Content-Based Search Techniques for Searching CAD Databases

Satyandra K. Gupta[1], Antonio Cardone[2] and Abhijit Deshmukh[3]

[1]University of Maryland, College Park, skgupta@eng.umd.edu
[2]University of Maryland, College Park, toniocar@glue.umd.edu
[3]University of Maryland, College Park, dabhijit@umd.edu

ABSTRACT

The popularity of 3D CAD systems is resulting in large assembly and part databases being created by product development organizations. Over the last few years several content-based techniques have emerged to search these databases. Ability to perform content-based searches on CAD databases is expected to help the designers and manufacturing engineers in many different ways. Representative examples include part-family formation, redesign suggestion generation, supplier selection, cost estimation, tooling design, machine selection, stock selection, and design reuse. This paper covers the following three topics. First, it presents an overview of different types of part search techniques. Second, it presents an overview of the different aspects of assembly search techniques. Finally, it identifies the open challenges in these areas and outlines future research directions.

Keywords: Part Search, Assembly Search, and Similarity Assessment.

1. INTRODUCTION

3D CAD systems have become very popular in the industry. These systems are being used to generate 3D models of parts and assemblies. These models are used as a basis for engineering analysis and generate process plans. The use of 3D models also allows virtual prototyping and hence reduces the need for physical prototyping. Nowadays, organizations routinely set up databases of CAD models to enable all participants in the product development process to have access to 3D data to support their individual functions. In addition to designers, manufacturing and service engineers are expected to greatly benefit from these databases. These databases are updated with the latest versions of parts and assemblies and hence significantly improve information dissemination. CAD databases for even moderate size companies are expected to be large in size. A product assembly can contain many subassemblies and each subassembly can contain many parts. Therefore, even a small organization that has multiple product lines may add hundreds of assemblies and thousands of parts to their database every year.

Manufacturing companies are constantly looking for ways to reduce costs and the time-to-market. Intuitively, if two products are similar, it is possible to reuse information about one product to derive corresponding information about the other one. In addition to supporting downstream manufacturing and service operations, the part and assembly databases can be very useful during the design phase as well. There are many possible applications where reuse of information can be of significant value. Representative examples include part-family formation, redesign suggestion generation, supplier selection, cost estimation, tooling design, machine selection, stock selection, and design reuse. Section 2 describes several scenarios where content based search techniques can be useful for product development companies.

Currently, designers have access to the several types of search tools. If the parts and assemblies are stored in hard drives, they can use file name-based search tools. This strategy only works if a meaningful file naming convention based on CAD model contents is adopted. However, developing and deploying a content-based naming convention is impractical in many large organizations. In addition, such convention cannot be adopted for legacy data because of the huge effort involved. Another way is to attach text notations to parts and assemblies and store them in a PDM database. This scheme only provides limited search capabilities and has a limited discrimination power. Moreover, parts and assemblies need to be manually annotated. Therefore these methods have serious limitations. We need content based search tools that can work over parts and assembly databases.

Over the last few years, several search tools have emerged that can search for parts. Section 3 describes an overview of the techniques used for performing content based searches over part databases. Searching for assemblies is a fundamentally different problem from the part search problem because unlike parts, assemblies not only depend on the geometry but also on the relationship between the parts. Therefore different techniques are needed to perform content based searches over assembly databases. Section 4 describes techniques for performing content-based searches on assembly databases.

Despite significant progress in content based search techniques for parts and assemblies, there are still many research opportunities for advancing the state of the part in these areas. Section 5 describes future challenges in these areas.

2. SCENARIOS ILLUSTRATING NEED FOR CONTENT BASED PART AND ASSEMBLY SEARCH

2.1 Design Reuse

Reusing design/manufacturing information stored would result in a faster and more efficient product realization process. While designing a new part/assembly the designer can refer to existing designs and utilize the components used previously. Let us consider the design of the shaft of a turbine engine. Usually the designer has two options. The first option is to design the shaft from scratch and go through the process and manufacturing planning. The second option is to refer to the database of existing designs, and select an existing shaft and either use it as it is or make minor modifications to it. For example, drill a few holes or cut a few slots in it.

