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# A graph-based method and a software tool for interactive tolerance specification

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## Abstract

The paper deals with the problem of tolerance specification and, in particular, proposes a graph-based method and a preliminary software tool: (i) to accomplish the tolerance specification for a mechanical assembly; (ii) to verify the consistency of the specification and, (iii) to allow the tracing of relationships among parts and features of the assembly. The method adopts Minimum Reference Geometric Elements (MRGE), directed graphs (*di-graphs*) and a set of dedicated algorithms to tackle the problems of consistency that occur during an interactive tolerance specification activity. Finally, an application illustrates the proposed method and its actual implementation.

*Keywords:* tolerance specification; GD&T; Datum; graph theory; MRGE; .

## 1. Introduction

Product development is essentially composed by three main phases: design, manufacturing and control. The first one develops a “virtual” product, the manufacturing phase releases a real product affected by inevitable dimensional and geometrical variations, while control phase assures the verification of acceptable variations and, therefore, guarantees the fulfillment of product functional requirements (FRs). Tolerances are the link between these three phases and tolerancing is a mandatory step to assure functional requirements.

Tolerancing is usually divided into several specializations: tolerance specification [1]; tolerance modeling and analysis [2]; tolerance verification; each specialization has detailed goals and, actually, shows significant pillars and, at the same time, limitations and challenges. The present paper deals with the tolerance specification task.

Tolerance specification is a strategic activity in product development and, even more, in assembly design where multiple inter-part relations are involved [3]. Tolerance specification activity essentially aims to define: (i) datum references at part and assembly level; (ii) tolerance type and ranges for each geometric feature involved, in order to assure a set of assembly functional requirements. A traditional and unchanged challenge is to coherently assign tolerance type and range, including datum references frame for the set of parts composing an assembly, as a whole. Geometric Dimensioning and Tolerancing (GD&T) standards, like ANSI-ASME or ISO-GPS Standards [4-6], provide a wide range of symbols and rules to do tolerance specification for each geometric feature. However, international standards are part-centric and not assembly-centric; therefore, standards lack rules on assembly-centric specifications and these are essentially relied to designers’ skills. Specific CAT commercial software, such as VisMockup® or 3DCS and 3D CAD systems, provide useful tools for tolerance specification, annotation and analysis but a tolerance consistency tool is still not implemented. Therefore, a senior designer could easily assign tolerances, assuring coherence at part level. On the contrary, (s)he has no software tools to assure the global consistency of specification as well as the explicit tracking of relationships

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between functional features and tolerance specifications, at assembly level. Several contributes are known in literature about the problem of tolerance specification and, in particular, the consistency, the traceability at assembly level and the use of graph representations. Ballu et al. [7] uses the axiomatic design framework to accomplish a functional method for the managing of features, parameters and tolerances. In particular, they present a tool that uses a skeleton of the assembly to enhance the design of variants. No details are presented to assure consistency of tolerance specification. In [8] authors deal with the consistent tolerancing of a single part and deepen a set of detailed positioning tables and related links between contact surfaces. The wide study gives rise to a VBA implementation, but it does not tackle the problems related to the traceability of tolerance specification within the assembly context. In [9] an innovative product model is presented; the model allows the formalization of tolerancing expertise and enhances the traceability of the geometric conditions throughout the design steps. The work does not take into account the geometrical specifications on 3D CAD models and the possibility to accomplish a CAT analysis. Giordano et al. [10] propose a very useful tool for tolerance representation of mechanical assembly: the hyper-graphs. They define three graph levels: assembly graph (highest level) where nodes represent the parts and arcs represent the joints; contact graph where nodes represent functional features (contact faces implied in joint) and arcs represent the relations between functional features; tolerancing graph (part level) where nodes can represent toleranced features or geometrical or dimensional tolerance and arcs represent the links between two of them. Hyper-graph is the complete tolerancing graph. Although hyper-graph provides a clearer tolerances representation it is difficult to automatically build the graph. A successive and exhaustive dissertation to accomplish the graphical representation of mechanical assemblies with specifications is presented in [11]; there, the authors formalize an extension of the graphs used to represent joints and links of a mechanism by adding functional requirements, surfaces for tolerancing, situation features and, finally, specifications between surfaces. They voluntarily do not tackle the problem of identifying the key objects or specification as their final goal is the complete graph representation.

