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## Computer Vision Analysis of 3D scanned Circuit Boards for functional Testing and Redesign

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Testing, repair and overhaul of long-living printed circuit boards (PCBs) is a laborious task if no schematics or layout plans are available. Existing Reverse Engineering (RE) methods are time-consuming, error-prone, and destructive and require reference samples which makes them not feasible for non-OEM users of electronic devices. The Fraunhofer Institute for Production Systems and Design Technology (IPK) in Berlin and the Technical University Berlin have defined a new process for automated and non-destructive schematic and layout reconstruction based on electrical and optical measuring techniques. Current results and innovative approaches using computer vision analysis for recognition of PCB structure aiming to build error-free net lists through a net list merging algorithm are depicted in this paper.

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*Keywords:* computer vision; reverse engineering; PCB; netlist; schematics; MRO; repair; redesign**1. Introduction**

Maintenance, repair and overhaul of electronic devices are significant challenges for companies in aviation industry, rail transport or plant manufacturing. Functionality of printed circuit boards (PCBs) has to be tested and faults have to be located and repaired. In case of obsolete PCBs, meaning that no spare parts are available, a redesign of components is the only way for on-going operation. These working activities require schematics, layout plans and BOMs (bill of materials) which often do not exist or are not provided by OEMs due to confidentiality. Companies try to help themselves with reverse engineering strategies for retrieval of necessary information and plans [1, 2]. Many repair or redesign tasks are so difficult and time consuming that there is still no economic solution existing. High costs emerge for these kinds of maintenance and obsolescence management tasks [3, 4, 5]. For example the Brazilian airline TAM experienced frequent failures of an inverter of PCBs. Although TAM is certified to

repair this part themselves it was not possible due to lacking schematics and part lists. Consequently TAM had to buy new inverters from the supplier which caused estimated annual costs of 50,000\$. This worked only till the supplier stopped his production of spare parts [6].

Another example is the German railway company Deutsche Bahn which has to maintain their communication systems. An important supplier lost his know-how due to a company take-over so that Deutsche Bahn was forced to replace the complete communication infrastructure of older ICE trains which were built in the eighties. Costs were about 500,000€.

This paper firstly depicts challenges of state of the art reverse engineering processes. Secondly, research approaches aiming to overcome deficits and to exploit automation potential through analysis and processing of optically acquired 3D data sets of PCBs are presented. These research approaches comprise a PCB optimised principle for 3D digitization with computer tomography and 3D scanning,

computer vision methods for recognition of single parts, pins and PCB tracks as well as improvement of reconstructed netlists. Finally future work for implementation of an improved process for schematic and layout retrieval is described.

## 2. Challenges

State of the art reverse engineering services based on electrical or 2D optical measuring technologies for reconstruction of schematics, layout plans and bill of materials have still a low degree of automation and are often destructive and error-prone. The most advanced technology for electrical tests are flying probe testers which can test all connections of a PCB based on an input of a coordinate list with all test points. These test points have to be determined by 2D optical inspection and manual setting of coordinates. Result is a netlist which can be used to model schematics with an ECAD (Electronic Computer Aided Design) system including some semi-automated features like auto routing or component placement. Electrical tests also allow measuring of some part specific values like capacity or resistance. Integrated circuits cannot be determined. Optical 2D filter pipelines are used to separate PCB tracks for remodelling of layout plans whereas part identification and placement are additional manual tasks.

Both electrical and optical methods face high challenges, especially for complex boards with dense component placement, multilayer and many integrated circuits. Test points and strip line are often not completely visible or accessible by needles of a flying prober. Thus, parts have to be completely unsoldered. Furthermore protective lacquers have to be removed. These operations are in many cases not reversible. Consequently these principles are not applicable for repair of obsolete components where no spare parts are available. In addition these methods are not without fault. Due to mentioned obstacles like protective lacquers or non-

accessible pins, flying probe needles miss contact with test points which results in incomplete netlists and error-prone schematics. This is not sufficient for industrial needs, because such errors can hardly be identified and corrected afterwards. Plausibility checks of determined netlists can only be done by comparison with results of an error-free golden board.