Reuse of existing designs is beneficial from many different perspectives. It reduces design time by eliminating the need for modeling and analysis for the assembly being reused. Furthermore, the existing assembly is already tested and has an established manufacturing plan. This further reduces the product development time and cost. Sharing assemblies across multiple product lines also allows a company to take advantage of the economy of scale.

2.2 Cost Estimation Based on Similar Parts

For some manufacturing domains such as rapid prototyping, reasonably accurate estimates of cost can be generated by estimating the volume or weight of the part. However, for domains such as 3-axis machining, the accurate cost estimation is much more difficult. Cost for a machined part can be defined as a summation of material costs, setup costs, tooling costs, and operation costs. Material costs depend upon the cost of stock being used. Setup costs depend on how many setups are needed and fixturing methods used in each setup. Therefore, setup costs depend on how features are oriented in space and how they interact with each other to affect fixturing and introduce precedence constraints. Tooling costs depend on tools being used. Therefore, tooling cost depends on machining feature types. Operation costs depend on the time taken to machine various features. Therefore, they depend on feature types, dimensions, and tolerances.

Given a set of machining features belonging to a part, it is easy to estimate operation costs. However, it is difficult to estimate setup costs from the description of machining features alone. Setup costs not only depend upon the total number of feature access direction but also on the type of precedence constraints that exist among features and how each setup is fixtured. Currently there is no automated method for performing setup planning in commercially available process planning systems. Hence unless a detailed setup plan is manually developed, machining cost cannot be estimated accurately from the description of machining features alone. Therefore, currently cost estimation is done manually for machined parts if high accuracy is desired in cost estimates.

Accurate cost estimation can take any where from few minutes to few hours depending upon the expertise of the cost estimator and the complexity of the part. Based on our conversations with human cost estimators, it appears that many of them implicitly use estimates from previously completed tasks to generate new quotes. Manual cost estimation is inefficient especially when the designer submits the 3D model over the Internet for getting quotes. One way to achieve this is to search a database of previously manufactured parts and locate parts similar to the newly designed part automatically, so that the manufacturing cost of the retrieved parts can be used to estimate the cost of the new part. Thus, the ability to quickly find previously manufactured parts similar to query part can be used to facilitate cost estimation.

2.3 Tooling Reuse

Manufacturing of many parts is a two-step process. During the first step the tool is designed and constructed for making the parts. During the next step, parts are produced using the tool. Often tool makers and manufacturers are two different organizations. Let us consider molding of plastic parts. Selecting a tool maker is an important step in this process. Many different kinds of tools exist that can be used to create plastic parts depending upon the shape of the part. Different tool makers specialize in different kinds of toolings. Therefore, one has to analyze the shape of the part to determine the most appropriate tool maker based on the type of tool needed for the part. Internet-based tool ordering systems give an organization an opportunity to contact a wide variety of tool makers (many of them located in different geographical locations) to solicit quotes from them in order to get the best deal. However, contacting a very large number of tool makers to get quotes is not practical due to the time needed to send the data and analyze the quotes. Therefore, designers and manufacturers often rely on their prior experience to contact the tool makers that have capabilities to handle the new part. This model worked well when designers and manufacturers were dealing with a small number of local tool makers. In the era of global operations and access to a large number of tool makers, designers and manufactures can benefit from software support to help them in identifying potential tool makers.

A possible way to identify potential tool makers is to find similar parts to the given part and identify tool makers based on the tool makers for these similar parts. The same toolmaker that fabricated the mold for the retrieved plastic part can be approached to provide a mold for the new plastic part. This methodology is currently being practiced by experienced part designers. However, they currently rely on their memory to locate the similar parts. This approach does not work well when the part libraries are very large.

2.4 Accessing DFMA Knowledge

A possible use of content based part and assembly search technologies is to provide access to existing design knowledge. Designing assemblies requires considerable effort. Creating good assembly designs require thoughtful analysis and careful application of Design for Manufacturing and Assembly (DFMA) principles. Part and assemblies tools provides two benefits. First, new designers can adopt and copy successful design templates found in the search. Second, designers can access associated data such as cost, reliability and failure reports.

Archived redesign projects that are driven by DFMA principles can provide meaningful suggestions on how to carry out the redesign in a new project. This way redesign cost will be reduced by exploiting past redesign experiences. We expect future design repositories to include the models of both the initial design and redesign.

