KAUNAS UNIVERSITY OF TECHNOLOGY

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The development, analysis and implementation of algorithms for projection of electronic circuit components topology onto 3D surfaces

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

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Elektroninių schemų komponentų topologijos vaizdavimo trimačiuose paviršiuose algoritmų sudarymas, tyrimas ir taikymas

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General outline of the work

Relevance of the problem

As more and more miscellaneous products contain integrated parts, mechanisms – knowledge from various fields is required in order to manufacture them. Arrangement of electronic components (interconnect and packaged components) within mechanical structure is an example of such integration.

Since size requirements for many devices equipped with electronics are getting stricter – thus electronic piece parts should be as small as possible. While placing electronic components within mechanical structures, unused space must be minimized. Most of device’ space is usually occupied by interconnect bare board. In this thesis a few algorithms used to project electronic components onto 3D mechanical objects are proposed. They allow minimizing the overall size of electromechanical product by placing interconnect and packaged components directly onto 3D body, thus eliminating planar bare board.

In various papers it is proved that considering many aspects (mechanical constraints applied to electronic circuitry, thermal, pressure analysis, etc.) in early design stages saves manufacturing time and money. Appearance of commercial software confirms the importance of this topic. Majority of companies producing multi discipline products aim to solve integrated tasks.

The goal of the work

Major goal of this work is to develop, test and deploy algorithms for projecting electronic components onto a mechanical 3D object.

Tasks solved in the work

1) Analyse available mapping algorithms, modify and adopt them in order to achieve the goal of the work. Also develop new mapping algorithms.
2) Choose a solid model and approximation method for visualization of 3D object.
3) Analyse the electronic and mechanical product life cycles and possibilities to link the data used there.
4) Algorithms used to project electronic components onto 3D mechanical objects must satisfy the following constraints:
    a) geometry of packaged components must remain unchanged,
    b) bounding box of footprint may be minimally modified (so that avoid overlapping with other footprints and preserve

requirements for connectivity),

c) the width of the track must remain the same after the projection onto 3D object,
d) initial components' topology must be retained,
e) components should not overlap.

Basis for the thesis

Analysed and newly developed algorithms of the projection of electronic components onto 3D surfaces are similar to the texture mapping algorithms in computer graphics. The only difference – the task of projecting electronic components has constraints not relevant to regular texture mapping. Those constraints significantly increase the complexity of this task.

One of the major requirements for the projected electronic components is the preservation of their topology. Topological structures existing in various formats and standards were analysed in order to meet this requirement.

Scientific foundation

Three algorithms for performing projection of electronic components onto 3D objects are proposed and implemented in the thesis:

1) the algorithm based on orthogonal projection,
2) the algorithm based on parametrical equations of the surfaces,
3) the algorithm dedicated to projection of electronic components.

Author of the thesis tries to provide independent solution for the integration of electronic and mechanical design and manufacturing processes. This work is different from many other researches, since mechanical objects are associated with PCA components, as well as with PCB components (traces, pads, etc.).

Design and projection of electronic components onto 3D objects did not gain sufficient attention in recent 3D-MID technology investigations. In this work the effort is made to compensate this lack of attention by proposing three original algorithms.

Practical importance

Since 3D-MID technology is used in telecommunications (mainly mobile phones), cars (electronic sensors, controlling devices), hand held devices, TVs etc, practical importance of the work is very high.

Software implemented in this work reduces the time needed for designing and manufacturing of electro-mechanical products, because it allows automating a few previously manual stages.

Application of results

Three algorithms for projection of electronic components onto mechanical objects were the basis for two software packages (Z-Belichter and JMID-210). This software is successfully deployed at LPKF (one of the worldwide leaders in the manufacturing of laser equipment) and Stuttgart University (Germany). It is used to control specialized hardware. Software was implemented as a part of projects sponsored by German government. Solutions for data enhancement and healing tasks were successfully used in software adopted by Boeing, Rockwell Collins companies and NASA JPL department.

Author's contribution

The author formulated methodologies, implemented and tested all of the algorithms described in the thesis. Author actively participated in the development and practical adoption of standards from ISO 10303 series (especially ISO 10303-210 and ISO 10303-521).

Defended proposals

1) Algorithms used to project electronic components onto 3D mechanical objects:
    a) the algorithm based on orthogonal projection,
    b) the algorithm based on parametrical equations of the surfaces,
    c) the algorithm Specialised for Electronic Components.
2) Data enhancement, healing and fixing algorithms.

Approbation of the dissertation

Author published 3 articles, recognized by the Science Council of Lithuania. He also made presentations in 5 Lithuanian and International conferences.