The present paper proposes a graph-based method to enhance interactive tolerance specification and to automatically generate the tolerances graph relations, allowing consistency analysis of mechanical assemblies as well as the tracing of relationships among parts and features of the assembly. Starting from the Minimum Reference Geometric Element (MRGE), belonging to Technologically and Topologically Related Surface (TTRS) model, and using graph theory, the approach proposed in [12] is here used to perform the consistency analysis of a tolerance specification set. The method detects errors when tolerance specification does not fulfil the geometrical rules and carries out a consistency analysis, at assembly level, through the use of directed graphs (di-graphs) and a set of dedicated algorithms.

## 2. Method overview

During the design phase, dimensional and geometrical tolerances have to be in a fully, correctly and consistency way defined. Furthermore, such a definition of the tolerance set has to be verified during all intermediate product development stages.

The proposed method intends to manage and record consistent tolerance set by simplifying the exploration and verification. The MRGE description of the features and a di-graph representation of the geometric relations, based on hyper-graph definition, are here used to assure the three key conditions for a consistent tolerance specification.

### 2.1. MRGE

The MRGE of a TTRS is the minimum set of points, lines or planes necessary and sufficient to define the reference frame corresponding to the invariant sub-group of that TTRS [13]. The MRGE remains invariant for the displacement it is defining. For each elementary surface, it is possible to associate an MRGE. Moreover, the MRGE describe the degrees of invariance associated to a surface or TTRS. For instance, the line or axis of a cylindrical surface can only be translated along or rotated about itself and it leaves four degrees of invariance: two in translation and two in rotation. However, in the present work the focus is limited to axes, planes and cylinders.

### 2.2. Directed-graph

Part and assembly relations can be represented by a di-graph [14-15] which consists of nodes and arcs. The first ones (as in hyper-graph [10]) represent the toleranced or functional features while arcs represent the geometrical or topological relations among them (Fig.1).

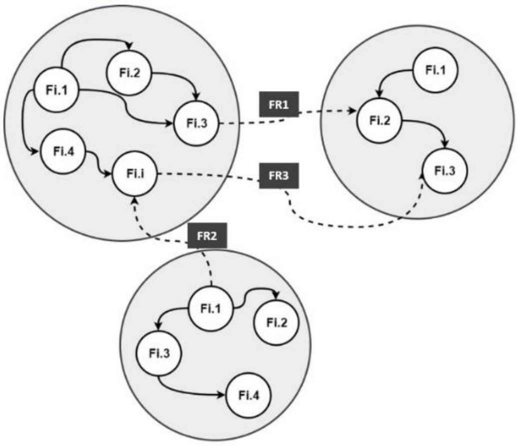


Fig. 1. Di-graph representation for a three-part assembly.

### 2.3. Consistency

A tolerance specification is assumed consistent when it is coherent, complete and non-redundant. Therefore, the consistency is obtained by the three following conditions:

- Coherency: a specification is coherent if it is logically connected; the coherency is accomplished through syntax and semantic controls on tolerance specification;
- Completeness: the tolerance process is complete when it specifies geometric variations that assure the assembly functional requirements. It must include all geometric features and parameters to describe the functionalities of a product [16].
- Non-redundancy: a specification is non-redundant when the extraction of information for each tolerance specification exists and no overlapped information is defined.