3. PART SEARCH TECHNIQUES

3.1 Search Based on a Query Part

In many applications, a query part is available and the goal is to find similar parts from a database of parts (see Figure 1). Various techniques have been developed to perform similarity assessment between 3D solid models. Similarity assessment between two 3D parts involves two main steps. The first step is to compute the shape signature of the object and the second step is to compare the shape signature by a suitable distance function. Major techniques used in the shape similarity assessment area can be classified on the basis of the type of shape signatures being used.

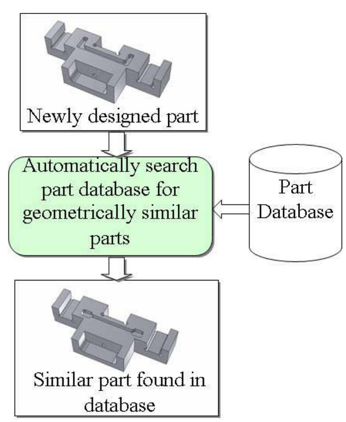

Fig. 1. Architecture for part search.

The shape similarity assessment technique described in [21] represents the object as a shape distribution sampled from a shape function measuring global geometric properties. This technique can be used as a first-cut filter to identify grossly dissimilar objects. In [9], new filters for shape matching have been proposed. These filtering techniques have been applied to large databases of mechanical parts. In [13], [18], each 3D model is voxelized and represented by a vector whose components are moment invariants, geometric parameters, principal moments and eigenvalues of the skeletal graph.

Graph-based techniques convert solid models into attributed graphs that represent relationships among various geometric and topological entities in the solid model. Among the types of graphs that have been used there are Model Signature Graphs [11], [19] and Multiresolutional Reeb Graphs [1]. These techniques are simple to implement, but may not have high discrimination power.

Spatial function based techniques use shape signatures that are spatial functions. Spatial functions have been introduced in [16-17]. A technique based on spherical harmonic descriptors is described in [12]. The Fourier transformation based technique described in [6-7] performs similarity analysis based on the boundary representation.

Feature-based techniques represent the 3D object referring to their features. Many different types of approaches have been developed [8], [3-4], [14], [23]. Feature based techniques appear to be promising for domains such as machined parts. Additional details on shape similarity assessment techniques can be found in [2].

Existing techniques provides excellent performance for filtering irrelevant parts. However, when locations, type, and orientations of faces play a major role in determining similarity, existing techniques do not seem to have sufficient discrimination capabilities. This information is important in case of similarity assessment of parts for manufacturing. Hence, we have developed a new shape similarity assessment technique. This technique is described in [5].

3.2 Search Based on a Sketch

3D models are not always available to act as queries in query based search. Creating a complex 3D model of part to act as query is time consuming activity. It is easier for a designer to represent the relevant characteristics of the required part in form of 2D sketches compared to preparing a 3D model. Thus, in many design reuse applications, users may not want to create detailed CAD model to begin search. In such cases, sketch based tools for representing parts can be used to search for the required part or for locating a query part. These sketches usually are standard 2D views, i.e. top view, front view and side view of the required part.

In [22] a technique capable of retrieving 3D parts from a database based on user free-from sketches is presented. The 3D part retrieval can be enhanced by user further feedback. The part can be searched based on up to three views with user assigned weights for each view. The technique consists of three main steps: (1) determination of 3D part relevant orientations, (2) generation of 2D sketches, and (3) computation of similarity degree between sketches and 3D part projections. In [20] another 2D sketch-based technique for 3D shape retrieval is presented. This similarity measure is invariant with respect to rotation. In this case 2D views are compared based on the Fourier coefficients of functions obtained by intersecting the 2D Euclidian distance transform of the image with a set of concentric circles.

3.3 Search by Visual Browsing of CAD Database

In many situations the user does not have a query part. Moreover, due to the part complexity and/or user's limited familiarity with engineering graphics concepts, it is not possible to use sketch based query methods. In such situations, visual browsing of CAD databases is a possible solution [15].

Suppose a designer would like to locate a part in the design database consisting of thousands of parts for reusing design information. There are two possible cases. In the first case the designer has a query part and wants to locate a part similar to the query. In such cases, geometry-based search techniques are useful for locating similar parts. However, in the second case the designer may not remember the exact geometric details of the part to locate it through the geometric search techniques. In such cases, the user will need to locate the desired object by browsing through the CAD databases. Once the designer locates a part similar to the desired part he/she can use that part as the query in geometry-based technique. Thus an integrated system that can assist the designer in locating similar parts by providing geometric as well as visual search is useful.

