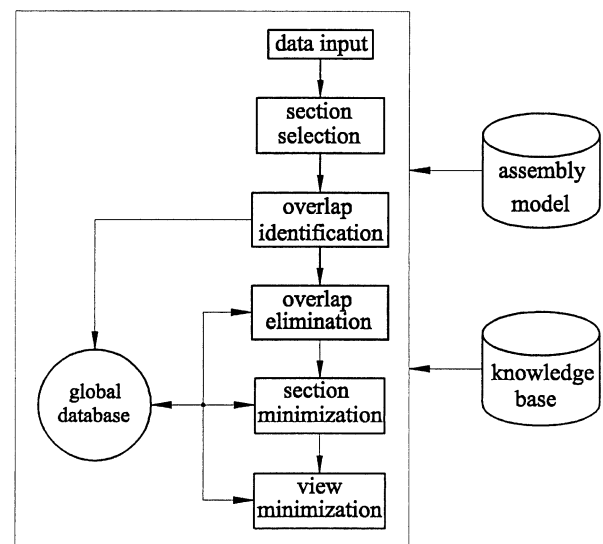


Fig. 2. Technical strategies of the layout expert system.

configuration of the product designed. The mathematical description of each component in the mechanical product models includes a list of surface equations, a list of curve equations, a list of the co-ordinates of end points, surface connectivity information, and the information that determines whether any location is inside, outside, or on the closed volume [1]. Modern assembly modeling systems have provided the capacity to create parametric constraint relationships between components and to measure size and dimension information from one component and apply it to another, thus freeing the designer from having to re-enter geometric data [1]. Therefore, the preliminary data needed for the layout expert system will be input or obtained automatically from the product assembly model by the expert system. These data are concerned with the shape, location and orientation of all the components in the assembly, assembly relationships among the components, possible view sets necessary for clear illustration of each component, and possible location ranges of necessary sectional views for each component in different view directions.

3.2. Global database

The global database for layout expert system is just like a ‘blackboard’ where the original scheme, intermediate schemes, and the final scheme (i.e. the optimum scheme of the layout of assembly drawing) are noted down alternatively. Some of the preliminary data input will be filled automatically in the frames of global database corresponding to six orthographic views, i.e., front, rear, right-side, left-side, top and bottom views [4,5]. Having been processed by ‘section selection’ and ‘overlap identification’ procedures indicated in Fig. 2, the preliminary data input to global database are formed into original scheme.

3.3. Overlap elimination

The primitive entities of components may be symmetrical or asymmetrical. Symmetrical primitive entities can be shown only by half or quarter. It is reasonable for its symmetrical portion to be overlapped. The overlap elimination procedure is aimed at eliminating unreasonable overlaps. The overlapping pairs are browsed from rear, bottom, left-side, right-side, top, to front view sequentially to find and delete the components in each pair that have been illustrated clearly by other views according to the information of its necessary view sets in the product assembly model. The procedure for deleting is called DELETE. If both components in a pair cannot be deleted, the component in the pair, which has equivalent view in other view without unreasonable overlap and with ‘good results and less trouble’, will be found and deleted, and its equivalent view will be inserted into its corresponding view of the assembly drawing. Otherwise the sectional view for one of components in the pair will be moved to an other space as a

removed sectional view. The equivalent view is the view that has the same information but in the other view of the assembly drawing and selected from its possible view sets in product assembly model. The procedure for adding the equivalent view in other corresponding view is named FILLING, and the whole procedure for eliminating the unreasonable projective overlap called OVERLAP ELIMINATION.