## 3. Tolerance specification method

The proposed method is composed by four main activities:

Feature parametrization – it is based on MRGE. Each feature is defined by a triad and characterized by a specific set of data. For example, an axis is parametrized by a point $\boldsymbol{P}_0$ belonging to the axis, a versor $\boldsymbol{V}_0$ (defining the orientation – parallel to the axis) and a frame $\boldsymbol{\Omega}_0$ ; a plane is parametrized by a point $\boldsymbol{P}_0$ belonging to the plane, a versor $\boldsymbol{N}_0$ (defining the orientation – normal to the plane) and a frame $\boldsymbol{\Omega}_0$; a cylinder is parametrized by an axis plus a radius.

Datum definition – it sets the datum reference frame (DRF). DRF can be defined as the way to position the part in the assembly, therefore it should be based on the assembly sequence and the relations among parts. Based on [11], DRF is defined by using a combination of Datum Features which are theoretically exact geometries such as point, line and plane. The mathematical representation of DRFs consists in a frame of three orthogonal vectors and a point which defines the origin of the frame.

Tolerance specification – it aims to assign tolerance type and range. Specifications are array based and selectively chosen. Tab. I shows a Boolean representation of the relations between tolerance and feature.

Tab. 1. Boolean representation of the allowable relations between tolerance and feature.

| | straightness | flatness | circularity | cylindricity | parallelism | perpendicularity | angularity | position | symmetry | concentricity | circular runout | total runout |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Axis | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Plane | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |

Graph based relations – tolerance specification is made first at part level and then at assembly level. Data are recorded and managed using graph theory. Parts can be classified in:

- ○ Datum part – a part which has no target part;
- ○ Target part – a part whose feature are used to constrain another part;
- ○ Object part – a part assembled by means of a feature belonging to a target part.

Consistency analysis algorithm is based on graph theory, too. Data are structured by means of: (i) adjacency matrix (A), (ii) incidence matrix (I), and, (iii) list of edges (L). The $\boldsymbol{a_{ij}}$ element of the adjacency matrix are characterized by three values: 0 if no connection exists between node $\boldsymbol{i}$ and $\boldsymbol{j}$; 1 if an edge exists from $\boldsymbol{i}$ to $\boldsymbol{j}$; -1 if an edge exists from j to $\boldsymbol{i}$. Using the above data structure and synergic operation of graph algorithms, a consistency algorithm (flowchart depicted in Fig.3) has developed. It consists of three checks:

- Coherence: algorithms based on assignations and dependencies rules (as table1) driven each specification in terms of syntax and semantic correctness (no errors occur). All dependency relations are mapped as in Tab.1. Each specification needs an entity and tolerance type selection which corresponds to a specific mapping table uses to check the assignation coherence at part level. For example, the method does not allow to specify a flatness for an axis because the Tab.1 has value 0 in the corresponding cell. Besides, an algorithm checks that no isolated features exist at part level (all features are connected). For each part, the method provides an adjacency matrix which manages the features relations. The isolated feature algorithm detects that for each raw and each column of the matrix a non-zero element at least exists.
- Completeness: it is analyzed through the graphs; an algorithm, named requirement isolated, detects that no isolated FRs exist and all created nodes are connected at least to one chain. The operating flow is similar to isolated feature algorithm, but requirements isolated algorithm concurrently operates both at part level and assembly level. Requirement definition generates an augmented incidence matrix composed by all defined requirements and all features of the assembly. A node not connected in the graph means that it does not add useful information to the analysis.