The following scenario illustrates the need for the geometric and visual search tools for reusing design information. After 10 years of service a senior designer leaves the company. His folder consists of 936 parts. A new designer has taken over the projects. The new designer wants to design a shaft of an engine. He has two options. The first is to design the shaft from scratch and go through the process and manufacturing planning steps. The second option is to select an existing shaft from one of previously completed projects. However, he does not know the file name of the part. The only possible way he can search is by examining all the relevant project folders and opening each part file one-by-one until the desired part is found. If the 486th part file were the one he is looking for then it would have taken him, approximately, 2 hours and 45 minutes to open 486 part files in a typical CAD system. Instead if he had used visual navigation and geometric search tools, he would be able to browse through the parts using the visual search tool, select a suitable part and search for similar parts using the geometry-based search tool.

4. ASSEMBLY SEARCH TOOLS AND TECHNIQUES

4.1 Overview

Part based search techniques cannot account for relationships and structure that exist in assemblies. Hence new techniques are needed to support content based assembly searches. A content-based assembly search system should be able to search for assemblies from a database of existing assemblies based on different characteristics (see Figure 2). The characteristics used by the system to search the database need to be extensive and also include most of the characteristics of a typical assembly. Hence, the system will need to support a comprehensive list of characteristics of assemblies based on which the user can define a search. The characteristics included in the system are enumerated in subsequent sections. The system should be flexible and allow the user to search based on any combination of the characteristics. It should also handle cases that result in too few or too many search results. Thus, if the search system results are too few then the user should be able to lower the constraints (strictness) on the search criteria by increasing the cut-off values. Also, if the search results are too many then the user should be able to perform iterative refinement. This can be achieved by constraining the search by including more assembly characteristics in the search, then performing search and again refining search definition. This iterative refinement is very effective in producing the right number of search results. At any time in the search, the user should be able to exclude any assembly from further search. Finally, the system should have an easy-to-use interface and should be efficient so as to locate assemblies from a database in few seconds. In our previous work we have developed a comprehensive framework for performing content-based search on assemblies [10].

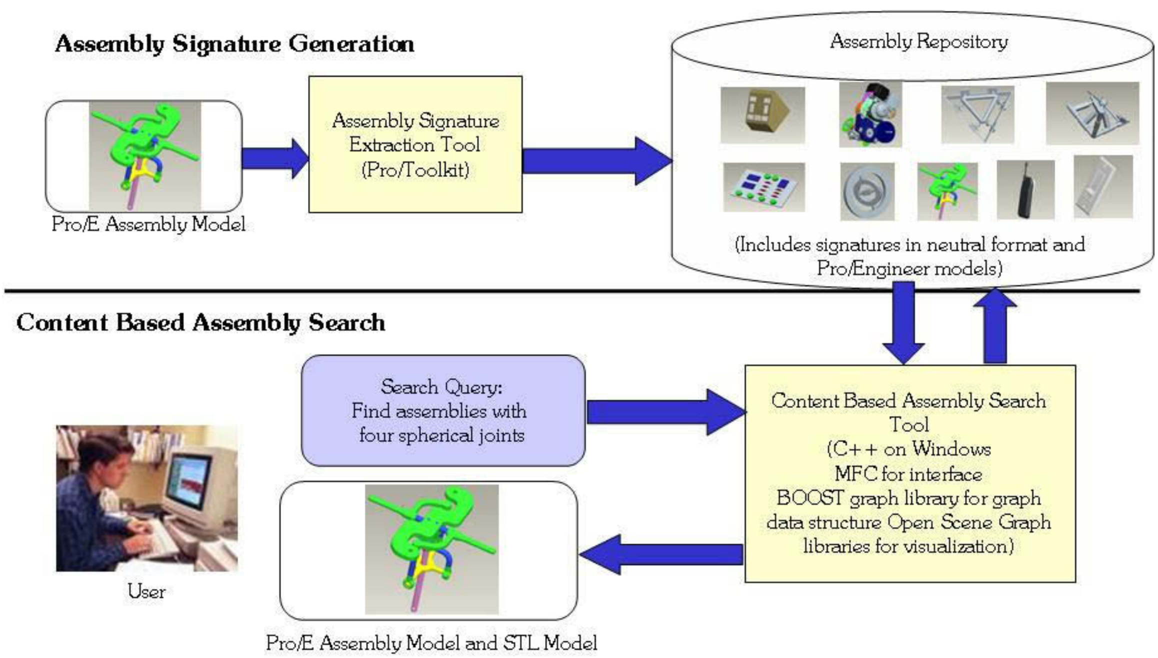

Fig. 2. Architecture for assembly search.