Scope and structure of the work

Thesis consists of ten Chapters (including conclusions, references and appendices). Thesis is written in 144 pages. The main part, which contains 61 pictures and 11 tables, consists of 114 pages. The remaining 30 are filled with appendices.

Work is split into ten Chapters, since the topic is rather broad and the author tries to solve multi disciplinary problems. The author analysed topics from different areas important for this work.

Chapter 1 consists of a short description of the goal, requirements, tasks and currently available methods to fulfil them. This chapter also contains a description of results achieved. Results are analysed from the practical, scientific and innovation perspectives.

Chapter 2 includes extensive analysis of worldwide research in the field associated with the thesis. Currently available algorithms, suitable for projecting of electronic components onto 3D objects are reviewed in this Chapter. Texture mapping techniques are recognized as at least partly suitable for this work and they are analysed the most. Chapter 2 also includes analysis of solid models and approximation techniques for 3D objects. The A-BREP solid model and projection based triangulation technique are chosen as ones best suiting this work.

Data enhancement, healing and fixing issues are analysed in the Chapter 3. The same chapter also covers application of results.

The Chapter 4 includes a description of algorithms for projection of electronic components onto 3D objects. This chapter also contains a description of algorithms for generating 2.5D shapes of electronic components. Further, application areas for algorithms described in this chapter are researched.

Experiments with previously described algorithms are set forth in the Chapter 5. This chapter also introduces calculation time dependencies of algorithms.

Overall conclusions of the thesis are listed in Chapter 6. All references cited throughout the work may be found in the Chapter 7. The Chapter 8 is a short dictionary of terms and abbreviations. The Chapter 9 contains the list of publications written by author during doctoral studies. All appendices are given in Chapter 10.

Summary of the work

Currently available algorithms, suitable for projecting of electronic components onto 3D objects are reviewed in Chapter 2. Biggest attention is dedicated to texture mapping techniques, which are recognized as at least partly suitable for this work. Finally, the following classification of solid models and methods is proposed in the work:

1) Initialization of primitives. This model is a semantically simple model, but consumes a lot of memory if used to describe larger objects. This method is usually used as an underlying method in more complex models.
2) Spatial subdivision, decomposition. Tree structures are used to model 3D objects. The trees of eight branches (octets) are most popular. Smallest part of this structure is called volume element or voxel. If spatial subdivision is used, memory footprint is too big for advanced 3D objects.
3) CSG model. It is based on specialized trees, which consist of primitives and logical operations (AND, OR, NOT etc.) with primitives. The same 3D object can be modelled in many ways if CSG model is used. The biggest advantage of CSG model – valid object always remains valid after any CSG operation performed with object. CSG model is one of the

most popular models in CAD systems.

4) Sweeping method. It is based on Minkovsky sum. The basic idea is to modify one object by many copies of other objects. This operation can be performed in 2D and 3D. All operations based on Minkovsky sum are classified as follows:
    a) Dilation. For example, movement of sphere along the boundary of the cube. The result of this operation is a cube with rounded corners.
    b) Erosion. In the case of the example given above, the result is a cube with the path of the sphere subtracted from it;
    c) Extrusion. Usually, it is the path of closed shape along some curve (e.g., extrusion of the plane along its normal).
5) Interpolation and approximation. Curves and surfaces are interpolated when points of curve or surface go through all controlling points. Approximation is used only if end points are passed by curve (surface), intermediate control points are only approximately passed by curve (surface). The latter method is becoming increasingly successful in applications like b-spline and bezier curves and surfaces.
6) The A-BREP model. One of the most popular models. In comparison to CSG model A-BREP model has both drawbacks and advantages. All kinds of surfaces and curves can be used by A-BREP model. This is used as a key model in this work.
7) Non-manifold surfaces. Most of CAD systems use 2-manifold surfaces. Non-manifold surfaces do not satisfy usual topological requirements defined by CAD systems. Therefore non-manifold surfaces are only used in some exceptional cases only (e.g. when there is a need to have dangling curves or surfaces).
8) Polyhedra and mesh model. If this method is used, 3D objects are approximated by planes, which are bounded by polygons (usually triangles or quads). One of the biggest drawbacks of this method is high memory consumption. Triangulation technique is based on this method.
9) Feature based modelling. Typical features are through hole, rounded or truncated corner, and etc. Features usually reflect specific manufacturing actions (drilling, milling, casting, etc.).

The following properties of the models and methods (provided above) are compared: precision, validity, unambiguity and uniqueness, memory consumption, adaptability, smoothness, rigidity, determination of outer boundary, and simplicity of boundary subdivision. After analysis of properties of models and methods mentioned above, the A-BREP model was chosen as a key model to use in this work.

Polyhedra and mesh model is indirectly used in the work as well, because triangulation technique is one of the applications of this model.