3.4. Section minimization

After ‘overlap elimination’, there are six or even more views in the global database without the unreasonable projective overlap of components among sectional views in each view. It is possible that some of components are illustrated repeatedly, and the sections in some of the views are superfluous. The expert system will then reduce the numbers of both sectional views in each view and the views in assembly drawing or replace some of the views by partial sectional views for reducing the size of assembly drawing. The strategies of section minimization are as follows:

The sectional views having least components are checked again from rear, bottom, left-side, right-side, top to front view sequentially to delete other fasteners in a set if one in the set has been illustrated clearly and leave their center-lines in the views, and to delete the components that have been illustrated clearly in the other view or that can be illustrated by inserting its equivalent view into the other corresponding view without new unreasonable overlapping. The sectional views can then be deleted if there is no component remained in it. This procedure is named SECTION MINIMIZATION and will be implemented until no sectional view can be deleted in all views.

3.5. View minimization

The view having least components are first checked to determine whether the components in it have been illustrated clearly in the other views. If the answer is yes, the components will be deleted using the ‘DELETE’ procedure. Otherwise, an equivalent view of the component will be filled in the other corresponding view of the assembly drawing using the ‘FILLING’ procedure if a new unreasonable overlap will not happen. The view in the assembly drawing will be deleted naturally if all the components illustrated in it have been deleted. After that, the next view illustrating the least components in assembly drawing will be considered to be deleted in succession until the components in the remained view cannot be deleted. This procedure is named VIEW ELIMINATION.

After the optimal adjustment of views and sections, the scheme remained in the global database is the final scheme or optimum solution for the layout of assembly drawing.

4. Data structure of global database in layout expert system

The data structure of the global database in the layout expert system is frame structure. Originally there are six frames corresponding to six orthographic views of an assembly drawing. Each view frame consists of three sub-frames: component frame, section frame, and unreasonable projective overlapping pair frame. The component frame contains the information about the labels of the components illustrated in the view and their relevant view names in their own modeling co-ordinate systems [6–8]. The section frame contains the information about the labels of the sectional views illustrated in the view, the location of each sectional view, total number of the components illustrated in each sectional view, and these component labels and their relevant view names in their own modeling co-ordinate systems. The unreasonable projective overlapping pair frame contains the information about the labels of the components in the pair that overlap each other unreasonably among sectional views in the view. The data structure for one view, for instance, is indicated as follows:

```
(view name in assembly drawing
  (total number of components illustrated in this view  $n$ 
    (component 1, its view name), (component 2, its
    view name), ..., (component  $n$ , its view name))
  (total number of sections in this view  $m$ 
    (section view 1, its location, total number of compo-
    nents illustrated in this section  $a_1$ 
      (component 1, its view name), (component 2, its
      view name), ... (component  $a_1$ , its view name))
    (section view 2, its location, total number of compo-
    nents illustrated in this section  $a_2$ 
      (component 1, its view name), (component 2, its
      view name), ..., (component  $a_2$ , its view name))
    ...
    (section view  $m$ , its location, total number of compo-
    nents illustrated in this section  $a_m$ 
      (component 1, its view name), (component 2, its
      view name), ..., (component  $a_m$ , its view name)))
  (total number of unreasonable projective overlapping
  pairs  $k$ 
    (component 1.1, component 1.2), (component 2.1,
    component 2.2), ..., (component  $k.1$ , component
     $k.2$ )))
```

The original scheme in global database includes six such view frames corresponding to six orthogonal views in assembly drawing. In each view frame, the section frame and overlapping pair frame are empty until 'section selection' and 'overlap identification' procedures are implemented. The final scheme in global database is the 'solution' in which the number of view frames is minimized and usually less than six. Each view frame in the 'solution' corresponds to each necessary view for the assembly drawing, and

contains necessary section frames with the labels and relevant view names of necessary components in each necessary sectional view; but its unreasonable projective overlapping pair frame should be empty since the 'overlap elimination' procedure has been implemented.