## 3. Research objectives

The research aim is to find single solutions for the mentioned challenges and to combine them in an automated process for reconstruction of schematics, layout plans and bill of materials in order to enable repair and redesign tasks of long-living electronics even when no spare parts or reference samples are available. Solutions comprise non-destructive measuring methods, PCB structure recognition and creation of error-proof netlists. Therefore a new process was defined and shall be implemented for a proof of concept and performance analysis (Fig. 1, cf. [7]).

This process combines two ways for netlist retrieval: The electrical state of the art flying prober test and a highly innovative optical computer vision based PCB analysis. Key elements are described subsequently in this paper.

## 4. PCB specific 3D digitization

The 3D digitization of circuit boards is a non trivial task which requires the use of advanced scanning technologies and combination of different principles.

### 4.1. Approach

To capture the entire geometry of a complex test PCB with dense parts placement, four layers and dimensions of approximately 300mm x 180mm two scanning technologies were used for testing digitisation quality. The PCB's surface was scanned with the structured light 3D scanner GOM

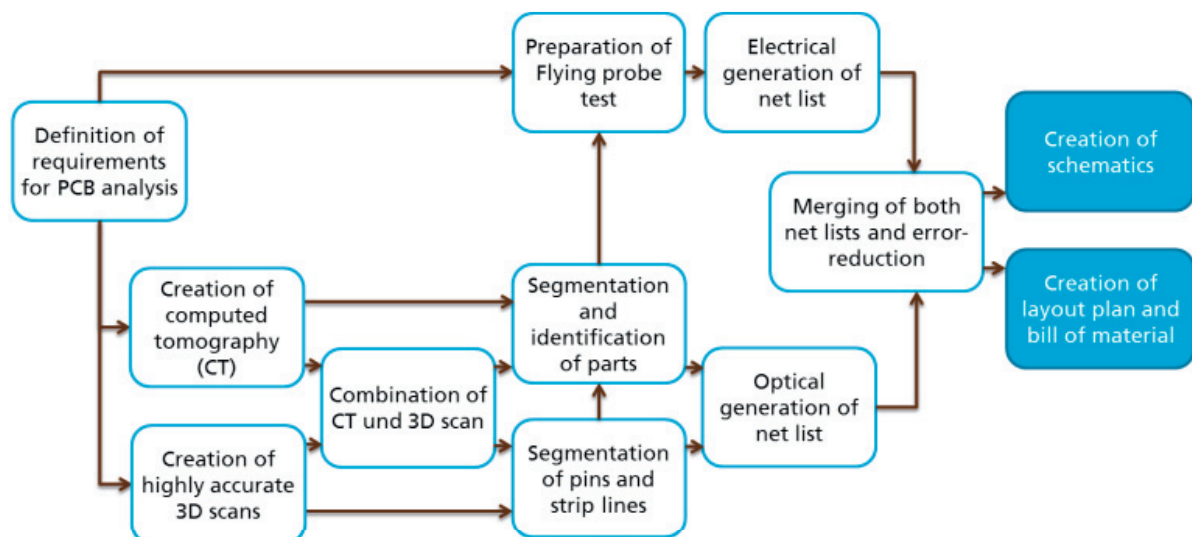


Fig. 1. New process for reconstruction of PCB schematics and layout plans.

ATOS III Triple scan. For visualisation of inner structures a computer tomography (CT) was provided by a service company with state of the art equipment. The optical 3D scan was combined with photogrammetry and delivered information about geometry, texture and labels of the visible surface while the CT scan showed in addition inner layers. The resulting mesh by the optical 3D scan and the resulting voxel array by the CT scan were compared regarding completeness of surface acquisition and accuracy (Fig. 2). Further 3D measuring principles were taken into account: Shape from focus, gray-code principle, time-of-flight, white-light interferometry and shape-from-shading.

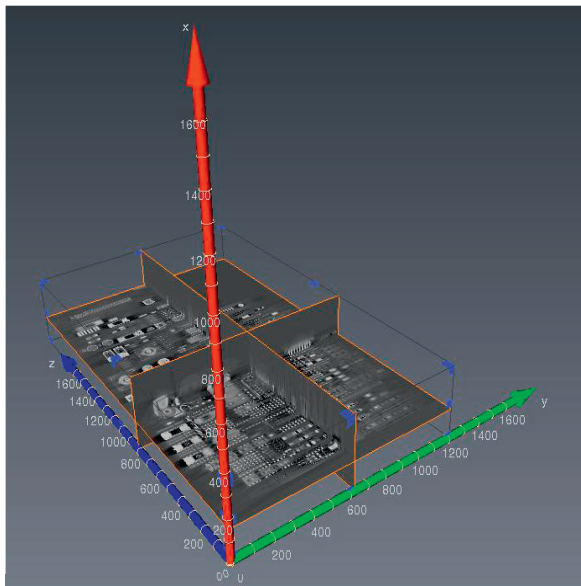


Fig. 2. Analysis of a PCB CT scan with software AVIZO® Standard.