There are many triangulation algorithms described in the literature. The following algorithms are analysed and compared in the work: Ear-Clipping, FIST, Seidel, Kumar and projection based algorithms. The latter one was chosen, because it is suitable for approximating any 3D object (with holes and any surfaces), and it also generates good topological structures.

Major goal of this work is to develop, test and deploy algorithms used to project electronic components onto 3D mechanical objects. Electronic components are processed as graphical models. Functional aspects of electronic components are not analysed in the work. Geometrical model is treated as a set of curves and polygons, which are mapped onto 3D surfaces.

Tasks of data enhancement and healing are covered in the **Chapter 3**. Detection and calculation of boundary of shape is the most popular data enhancement topic. Many algorithms require board and component outline to be closed. Unfortunately, many CAD systems do not guarantee that. Simplest and in some cases the only way to detect the boundary is to calculate the bounding box of available shape. This approach was used the most in this work. In order to calculate outline of the traces – widening algorithm was used in the thesis.

Calculation of material to be removed from power and ground planes and explicit storage of a result was another data enhancement task solved in this work. Majority of CAD systems only store data about the amount of material required to be removed (if any). But some algorithms (e.g. generation of extruded shape of PCB) use explicit shapes for removals and additions. CSG operations like "union" and "subtract" were used while solving this problem.

Data structures for connectivity were also improved in this work. For example, even if some ECAD systems claim to have good topological structures, those structures are not optimized for various queries outside ECAD systems. Topological structures consist of a list of traces and pads belonging to the same network, but there is no information about pairs in which packaged components are connected. Unrouted networks are also modelled in most of ECAD systems not completely. Those problems were solved in this work as well.

One of the biggest drawbacks of current ECAD systems – they do not allow independent identification of pads or any other PCB components. As a result, users must define "dummy" PCA components even if they only want to have externally accessible pads or vias. In this work, "dummy" PCA components are eliminated by using some extra classification (e.g. if package has just one terminal, its part number is within particular range or if package belongs to particular category).

Another poor design paradigm used in most of ECAD systems (especially low-end) is to mix design and annotation data. Usually, data in ECAD systems are divided into logical layers. Unfortunately, in most cases, user has too much freedom and he/she can mix design and annotation data, which are very hard to separate afterwards. AP210, used in this work, allows to clearly distinguish those two types of geometrical data. In most cases annotation data can be and needs to be filtered out of the design data. If only annotation data is available in an ECAD system (e.g. CadSoft Eagle), bounding box of shapes needs to be calculated and stored as shapes for design data.

Various kinds of undetected errors stemming from ECAD systems are most popular candidates for data healing. Examples of such errors include incorrect usage of traces, overlapping of pads, traces etc., and redundant points in geometrical shapes. All of these errors were successfully corrected in this work.

Semantic richness of data depends on the ECAD system, which produced data. If data are of poor quality, many assumptions are just implicitly captured by the designer. Data enhancement is performed in order to improve data quality. As a result of this operation, implicit assumptions become explicit. Type of drill hole (plated or unplated, used for via or terminal of packaged component), vias (blind, buried, through), many implicit CSG operations, layer stack up (thickness of all layers, their sequence, characteristics), fiducials are examples of information, which maybe implicitly known by the designer and not stored in ECAD file. In this work all those examples are successfully processed and stored explicitly in data structures defined by AP210.

The **Chapter 4** is dedicated to algorithms used to map 2D components onto 3D objects and to algorithms generating 3D shapes of components out of 2D shapes. Generation of 2.5D or extruded shapes is a special case of the latter algorithms. Most of extruded shapes, generated by specialised ECAD software are based on packaged components. Details of printed circuit board (like traces, lands, even cutouts) are usually ignored. In this perspective this work is original, because an extruded view of PCB is generated as well. Extruded view of PCB improves visual perception of the design. Collision detection and calculations of total occupied space is more precise if extruded view of PCB is used.

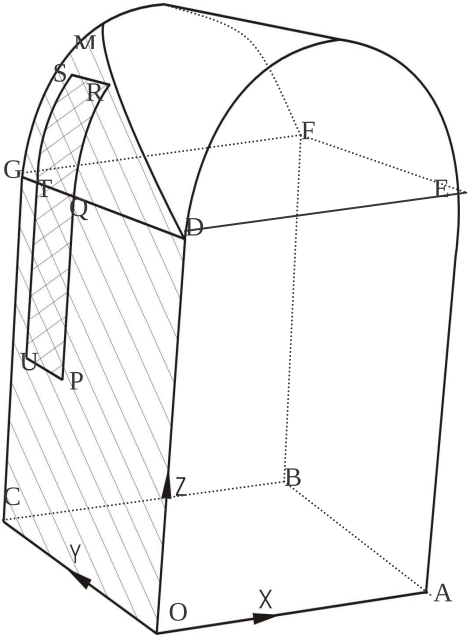

Figure 1. Example defined in ISO-10303-521.