5. Section selection

In order to indicate the relationship of various components in a product, the interior detail of the product should be shown by sectional views. If the illustrated portions of components are not located on the same cutting plane, more than one cutting plane is needed to cut the product to generate different sectional views. The 'section selection' procedure aims at minimizing the number of sectional views in each view of an assembly drawing on the premise that all the components in the view are illustrated clearly. This is a problem of integer programming [9] that can be solved as follows:

5.1. Possible locations of sectional views for each component

The possible locations of a sectional view for an individual component can be indicated mathematically by the following formula:

$$\Omega_{ij} = [a_{ij}, b_{ij}] \quad (1)$$

where i is component number ($i = 1, 2, \dots, q$), j the region number of necessary sectional views ($j = 0, 1, 2, \dots, r$), a_{ij} the lower limit of the j th region of sectional view for the i th component, and b_{ij} the upper limit of the j th region of sectional view for the i th component. The a_{ij} and b_{ij} are evaluated during component modeling.

Although an individual component may need different numbers of sections as shown in Fig. 3(a) where two sections are needed, there are two possibilities for each section. The first possibility is that the location of the section is unitary as shown in Fig. 3(a). It can be represented schematically by a thick line as shown in Fig. 4 for component 5 and its regional formula can be represented as:

$$\Omega_{ij} = [a_{ij}, a_{ij}] \quad (2)$$

The second possibility is that the location of section can be in any place within a certain range, which can be inside the component from (e)–(f) as shown in Fig. 3(b) or from outside the component to illustrate its appearance to the inside as shown in Fig. 3(c). The former can be represented schematically by a hatching area as shown in Fig. 4 for components 1, 2, and 4, and its regional formula can be represented as:

$$\Omega_{ij} = [a_{ij}, b_{ij}] \quad (3)$$

The latter can be represented schematically by a hatching area without a border as shown in Fig. 4 for component 3,

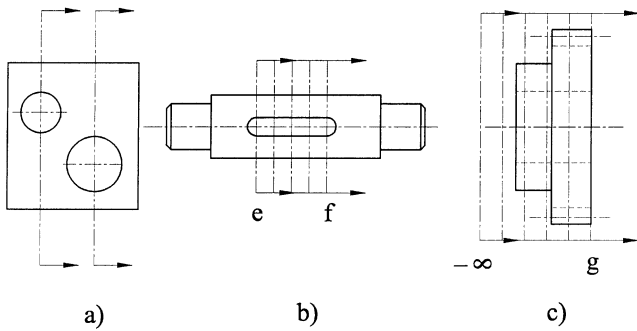


Fig. 3. Locations of sectional views for different components.

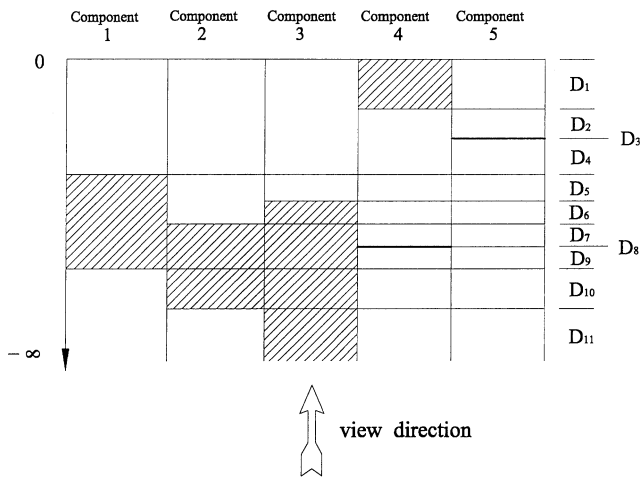


Fig. 4. Possible location regions of sectional views.

and its regional formula can be represented as:

$$\Omega_{ij} = [-\infty, b_{ij}] \quad (4)$$

5.2. Possible regions of sectional views in each view of assembly drawing

A view of the assembly drawing may contain many components that have different necessary section regions as shown in Fig. 4, for example, where there are five components in a view and their necessary section regions are represented by hatching areas and thick lines. The possible positions of sectional views for each view can be determined as follows:

If the lower and upper limits of each section region of all the components in one view of assembly drawing are arranged lengthwise, p regions, D_m ($m = 1, 2, \dots, p$), can be obtained. In Fig. 4, there are eleven regions for five components (i.e., $p = 11$). Some of regions are empty without hatching for all components, such as D_2 and D_4 , where no component needs to be sectioned. Two regions (D_3 and D_8) are zero regions where a section is needed and its location is unitary. The others are the section regions with hatching area of at least one component, including one region

(D_{11}) without a border for their appearances, where one section, if needed, can be located in any place within the region. The necessary number of sectional views in each view of assembly drawing is usually less than p , and can be calculated by using integer programming.

5.3. The mathematical model for section selection

If the i th component is sectioned in region D_m , the component section variable N_{im} is set as 1, i.e., $N_{im} = 1$, otherwise, $N_{im} = 0$. If one section inside D_m region is selected, the region section variable x_m is set as 1, i.e., $x_m = 1$, otherwise, $x_m = 0$ ($m = 1, 2, \dots, p$). The objective function can be then expressed as follows:

$$Y = \sum_{m=1}^p x_m, \quad (x_m = 1 \text{ or } 0) \quad (5)$$

where Y is the number of sectional views in a view of assembly drawing and should be minimized. Since every necessary section region of each component should be sectioned only one time, i.e.:

$$\sum_{m=1}^p (N_{im} \times x_m) = r_i, \quad (i = 1, 2, \dots, q) \quad (6)$$

where r_i is the number of sections needed for the i th component. For the example shown in Fig. 4:

$$r_i = \begin{cases} 1, & \text{if } i = 1, 2, 3, 5 \\ 2, & \text{if } i = 4 \end{cases}$$

Therefore, the mathematical model for section selection can be expressed as follows:

$$\text{Minimize } Y = \sum_{m=1}^p x_m \quad (7)$$

subject to the constraints:

$$\sum_{m=1}^p (N_{im} \times x_m) = r_i, \quad (i = 1, 2, \dots, q)$$

$$x_m = 1 \text{ or } 0$$

5.4. Optimization

The minimum number of sectional views Y and their corresponding locations can be calculated by solving the above mathematical model [9]. For the example shown in Fig. 4, the minimum number of sectional views is three, they are D_1 , D_3 and D_8 .

6. Elimination of the unreasonable projective overlap of components among different sections in each view

If the sectional views generated by different cutting planes overlap each other unreasonably in a view of the

assembly drawing, the related component configuration and their assembly relationship cannot be illustrated clearly. In this case, the projective overlapping portion of some components should be deleted by using partial sectional view, applying dashed lines, or moving it to another place as a removed sectional view. There are several different situations for eliminating the unreasonable projective overlapping:

1. Only one component in an overlapping pair can be deleted since the configuration of this component has been illustrated clearly in other views of the assembly drawing.

Every component in a product has an assembly relationship with other components. If a component is simply deleted, it is possible to make some confusion for assembling other components. For instance, if the shaft is simply deleted from the assembly drawing shown in Fig. 5(a), the assembly relationship of all the components on the shaft will be confused. If the gear is simply deleted, the shaft seems to be useless, and the sleeve and the key are not fixed. Therefore, the strategy for eliminating the unreasonable projective overlap is that all the components having an assembly relationship with the deleted component portion should be searched and their sectional views should be properly processed after deleting the component.

The assembly relationship in Fig. 5(a) can be illustrated by a network [10,11] as shown in Fig. 5(b). The interrelated degree of a component in a product can be expressed by the number of other components that have assembly relationship with it, and named as BRANCH. For instance, the gear in Fig. 5(a) has an assembly relationship with the shaft, sleeve and key, its BRANCH is equal to three. All the components having an assembly relationship with the deleted component can be searched following the network. If the component having an assembly relationship with the deleted component is allowed to be deleted, further searching from it has to be done to find more components that have an assembly relationship with it. If the component having an assembly relationship with the deleted component is not allowed to be deleted, the portion of its sectional view where it connects with the deleted component should be cut away partially. When the searched component cannot be deleted and the proper processing for the related components is made, the searching along the branch in the network is stopped. When the searching along all the branches from initiatory node or component is finished, the whole searching process is stopped. This process is named as 'DELETE' procedure.