4.2 Search Based on Assembly Statistics

A possible way to search for existing assemblies is based on the overall assembly statistics. The following scenario illustrates why this type of search is useful in certain situations. Let us consider an organization that designs and builds prosthetic devices. Let us now consider the case when a customer approaches the organization with his own specific requirements. The designers in this organization would prefer to locate an existing assembly that is close to the given requirements and then adopt this existing assembly to the new requirements. The ability to effectively locate the most appropriate existing assembly will eliminate the need to design the assembly from scratch and hence reduce the design time significantly. A possible way to search for existing prosthetics will be to search based on the size of existing prosthetic assemblies. This scenario illustrates the benefits of being able to search based on overall assembly statistics.

The following are representative assembly statistics based on which a user should be able to perform search.

- **Size:** The user can search assemblies based on the bounding box size or bounding sphere size of the assembly.

- **Number of Parts:** The user can search assemblies based on the number of parts in an assembly. In addition, the user also has an option to either include or exclude the standard fasteners from the part count in the assembly. This option is useful to overcome the situations where a user would remember the main parts in the assembly but not remember the total number of fasteners used in the assembly.

- **Number and Types of Articulated Joints:** The user can also search assemblies based on the number and types of joints in the assembly. Typical joints include: revolute, prismatic, and spherical. This type of search is defined by indicating the number of joints in each selected joint type.

- **Number of Usages in Other Assemblies:** An assembly such as a motor may be a popular assembly and hence used in many other assemblies. So some users might remember the large number of usage associated with an assembly. Hence, users can specify the number of usages of an assembly in other assemblies as a possible definition of search. This might be an effective way of searching a frequently used assembly.

- **Overall Shape Characteristics:** Assemblies may have overall shape characteristics that a user might remember. For example an assembly may predominately consist of rotationally symmetric parts or sheet metal parts. Such characteristics can often be used as a possible way to search for an assembly.

4.3 Search Based on Constituent Parts

Assemblies can be searched based on the constituent parts of the assembly. Consider a scenario where the designer wants to search for a rocket motor assembly that contains a Beryllium liner of a specific size. Rocket motor assemblies are custom made to satisfy specific requirements. The designer would search for an assembly by specifying the size and material for a part of the assembly. These criteria will allow the designer to search for an assembly containing a part with specified size and material. The DFMA rules embedded in the assembly can be reused for the design of a new assembly.

The system need to support search based on the geometry of the part and the characteristics of the part. The two representative criteria for search are:

- **Geometry**: The geometry-based assembly search will have different inputs based on whether a part is a standard part or a custom part.

  - **Standard Part**: Every organization has a library of standard parts. A single assembly can contain a set of many of these standard parts. This criterion is useful when designer knows that a certain set of standard parts were used in the assembly. In this method, the user can select any set of standard parts from the library and search for assemblies containing these parts.

  - **Custom Part**: This is useful in a scenario when the designer knows that a part used in the assembly is exactly similar to a part in the database or approximately matches with a part in the database. The system needs to support search based on exact and approximate geometry matching.

- **Part Characteristics**: The following criteria for part characteristics-based search need to be supported:
  - **Material of the part**: Some assemblies contain a part made of a specific material. This criterion is useful to search for assemblies that contain a part that is made of an uncommon material. Users can specify any material from the available list of materials in the database of the organization.
  - **Part Attributes**: Attributes are the textual data stored in the CAD files. Organizations have a set of standard attributes that help classify the assemblies in the database. For example, an attribute called part source can have values 'bought out part' or 'in house part'. Attributes can have values in the form of a numbers or strings. The system needs to support search for both the types and values of attribute.