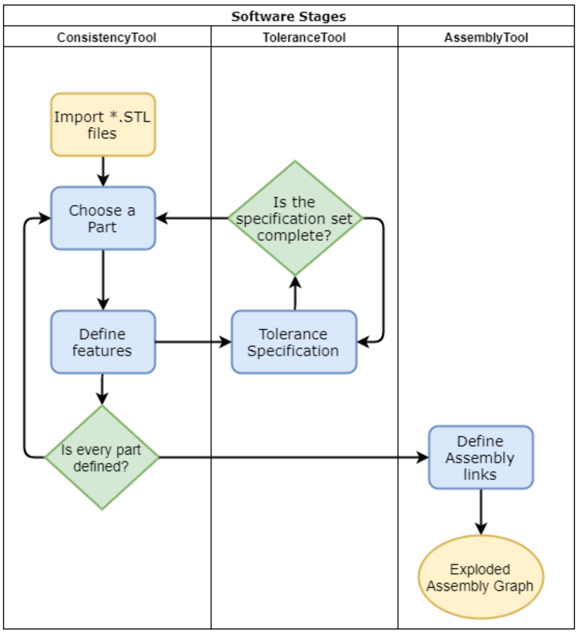


Fig. 2. Software tool structure

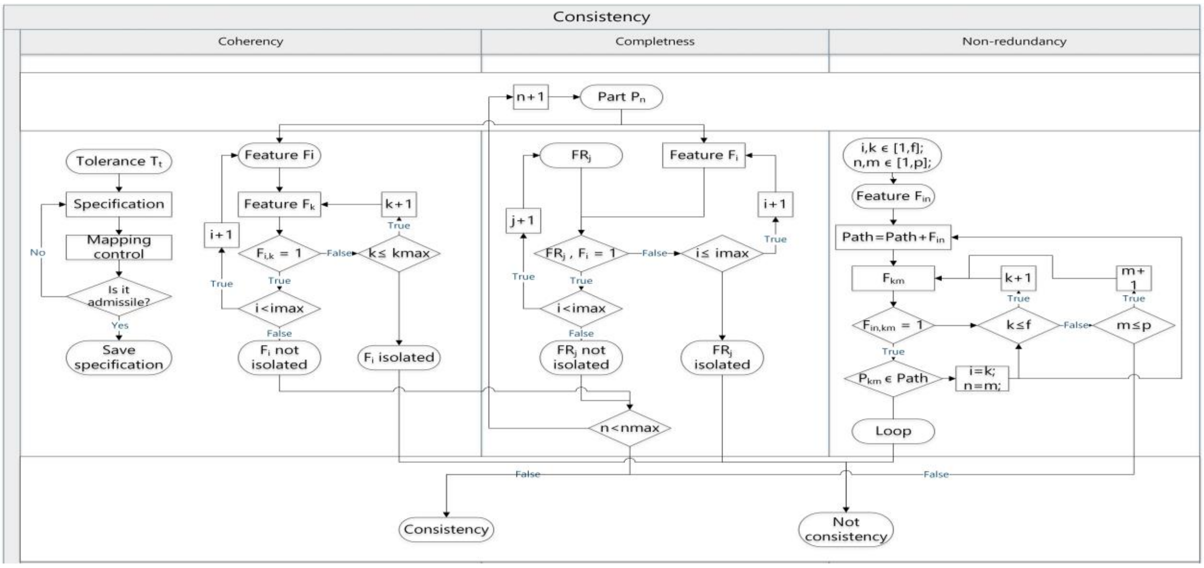


Fig. 3. Flowchart of the consistency algorithm

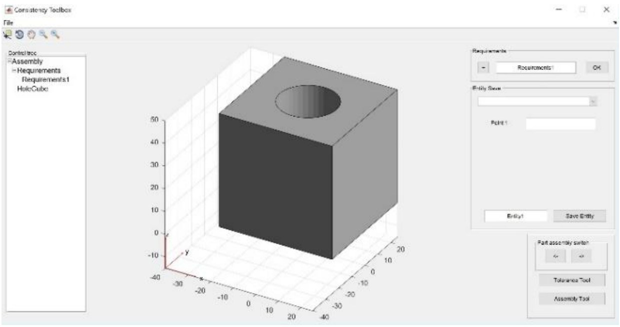
- Non-redundancy: it is evaluated through the loop detection within the graph generated for the tolerance specification set. The loop detection algorithm operates, at assembly level, on the augmented incidence matrix. The algorithm, starting from each assembly features, generates a vector which represents the sequence of nodes. A belonging check runs for each new vector node, if the node already belongs to the vector a loop is detected.