For example, if the gear in Fig. 5(a) needs to be deleted, the 'DELETE' procedure will delete the gear and find that a shaft, a key and a sleeve connect with the gear, and determine that the key is able to be deleted wholly and that the graphic portions of shaft and sleeve where they connect with gear have to be cut away partially, as shown in Fig. 5(c).

2. Both components in an overlapping pair are allowed to be deleted since they have been illustrated clearly in other views of the assembly drawing.

In this case, there is no need to keep their sectional views in the view of the assembly drawing, and the 'DELETE' procedure will be implemented to delete the two components and to process the related components as described above.

3. The configurations of both components in an overlapping pair have not been illustrated clearly in other views of the assembly drawing.

In this case, one component in the overlapping pair should be deleted by adding its equivalent view to corresponding views of assembly drawing, expressed by dashed lines, or moved to another place as a removed sectional view. There are also three possibilities for this case:

- (1) Only one component in an overlapping pair can be deleted by adding its equivalent view in another corresponding view of an assembly drawing without new unreasonable overlapping.

In this case, the component will be deleted, and its equivalent view will be filled in another corresponding view. The assembly relationship network will be searched from the deleted component to find all other components having an assembly relationship with it. If the component searched can be deleted and its equivalent view can be filled in another corresponding view without new unreasonable overlap, the assembly relationship network will be searched continually from the deleted component to find other components having an assembly relationship with it. If the component searched cannot be deleted or filled in, some graphic portions where it connects with the deleted component have to be cut away partially or those where it connects with the filled component have to be filled partially in their equivalent view. The criterion for stopping searching along the branch in assembly relationship network is that the components concerned cannot be deleted or filled in and special processing has been made. When all branches of the initiatory node or component in the network have been searched, the whole searching process is stopped. The process is named as 'FILLING' procedure.

- (2) The equivalent view of both components in an overlapping pair cannot be filled in other views in assembly drawing.

In this case, there are two choices. One is that the dashed lines can be used to express the overlapping portion of the component. Another is that the sectional view can be moved to another space in the form of a removed sectional view to illustrate the deleted component and the other components having an assembly relationship with it. The final decision is made by designers interactively.

- (3) Both components in an overlapping pair can be deleted by adding their equivalent views in other corresponding

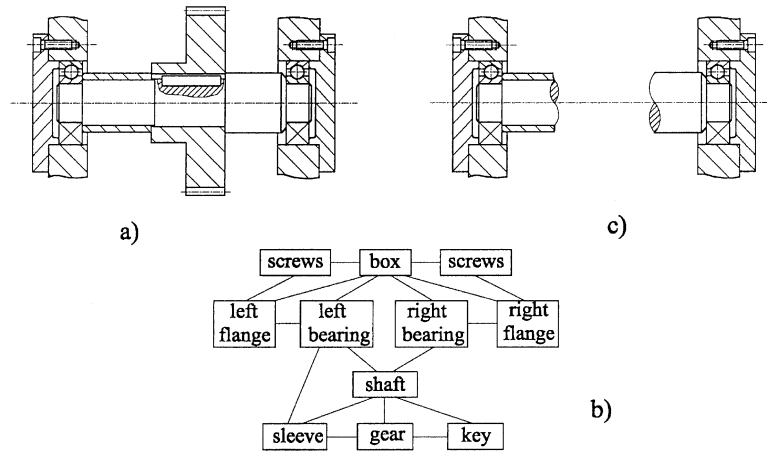


Fig. 5. An example of assembly relationships.

views of assembly drawing without new unreasonable overlapping.