Two algorithms described in the **Chapter 4** are based on texture technique known in computer graphics. The basic idea is to use electronic components and the whole PCB as one texture and map it onto 3D object. The first algorithm is based on orthogonal projection, which is also used in computer graphics (3D objects are displayed in such a way that their size does not depend on the distance from the object). This algorithm is simple to implement and visualize. It does not depend on the surfaces of 3D object to which it is applied. Unfortunately, the algorithm based on orthogonal projection has more drawbacks than advantages. It almost always causes distortion of original shape. It may also cause overlapping of shapes, etc. So in principle, this algorithm does not satisfy the requirements defined in the thesis. The second texture based algorithm uses parametric equations of the surfaces. This algorithm causes no or only minimal distortions, so it is suitable for projection of traces and lands. But this algorithm is not suitable for packaged components, as packaged components become non planar after they are mapped onto non-planar surface. ISO 10303-521 standard was initiated aiming to improve parametric-based algorithm. The author of this thesis contributed to the release of this standard as well. This standard allows having a topological model, which guarantees that 3D curves and surface parts (called subsurface) bounded by it, are precisely laying on the particular surface (if it is required). For example, subsurface "UPQT" is laying precisely on the surface "ODGC" (Figure 1).

Texture based algorithms are easy to implement and do not cause any problems during visualization (since texture is always guaranteed to be on the surface). In spite of the advantages mentioned above, texture based algorithms do not satisfy most of the requirements defined in this work. Texture based algorithms do not guarantee avoidance of distortion and overlapping. They also do not retain width of track and initial topology. Taking into account all of these conclusions, the third algorithm was developed in this work. After the projection, texture based algorithms process geometrical data without any topology or associations what the geometry is used for.

The third algorithm (called „Algorithm Specialised for Electronic Components“) is dedicated to one task only – to map PCB and PCA components onto 3D object. This algorithm requires data to be semantically rich. Algorithm Specialised for Electronic Components consists of two major parts: mapping of packaged components and mapping of traces. Mapping of footprints is treated as a part of packaged components mapping, in view of the fact that footprints are fully dependent on the packaged components. Data preparation phase is the same for both parts mentioned above. It consists of the following steps:

1) Transform all the triangles of a 3D object by transformation defined by the end-user (user has to define orientation and position of 3D object, which is most suitable for the projection for PCB and PCA components).
2) Eliminate triangles having negative Z value of the normal.
3) Apply modified Z buffer (eliminate triangles with smaller Z value only if they are fully covered by triangles with bigger Z value).
4) Transform triangles so that their normal vectors become equal to (0, 0, 1).
5) Determine neighbouring triangles.

A simplified algorithm for mapping of packaged components consists of the following steps:

1) Calculate geometrical centre point of bounding box of packaged component.
2) Determine point on 3D surface onto which this geometrical centre point will be projected.
3) Determine triangle containing projection point found in the previous step.
4) Calculate the normal vector of the triangle determined in the previous step.
5) Packaged component must be projected as close to the triangle determined in the third step as possible. The steps sequence required to perform this operation is presented in **Figure 2**.