## 4. Tolerance specification software tool

A graphical user interface (GUI), developed in MatLAB® environment, was accomplished in order to enable the interactive tolerance specification and automatic consistency analysis. Fig. 2 shows the logical structure of the developed tool.

The main window named "Consistency tool" (see Fig.4) is divided in three fields: the control tree (left side) where all imported parts, defined requirements and features are shown; the 3D view where the active part is visualized; editing panels on the right side where features can be created and assembly or tolerance tool can be run.

Assembly is imported into software, parts by parts, using STL file format. Feature recognition is operated by users through the "entity save" panel. For example, a feature plane is defined by the selection of three points enhanced by a object snap function. The operations are driven by a snap grid.



Requirements: Requirements1

Entity Save: Entity1

Fig. 4. Main window of the software tool

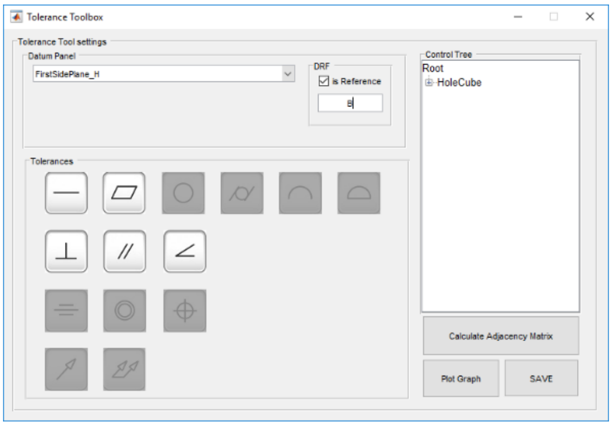
### 4.1. Tolerance toolbox

Tolerance toolbox (Fig.5) allows to define datum reference frame and tolerance for each part. Tolerance specification is done in the following way: (i) select feature in the "Datum Panel" and, eventually, specify if it is a datum; (ii) assign tolerance in "Tolerances" panel. To improve interactive tolerance specification, a feature identification algorithm was implemented. The algorithm identifies the associated elements and enables only the associable tolerances.

To avoid inconsistent specification, a reference dependencies algorithm was implemented. It checks redundancy for each tolerance assignment and it allows recording assignment without redundancy.

The Toolbox stores all information and retrieve data for each feature. When it is necessary to qualify references elements through the application of appropriate tolerances of shape, position or orientation, both geometrical and semantic control are performed.

Finally, it is possible to plot the part-graph composed by the datum reference frame with its tolerance specification and all functional features connected to the references by geometrical tolerances.



Datum Panel: FirstSidePlane_H

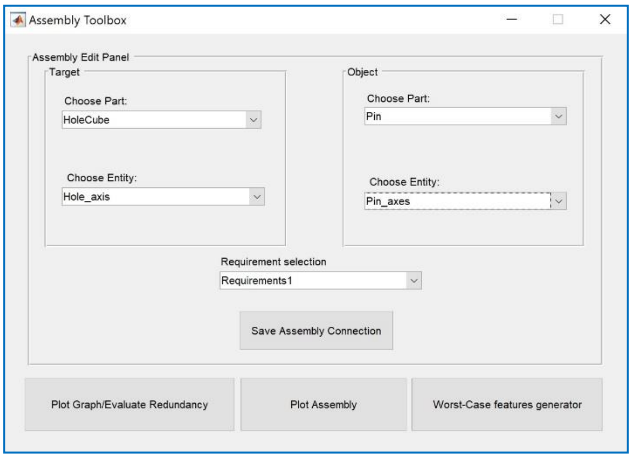
☑ Is Reference

B

Fig. 5. Tolerance toolbox window

### 4.2. Assembly toolbox

Assembly toolbox allows to define the relations between two parts. Selecting functional feature respectively for target-part and object-part a mating can be specify. Besides, for each mating part the assembly-graph can be plot. A set of searching algorithms [17] was implemented to interactively explore and verify the assembly tolerance specification: shortest path algorithm; ordered paths algorithm; ordered and constraint paths algorithm; shortest path to a source node algorithm; shortest path to source nodes algorithm.