In this case, it is necessary to determine which component in the overlapping pair, if deleted, will cause a better result in the original view, and less trouble in the filled views. The two requirements can be solved by the 'BETTER RESULT' procedure as described as follows:

There are four features affecting the better result and less trouble: the number of the components in the sectional view containing the component concerned, the value of BRANCH of the component concerned, the number of other components overlapped by the component concerned, and the number of components in the view where its equivalent view will be filled in. If there are fewer components in the sectional view, it is more possible to delete the whole sectional view by deleting the component concerned so that the component has priority to be deleted. If the component has less value of BRANCH, the confusion caused by both deleting it and filling its equivalent view will be reduced so that the component has priority to be deleted. If the component overlaps more other components, more unreasonable projective overlapping pairs can be eliminated by deleting it so that the component has priority to be deleted. If the number of components in the view where its equivalent view will be filled in has more components, adding its equivalent view will make less trouble for view minimization so that the component has priority to be deleted. According to the four features, every component is compared with another component in an overlap pair and has three possibilities or levels: more, equal, or less. Its relative feature sets u_i can be written with binary numbers as follows:

$$u_i = \{u_{i1}, u_{i2}, u_{i3}\}, (i = 1, 2, 3, 4) \quad (8)$$

where:

$$u_{ij} = \begin{cases} 1, & \text{if } (j = 1 \cap \text{'more'}) \cup (j = 2 \cap \text{'equal'}) \cup (j = 3 \cap \text{'less'}) \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

The corresponding weight should be given to each feature

according to its importance for 'better result and less trouble' as follows:

$$A = (\alpha_1, \alpha_2, \alpha_3, \alpha_4), \sum_{i=1}^4 \alpha_i = 1 \quad (10)$$

The corresponding weight should also be given to each level according to its importance for the corresponding feature as follows:

$$A_i = (\alpha_{i1}, \alpha_{i2}, \alpha_{i3}), \sum_{j=1}^3 \alpha_{ij} = 1 (i = 1, 2, 3, 4) \quad (11)$$

These weights are determined by using Analytic Hierarchy Process (AHP) [12]. Thus, the assessment score of the component for 'better result and less trouble' can be evaluated by following equation:

$$V = \sum_{i=1}^4 \sum_{j=1}^3 \alpha_i \alpha_{ij} u_{ij} \quad (12)$$

The component in an overlap pair with a larger score has the priority to be deleted, and its equivalent view will be filled in a corresponding view.

7. An example

According to the above approach, a software prototype for implementing it was developed. By using this software prototype, many assembly drawings have been created successfully. Here, as an example, a simplified assembly drawing of the fixture in a modularized drilling machine, generated by the intelligent CAD system, is shown in Fig. 6.

The assembly drawing is composed of a front view and a right-side view. The main section in the front view is selected to pass the axis of the operating shaft. There is a partial sectional view in the front view to illustrate the configuration of the screw for installing the fixture body on its base. The upper portion of the right-side view is used to display the outside appearance of fixture, and the