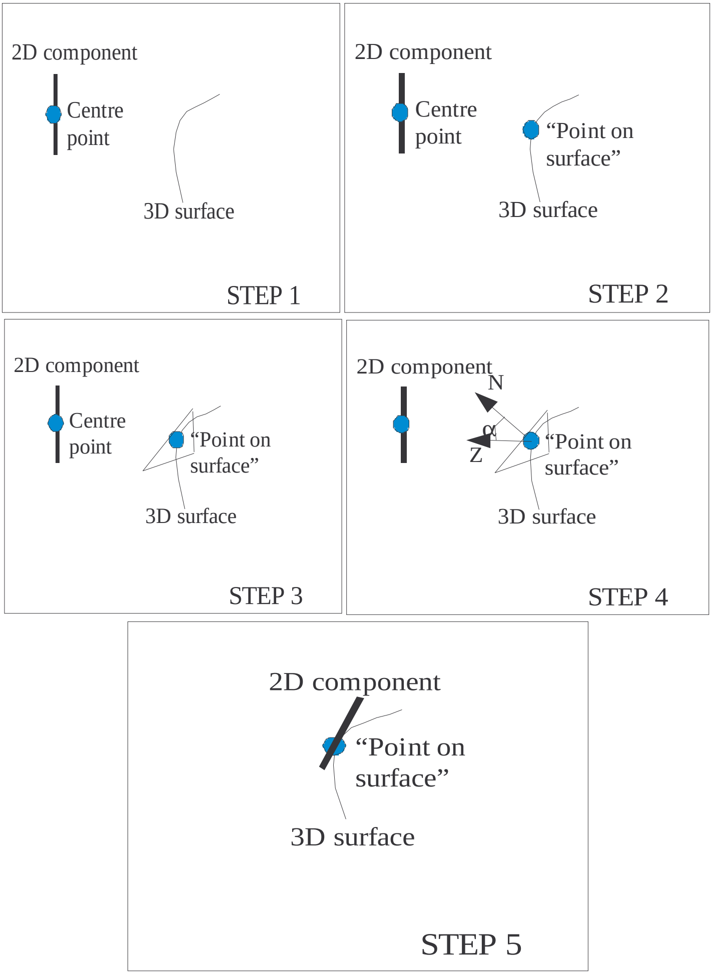

Figure 2. Sequence of transformations performed on each packaged component.

As previously mentioned, projection of footprint depends on the projection of its packaged component. All the steps described above are used for footprints as well. The only difference between mapping of packaged component and its footprint is that several extra transformations applied to the latter one. After step 5 in Figure 2, the footprint is locally projected onto surface using orthogonal projection. Subsequently, in case of non planar surface, packaged component will hang above the surface. Whereas the pads of footprints will be on the surface they are projected. This is needed in order to preserve the connectivity between traces and pads.

Projection of track is done separately for each segment of the track. The arc or circular segments are approximated by linear segments. As a result, the algorithm needs to process only linear segments. Centrelines of traces are mapped onto 3D object using orthogonal projection. In parallel, pads connected to traces are projected using much more complex algorithm (described above). This is the reason why connectivity between traces and lands is lost after they are projected using different algorithms. Additional heuristics are used during projection of traces in order to preserve initial connectivity among them. The point of track which is connected to a pad in the original design is projected using the same algorithm as the algorithm for projection of pad. In this way original connectivity is preserved. Further steps of the algorithm for each linear segment of the track are the following:

1) Determine the triangle in which there is the start point of the track segment.
2) Calculate intersection points of the linear segment of the track and the triangle determined in the previous step.
3) Create the square using the centreline of the track and its width. It will be used in further steps.
4) Transform the triangle determined in the first step so that intersection points calculated in the Step 2 remain in the same positions in 2D.
5) Calculate intersection area of the triangle transformed in the Step 4 and the track square from the Step 3.
6) Calculate barycentric coordinates of the square points according to the triangle transformed in Step 4.
7) Extend the square of the linear segment of the track by adding triangles created in the area of this track and processed triangles.
8) Go to the next triangle according to the structure of neighbouring triangles formed in data preparation phase. Steps 2-7 need to be repeated using current triangle and the same linear segment of the track.
9) Steps 5-8 need to be recursively repeated for all neighbouring triangles, until intersection of the triangle and the square of linear segment of track becomes empty.
10) Finish the analysis of the segment, if the triangle which is currently analysed contains end point of linear segment of the track. The algorithm will analyse next linear segment of the track.

Besides the algorithm described above, software implemented in this work contains a few unique add-ons. If a track can't be projected onto any 3D surface it will remain dangling in the air like “air wire”. It is possible to “glue” the track to the surface by editing track in 3D. Packaged components and footprints are dangling if they can not be projected. They are “hanging” in the air until they are locally projected onto 3D surface. Another specific option implemented in this work is the possibility to move traces and packaged components on the opposite side of 3D object (surface with inverse normal to the original front surface). This is achieved by using orthogonal exposure separately on each segment of the track.

Chapter 5 is dedicated to the description of experiments performed in this work. Firstly, 2 texture based algorithms are analysed and compared. As expected, orthogonal projection based algorithm turned out to be 2-4 times faster than the algorithm based on parametric equations of the surfaces. Next, Algorithm Specialized for Electronic Components was analysed and compared with texture based algorithms. It was determined experimentally that the order of the complexity of the Algorithm Specialized for Electronic Components is lower than $O(n^2)$, but higher than $O(n*\ln(n))$. Calculation time of this algorithm does not much depend on the number of components (traces, packaged components and footprints). This can be explained by the fact that most of the calculation time is spent on processing the triangles of 3D object (mainly determination of neighbouring triangles). Direct comparison of texture based algorithms and Algorithm Specialized for Electronic Components gave interesting results with the same 3D objects and PCB. Despite that texture based algorithms are much simpler and, consequently, should be faster, in practice they are not. Texture based algorithms need to process more of “dummy” graphical objects, while the Algorithm Specialized for Electronic Components processes few PCA and PCB components due to the fact that data related to components is semantically richer. So taking into account that Algorithm Specialized for Electronic Components satisfies all the PCA and PCB components projection requirements defined in the beginning of the thesis, this algorithm is certainly the best among three algorithms defined and implemented in this work.