Target
Choose Part: HoleCube
Choose Entity: Hole_axis

Object
Choose Part: Pin
Choose Entity: Pin_axes

Requirement selection: Requirements1

Fig. 6. Assembly toolbox window

## 5. Slider-crank assembly

A slider-crank assembly is analyzed to test the developed software tool. The assembly is composed by: a crankshaft; a bushing; a piston rod; a piston and a pin. The exploded view of the assembly is shown in Fig. 7.

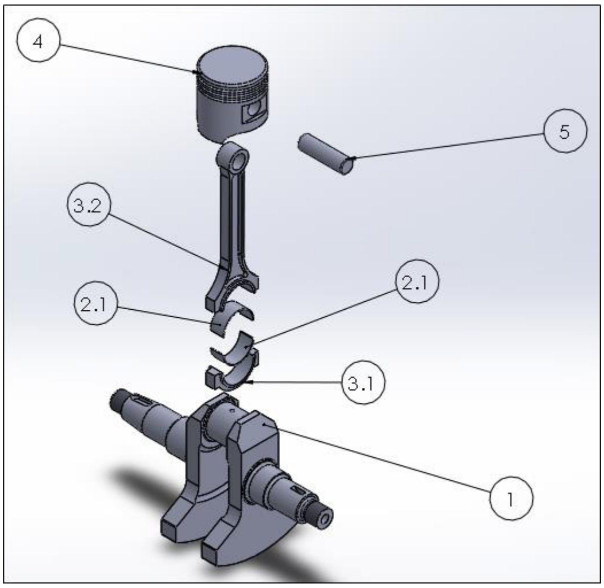


Fig. 7. Slider-crank assembly: 1) crankshaft; 2) bushing; 3) piston rod; 4) piston; 5) pin.

Slider-crank assembly is imported into software, parts by parts, using STL file format. A datum reference frame was defined and a tolerance specification set was done for each functional surface by using “Tolerance Tool”.

For example, Fig.8 shows the equivalent tolerance specification carried out by the tool. Fig.9 shows the part tolerancing graph, i.e. the relations among all crankshaft features. It represents the tolerance dataset of the crankshaft. Analogue tolerance specification was carried out for each component obtaining the following dataset: datum reference frame; tolerance specification set; part adjacency matrix.

Inter-part relations were defined by using assembly tool generating the assembly adjacency matrix which corresponds to assign joints between features of the parts. The obtained assembly-graph is depicted in Fig.10.