#### 4.2. Findings

No scanning system was able to offer sufficient results meaning depiction of needed elements such as parts, pins and PCB tracks. A combination of approaches might be suitable and depends on whether a textured scan is required or not. 3D structured light and CT scanned data together allowed an overall analysis of the PCB and the recognition of individual components. Optical scans turned out to be highly vulnerable to light reflections and hidden structures. Thus, it was not possible to capture the whole PCB surface without having holes in the resulting mesh structure. A new 3D scanner is needed based on combined use of telecentric and pericentric optics as well as an illumination system for shadow-free and reflex-free optical acquisition. To realise a sufficient resolution of  $10\mu\text{m}$  a precise calibration and referencing system with constant environmental conditions regarding e. g. temperature or vibrations is needed.

CT scans enabled visualization of inner layers and pins. PCB tracks were not completely visible. Reasons were found in an inclined voxel orientation and an insufficient resolution. There is no CT scanner on the market which can digitise

circuit boards being bigger than Eurocard format (160mm x 100mm) with sufficient resolution. There is also need for a PCB specific measuring strategy. Parameters like current, voltage, measuring distance, prefiltering, amplification factor, integration time, projection number and diverse software filter have to be chosen according to PCB characteristics.

### 5. Recognition of PCB parts

Optical recognition of single parts is still a challenge of the future. For creation of schematics and layout plans it is necessary to find out parts type, identifying name and specification.

#### 5.1. Approach

Experiments showed that there is no optimal technical solution for tackling the problem of recognising PCB parts with computer vision approaches. The entire process is more a concatenation of algorithmic approaches which were decomposed into a post-processing pipeline.

Optical detection: Application of basic image processing algorithms was tested to gain information about parts mounted on top of a PCB. Those included OCR (optical character recognition), Canny edge detection [8] and a simplistic watershed image segmentation [9]. Apart from the image segmentation all algorithms were used directly from third party libraries like OpenCV.

3D data segmentation: The segmentation was tested on the voxel data set from the CT as well as the triangulated mesh from the structured light scanner. As mentioned above the latter tended to produce holey scans when trying to capture small slits and indentations. That error in mesh completeness continued to complicate the segmentation process as it gets significantly harder to separate single parts the more information is missing. In that case the voxel data was, again, the better option. An algorithm was used that encoded the entire voxel buffer as a graph and performed an adaptive broad search to separate mounted parts [10].

Identification: The market offers a variety of ready to use software for mechanic and electronic part databases with shape search functionality. CADENAS PARTsolutions was chosen as the host of the part database in this experiment. A sample database containing about 10 parts was set up as a base to perform queries on.

#### 5.2. Findings

Fig. 3 shows a separated capacitor based on grey-scale segmentation, highlighting the complete capture of geometry. Segmentation was realised through implementation of a filter pipeline consisting of a diffusor for elimination of image noise, a canny algorithm for edge detection and histogram segmentation for focus on relevant grey values. Resulting surface quality is not sufficient yet and has to be optimised in the future.

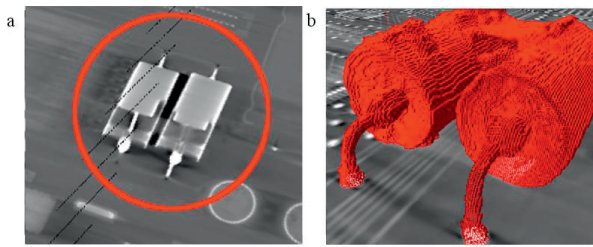


Fig. 3 (a) Planar view on a part; (b) Extracted segmented voxels.