Another group of experiments is performed in the area of data enhancement and re-creation of topological structures. A few conclusions are made after those experiments:

1) The time taken by data healing and enhancement algorithms is of the same order in cases when connectivity data are not available and in case of incomplete or erroneous connectivity data.
2) Processing time of traces is significantly longer than processing time of pads and other PCB components. This is due to the fact that typical design contains much more traces than other PCB components.

Endmost topic covered in **Chapter 5** is application of algorithms in software packages. Software implemented in this work generates specialized

NC commands (mainly according EIA RS-273 standard), which control the hardware. Two types of machines were used during the tests. The first one was *3D-MID* machine with 5 mechanical and 3 optical axes. Software specialized for this machine was developed in this work. This software has two modes: Design Mode (where user has to transform 3D object and map 2D layout onto it) and Laser Mode (used to transform 3D object emulating axes available by the device). Another device controlled by the software is *MicroLine laser*. This machine was mainly controlled by the algorithm based on orthogonal projection. It must be mentioned that controlling actual hardware was very important part of verification and validation. This process also allowed identifying several areas need to be optimized. Removal of redundant and collinear points is one of the examples of such optimization performed in this work.

General conclusions

1) Algorithms and scenarios analysed in this work:
    a) algorithms for approximation of solid models,
    b) triangulation algorithms,
    c) scenarios for designing of electronic components.
2) Algorithms, newly developed and implemented in the thesis:
    a) the algorithm based on parametric equations,
    b) the algorithm Specialised for Electronic Components,
3) Algorithms, modified and adopted for this work:
    a) data enhancement and healing algorithms,
    b) the algorithm based on orthogonal projection.
4) Regular texture mapping algorithms are not suitable for the major goal of this work, because of the following reasons:
    a) usually texture is a bitmap, while electronic components used in the work are represented by geometrical models consisting of curves and polygons,
    b) distortions caused by the resizing of the texture are solved by antialiasing algorithms. Unfortunately, those algorithms are not acceptable for geometrical primitives like curves and polygons.

    So in order to use texture mapping techniques, they have to be modified in the work.
5) Projection algorithms are independent of the type of surfaces due to triangulation technique. This is true for all projection algorithms developed in the work except for the algorithm based on parametric

equations of the surfaces. So algorithms proposed in this work are universal.

6) In order to successfully project electronic components onto mechanical 3D objects, data for electronic components should be of good quality and semantically rich. If this requirement is not met, data have to be enhanced and corrected. So the following algorithms are implemented in this work:
    a) transformation of geometrical models (formation of outer boundaries, usage of CSG operations),
    b) changing the semantic meaning (conversion of traces into pads, specialization of more specific entities, based on topological information, removal of fictitious components),
    c) creation and augmentation of topological structures,
    d) data integration algorithms.
7) Advantage of the projection algorithms based on textures – there is no need to solve data enhancement and enrichment tasks.
8) Texture based projection algorithms have the following disadvantages:
    a) avoidance of overlap of electronic components is not guaranteed,
    b) preservation of packaged component’s geometrical model and preservation of initial thickness of a track is not assured,
    c) orthogonal projection based algorithm may cause big distortions.
9) Algorithm Specialised for Electronic Components meets all the major requirements raised for this work:
    a) geometrical models of electronic components (packaged components and track width) remain the same, or change a little only (footprints and padstacks),
    b) topology of electronic components is not altered,
    c) overlapping of electronic components is not caused,
    d) electronic components are projected onto any 3D object, if it is possible to do so in reality (the size of 3D object and the size of bounding box of electronic components to be projected are of the same order).
10) Electronic components can be mapped onto a surface with negative Z value of its normal (pointing away from the end-user) only if the algorithm based on parametric equations of the surfaces is used. If additional transformation of electronic components is performed, Algorithm Specialised for Electronic Components can project onto surfaces with negative Z value of their normal vectors as well.
11) Calculation time of Algorithm Specialised for Electronic Components is of the same order as orthogonal projection based algorithm (longer

than O(n*ln(n)), but shorter, than O(n^2)). In spite of the fact, that, theoretically, first algorithm is more complex than second one, it has to process less geometrical objects due to the semantic richness of data it is using.

12) Relevance of the problems solved in this work is proved by successful deployment of software implementations of the algorithms, formulated in this work. Software is deployed in companies like LPKF, Boeing, NASA JPL and Rockwell Collins. In latter one results of this work are used in real manufacturing process.