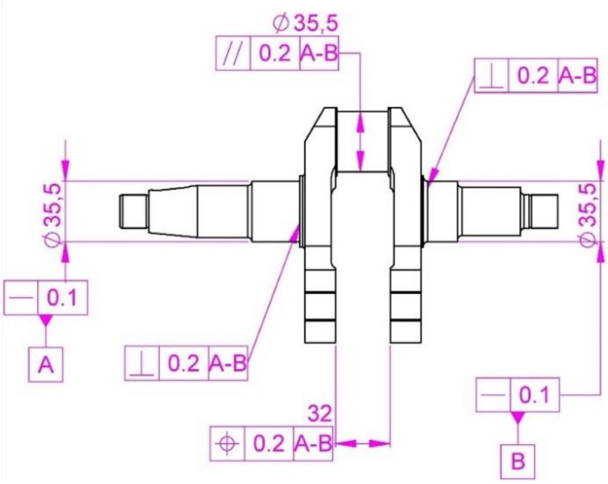


Fig. 8. Crankshaft tolerance scheme

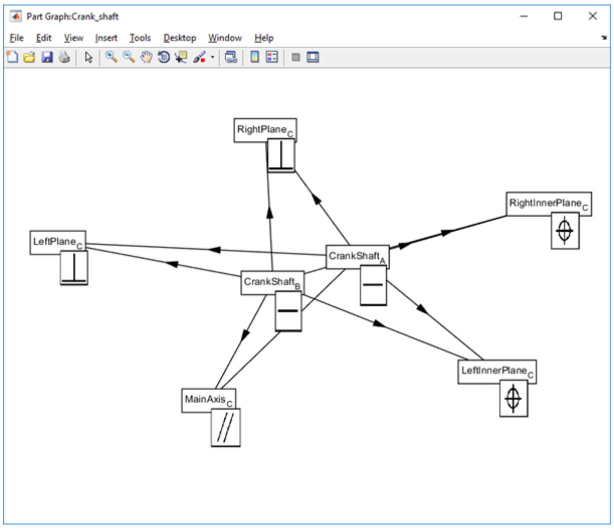


Fig. 9. Crankshaft part tolerancing graph

## 6. Conclusions

The present paper presents a graph-based method to manage and record tolerance specification set. Besides, a software tool, development in MatLAB® environment, to interactively assign tolerance specifications and to enabling both consistency analysis and automatic tolerance graph

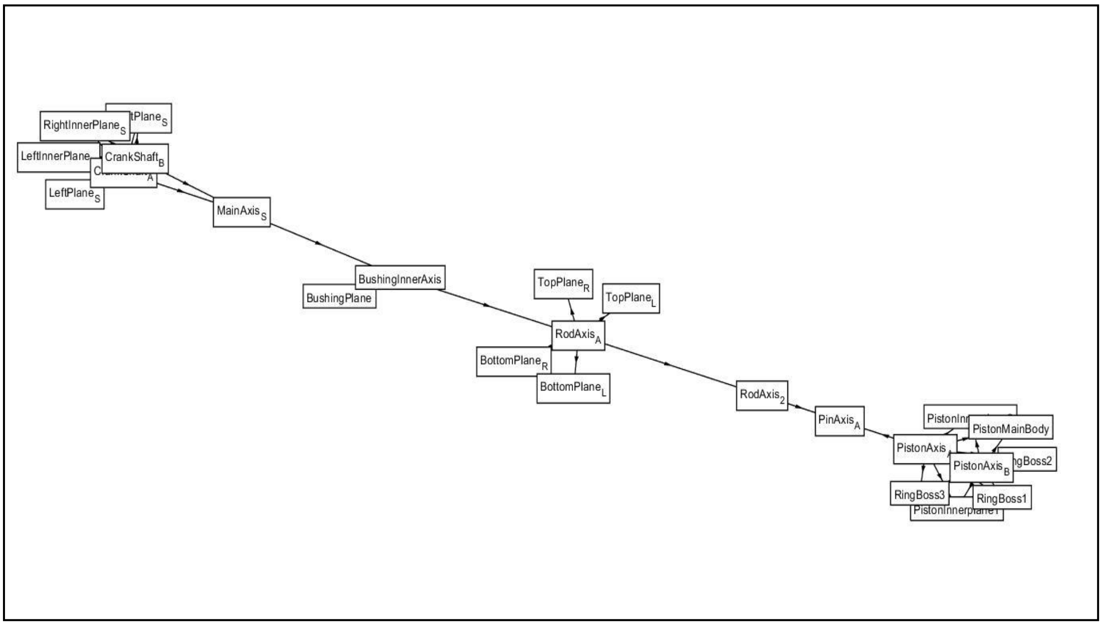


Fig. 10. Assembly graph of the slider-crank assembly

generation is presented. The proposed method is applied to a crank slider mechanism. Further integrations are needed for the automatic feature recognition in order to simplify the importing step of assembly.

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