4.4 Search Based on Mating Conditions

The mating conditions are the restraints (constraints) imposed on the location of a part with respect to other parts in the assembly. Different set of restraints imposed on same set of parts can constitute assemblies for different purpose. This search criterion uses mating conditions to search for an assembly. The designer specifies the mating condition between parts of a subassembly or an assembly by building a query mating graph. This query mating graph is compared with mating graphs corresponding to the assemblies in the database. The results of the search are all assemblies whose mating graphs are compatible with the query mating graph.

The designer defines an input mating graph representing a subassembly/assembly. The graph consists of parts defined as nodes and the mating conditions between the parts as edges of the graph. Each node also has part related attributes. In addition, a node degree is assigned to a node. It represents the total number of parts that are mated to the part represented by the node. The total number of parts attached to the part represented by node is the sum of all nodes attached in the graph and this attribute. Every edge in the graph has the following attributes. The first attribute is type, which represents the type of mating condition represented by an edge. The next two attributes represent the two nodes associated with the edge. Note that the query mating graph need not be a fully specified graph. Many of the attributes in the query graph can be left unspecified (i.e., equivalent to wild cards in string search definitions). This means that the query graph is not a unique graph and many different database graphs might be compatible with the query graph.

4.5 Search Based on Joint Relationships

Consider a scenario where a robot designer is searching for an assembly consisting of two revolute joints at right angles to each other to mimic the motion of a human arm. The main characteristic of this assembly is the joints defined between these parts. A possible way to search for this assembly is to specify the type of joint and their orientations with respect to each other. The joints in articulated assembly are important to define the function of the assembly. Hence a user should be able to perform search on joints and their interrelationships.

The angle relationship between joints will allow the designer to specify a range of values for the angle between the joints. The designer will provide a set of two joints and the relationship among them. The designer can provide a list of such sets that are the defining characteristics for the assembly and are important from the design perspective. Each set contains joints defined on a single rigid body part. The system searches for an assembly in the database that contains all the sets in the list defined by the designer.

5. CONCLUSIONS

Significant progress has been made over the last few years in the area of content based search for parts and assemblies. However, there are still many exciting new opportunities that await attention from the research community. The following is a partial list of areas where further work is needed:

- Shape signatures used in part search are abstractions of 3D shapes, and therefore they often possess reduced discrimination capabilities. Furthermore, computing signatures and matching them requires a certain amount of computational effort. Several different shape signatures have been proposed and their discrimination capabilities and computational performance have been illustrated on specialized datasets. Currently, it is very difficult to compare shape discrimination capabilities of two different signatures. Furthermore, it is difficult to predict how well a particular shape signature will perform in a new application. In order to effectively select and utilize existing shape signatures we need to develop formal methods for characterizing discrimination capabilities of shape signatures.

- In real-life applications, we believe that a single signature will not be good enough to provide adequate discrimination and computational performance. A signature that performs high-degree of abstraction usually has limited discrimination capabilities. On the other hand, a signature that performs lesser degree of abstraction is usually computationally not efficient. Therefore usually first using a signature that is computationally efficient but produces few false positives, followed by a signature that is computationally less efficient but able to eliminate false positives is a good strategy. Further work on the selection of optimal sequence of signatures is needed.

- A large number of part models are publicly available. However, they lack the application specific measures of similarity associated with them. Therefore, performing rigorous evaluation of proposed techniques is a difficult task. Hence, it is necessary to develop publicly available benchmarking databases that contain domain specific evaluation metric.

- Many previous approaches have favored symmetric distance measures. However, distance measures that are not symmetric in nature are of interest as well because of the following reasons. Let A and B be two objects. Let A contain subset of features of B. In this case, B can be used to estimate cost of A by simply deleting extra processing steps (i.e., steps corresponding to features that are not present in A) from B. So distance of A from B should be small. On the other hand A cannot be used to estimate cost for B. So distance of B from A should be very large. Therefore various asymmetric distance measures should be studied to better understand their properties.

- An assembly can be defined as a collection of parts to perform certain function. The function of the assembly is thus the primary characteristic of an assembly. However, a function of an assembly is not always explicitly stored in CAD files. Often, the function of an assembly cannot be inferred from its geometric characteristics. Hence, the designer cannot search for a design fulfilling a particular function. Therefore further work is needed to support queries based on functions.

6. ACKNOWLEDGMENTS

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