PUBLICATIONS

Publications recognized by the Science Council of Lithuania:

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REZIUME

Kadangi daugeliui įrenginių keliami vis didesni reikalavimai jų gabaritams, elektroniniai komponentai turi užimti kuo mažiau vietos. Elektroninius komponentus talpinant į mechanines struktūras – minimizuojamas nepanaudotas tūris. Šiame darbe yra pasiūlyti keli elektroninių komponentų vaizdavimo trimačiuose mechaniniuose objektuose būdai, kurie padeda sumažinti visą gaminį.

Pagrindinis darbo tikslas – sudaryti, ištirti ir įdiegti elektroninių komponentų vaizdavimo trimačiuose mechaniniuose objektuose algoritmus.

Darbe sprendžiami uždaviniai:

1) Išanalizuoti vaizdavimo (angl. *projection, mapping*) algoritmus, juos modifikuoti ir pritaikyti elektroninių komponentų vaizdavimo trimačiuose objektuose uždaviniui spręsti.
2) Išanalizuoti trimačių objektų geometrinius modelius bei jų aproksimavimo būdus ir parinkti geriausiai šiam darbui tinkamus.
3) Sudaryti programinę įrangą vaizdavimo algoritmų tyrimui ir jų diegimui.
4) Algoritmai, kuriais elektroniniai komponentai vaizduojami trimačiuose objektuose turi tenkinti tokius apribojimus:
    a) nepakeisti lustų geometrijos modelių,
    b) minimaliai keisti išorinius kontaktinių aikštelių kontūrus, kad išvengti geometrinių modelių užkloties ir tenkinti topologijos bei jungumo reikalavimus,
    c) nepakeisti atvaizduotų takelių storio,
    d) nepakeisti elektroninių komponentų topologijos ir nesukelti jų užkloties.

Disertaciją sudaro įvadas, 5 pagrindiniai skyriai, išvados, literatūros sąrašas, terminų ir santrumpų žodynas, publikacijų sąrašas ir priedai. Pagrindinė darbo dalis – 114 ir priedai – 30 puslapių. Disertacijos pagrindinėje dalyje yra pateikta 61 paveikslas ir 11 lentelių.

Pirmame skyriuje supažindinama su pagrindiniu darbo tikslu, keliamais reikalavimais ir apribojimais, suformuluoti uždaviniai, kuriuos reikės spręsti darbe. Čia praktiniu, moksliniu, novatoriškumo požiūriais reziumuojami darbo rezultatai.

Antrame skyriuje formuluojamas darbe sprendžiamas elektroninių komponentų vaizdavimo trimačiuose objektuose uždavinys. Jis analizuojamas tekstūrų vaizdavimo uždavinio atžvilgiu. Šiame skyriuje taip pat apžvelgiami

trimačių objektų aproksimavimo būdai ir naudojami modeliai. Čia argumentuotai parenkami A-BREP trimatis modelis bei projekcija grįstas trianguliacijos algoritmas, kurie yra naudojami darbe. Antrame skyriuje taip pat atliekama egzistuojančių elektroninių komponentų vaizdavimo trimačiuose objektuose metodų apžvalga. Galiausiai yra apžvelgiami trimačių paviršių plokštinimo algoritmai, kurie potencialiai gali būti naudojami darbe.

Trečiame skyriuje nagrinėjami įvairūs duomenų praturtinimo, „gydymo“ ir taisymo uždaviniai. Taip pat apžvelgiamos šių uždavinių taikymo sritys.

Ketvirtame skyriuje pateikiami sudaryti algoritmai, kuriais elektroniniai komponentai vaizduojami trimačiuose paviršiuose. Čia taip pat apžvelgti darbe realizuoti elektroninių komponentų 2.5D atvaizdų generavimo algoritmai ir jų naudojimo atvejai.

Penktame skyriuje yra aprašyti darbe atlikti eksperimentai su sudarytų algoritmų realizacijomis. Čia taip pat atlikta algoritmų skaičiavimo trukmės analizė. Šiame skyriuje pateiktas trumpas sudarytos programinės įrangos diegimo aprašymas.

Šeštame skyriuje – viso darbo išvados, septintame – literatūros sąrašas. Aštuntame – trumpas terminų ir santrumpų žodynas. Devintame skyriuje yra pateiktas disertacijos tema paskelbtų publikacijų sąrašas, dešimtame – priedai.