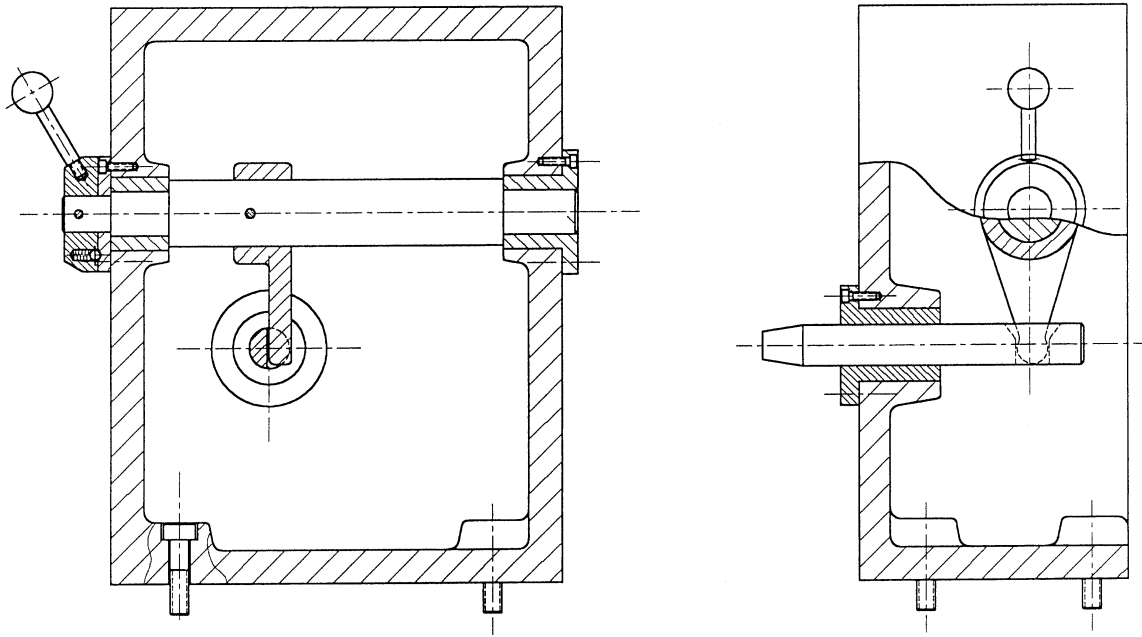


Fig. 6. Assembly drawing of the fixture.

lower portion is used to show the sectional view passing the axis of the pin. The cylindrical primitive entities of operating handle, shaft, and fork are symmetrical in the right-side view and can be illustrated clearly by their partial appearance and partial sectional view. The other screws in each set have been deleted since one in each set has been illustrated clearly, and their centerlines have been left in the views.

8. Conclusion

An intelligent approach for generating 2-D assembly drawings automatically from 3-D assembly models of mechanical products is developed in this study by simulating the experienced human designer's thinking mode with the aid of computer graphics and knowledge-based expert system. The attempts for selecting the necessary views in an assembly drawing, determining necessary sectional views in each view, eliminating the unreasonable projective overlapping of the components illustrated in both each view and each sectional view, and minimizing the numbers of both the views in an assembly drawing and the sectional views in each view have been realized in the intelligent software prototype. It is verified from the examples that the technical strategies and methods provided are feasible and the results are satisfied. Based on this software prototype, a more sophisticated system with more functions can be further developed in the future. The intelligent approach for determining the layout of assembly drawings can also be used to develop the intelligent approach for generating detail drawings of complicated mechanical components.

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Ke-Zhang Chen received his PhD degree from the University of Manchester (UMIST), UK in 1984. After he had worked at UMIST (UK), East China University (China), MIT (USA), and the University of California at Davis (USA), he joined the Department of Mechanical Engineering in the University of Hong Kong in 1996. His current research interests include design theory and methodology, concurrent engineering, intelligent CAD, and design for heterogeneous components.



Xin-An Feng received his BS degree from the Department of Mechanical Engineering, Dalian University of Technology, China, in 1956. He has then been working in the university, and is now a professor, deputy director of the CIMS Research Center, standing council member of China Association for Mechatronics Technology and Applications, and council member of the China Institution for Production Engineering. His current research interests include CAD/CAM, intelligent CAD, concurrent engineering, and CIMS.



Lan Ding received her BSc degree and MSc degree from the Department of Mechanical Engineering, Dalian University of Technology, China, in 1989 and 1992 respectively. Since then, she has worked in China Computer Software Technology and Service Corp. as a software engineering, Lotus (China) Software Ltd. as a senior system engineer, China Hewlett-Packard Co. Ltd. as an account manager, and Nortel Networks Beijing Office as a senior account manager. She is currently studying in McGill University, Canada.

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