Išvados

1) Darbe išnagrinėti šie algoritmai ir scenarijai:
    d) trimačių objektų aproksimavimo algoritmai,
    e) trianguliacijos algoritmai,
    f) elektroninių komponentų projektavimo scenarijai.
2) Sudaryti ir realizuoti šie nauji algoritmai:
    c) parametrinių lygčių,
    d) specializuotas elektroninių komponentų vaizdavimo,
3) Modifikuoti ir darbui pritaikyti algoritmai:
    a) duomenų praturtinimo ir taisymo,
    b) ortogonaliosios projekcijos.
4) Standartiniai tekstūrų vaizdavimo algoritmai nėra tinkami darbe suformuluotam uždaviniui spręsti, dėl šių priežasčių:

    a) Paprastai tekstūros sudarytos iš bitų masyvų, tuo tarpu darbe naudojami geometriniai elektroninių komponentų modeliai yra sudaryti iš vektorinių duomenų (kreivių, daugiakampių).
    b) Galimi mastelio keitimo sukelti iškraipymai kompensuojami glodinimo (angl. *antialiasing*) algoritmais, kurie yra nepriimtini naudojant vektorinius duomenis.

    Todėl norint darbe naudoti tekstūrų vaizdavimo metodus, juos reikia modifikuoti.

5) Trianguliacija leido sudaryti vaizdavimo algoritmus, nepriklausomus nuo trimačių objektų paviršių tipų. Todėl darbe pateikti algoritmai yra universalūs.
6) Darbe realizuoti elektroninių komponentų vaizdavimo trimačiuose objektuose algoritmai gali naudoti tik semantiškai turtingus duomenis. Nustatyta, kad daugumoje ECAD sistemų nėra pakankamos duomenų kontrolės ir jose realizuoti modeliai nėra semantiškai turtingi, todėl duomenis tenka taisyti ir praturtinti. Tuo tikslu darbe realizuoti tokie algoritmai:
    a) geometrijos modelių transformavimo (uždarų kontūrų sudarymas, apjungimas CSG operacijomis),
    b) semantinės prasmės keitimo (takelių vertimas kontaktinėmis aikštelėmis, topologiniu jungumu grįstų detalesnių esybių išskyrimas, fiktyvių komponentų atmetimas),
    c) topologinių struktūrų kūrimo ir papildymo,
    d) duomenų integracijos.
7) Darbe sudarytų tekstūrų vaizdavimu grįstų algoritmų privalumas – nereikia spręsti duomenų praturtinimo uždavinių.
8) Darbe sudarytų tekstūrų vaizdavimu grįstų algoritmų trūkumai:
    a) neužtikrinamas elektroninių komponentų geometrijos modelių užkloties išvengimas,
    b) neužtikrinamas lustų geometrijos modelio ir pradinio takelio storio išsaugojimas,
    c) ortogonaliąja projekcija grįstas algoritmas gali sukelti didelius iškraipymus (angl. *distortion*).
9) Autoriaus sudarytas specializuotas elektroninių komponentų vaizdavimo algoritmas tenkina apribojimus:
    a) trimačiame objekte atvaizduoti geometriniai elektroninių komponentų modeliai išlieka nepakitę (lustai ir atvaizduotų takelių storis), arba kinta minimaliai (kontaktinių aikštelių rinkinys),
    b) elektroninių komponentų topologija išlieka nepakitusi,
    c) nesukeliama elektroninių komponentų užklotis,

   d) elektroniniai komponentai atvaizduojami visuose trimačiuose objektuose, jei tai yra fiziškai įmanoma (trimatis objektas ir projektuojami elektroniniai komponentai yra suderintų matmenų).

10) Parametrinių lygčių algoritmas elektroninius komponentus gali vaizduoti paviršiuose, kurių normalinių vektorių Z dedamosios yra neigiamos (normalinis paviršiaus vektorius nukreiptas nuo vartotojo). Taip transformuotuose paviršiuose galima vaizduoti ir naudojant specializuotą elektroninių komponentų vaizdavimo algoritmą, komponentus papildomai transformuojant po vaizdavimo.
11) Specializuoto elektroninių komponentų vaizdavimo trimačiuose paviršiuose algoritmo skaičiavimo laikas yra tos pačios eilės, kaip ir ortogonaliosios projekcijos algoritmo (ilgesnis nei O(n*ln(n)), tačiau trumpesnis, nei O(n2)). Nors teorinis pirmojo algoritmo sudėtingumas yra didesnis, semantinio duomenų turtingumo dėka jame tenka apdoroti ženkliai mažiau grafinių objektų, nei jų apdorojama ortogonaliosios projekcijos algoritmu.
12) Darbe suformuluotos ir ištirtos algoritmų programinės realizacijos sėkmingai įdiegtos LPKF, Boeing, NASA JPL bei Rockwell Collins kompanijose. Pastarojoje šio darbo rezultatai naudojami realiame gamybos procese.

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