It turned out that amount of similar looking parts in the electronic context is rather big so that a shape based database search of these segmented single parts is only sufficient to roughly categorise PCB parts. Improved segmentation principles would possibly be able to deliver highly precise geometric part representations which are needed for better results of geometric database search. However, based on current segmentation results, parts identification does not work robustly so that alternatives were analysed.

2D image analysis is error-prone and highly depending on a proper camera angle. The character recognition method was able to retrieve a few parts in a test database that was set up beforehand. The biggest potential lies in the combination of optical character recognition and geometric detection algorithms. Future research aims to perform plausibility checks through redundant search for geometry and labelling. Databases should include both IDs and part geometry. However, those systems were not available at present.

## 6. Segmentation of pins and PCB tracks

PCB tracks achieve the electrical connectivity between electronic components such as resistors, transistors, capacitors, inductors or integrated circuits (ICs). Pins interface the transition between PCB tracks and electronic components. Therefore the segmentation of these two structures is necessary for the functional analysis of a PCB. As a side effect pin coordinates can also be used as input for a flying probe tester. PCB tracks are needed for layout remodelling.

### 6.1. Approach

Pins and PCB tracks are hidden by top mounted parts or take place inside the PCB. Therefore, only CT data was used for this segmentation task. CT scans consist of a voxel array organized in slices that allow a traversal working through a PCB's inner structures. Due to the fact that both pins and PCB tracks turned out to be represented not only by a single but multiple voxel slices a master view had to be compiled where all pins and PCB tracks were clearly visible (Fig. 4). In order to get an enhanced data set for later calculations the segmentation of pins and PCB tracks was split into different tasks to separate the data acquisition and pre-processing from the actual pattern recognition. A major problem during the pre-processing step was the erroneous rotation angle of the PCB within the voxel buffer. This problem cannot be avoided

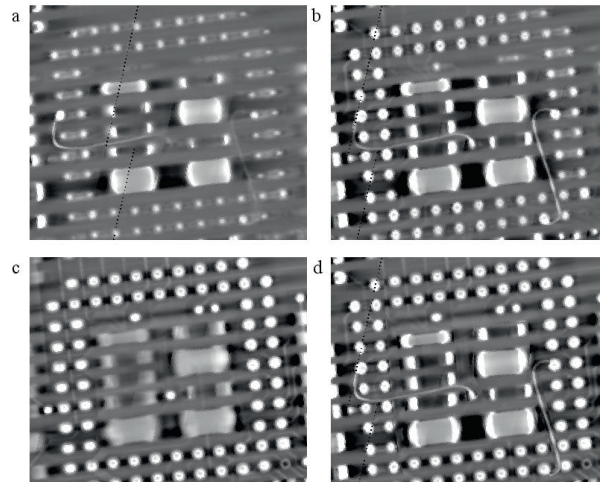


Fig. 4. (a) - (c) Three slices sequence; (d) Master view.

as a PCB cannot be placed in a perfect planar position inside a CT scanner. The solution was the implementation of an algorithm which detected the PCB's edges and computed the deviation against the slices of the voxel array. Subsequently the PCB scan was aligned inside the voxel buffer using the transformation matrix gained from the previous calculation.

After alignment greyscale colour correction and noise reduction were applied to maximize contrast throughout subsequent creation of a master view. This master view is a specific region of interest in the voxel buffer of which can be assumed that it contains all pins and PCB tracks (respectively of a single layer) but no mounted parts. All voxel slices belonging to that region were inspected in a loop and merged together pixel wise with the lighter pixel winning in comparison. The resulting 2D image was digitally scaled and interpolated showing pins at a very high contrast.

By applying thresholding and binarisation all pins were detected and the few remaining false positives could be eliminated with a semi-manual user interface.

### 6.2. Findings

While pin detection works robustly with a good image source the entire process is very dependent on the quality of the CT scan. Especially noisy scans resulting from deflected rays complicate the following computer vision process. Also if the rotation angle that needs to be corrected beforehand is too big the resulting data set can be slightly distorted.

## 7. Merging of netlists

Part recognition and segmentation of pins and PCB tracks allow a complete analysis of the PCB and the optical derivation of a netlist. This new optical acquired netlist is obtained by other physical methods than an electrical netlist. Therefore, it is assumed that matching results in both optical



and electrical netlists are correct and the deviant results must be re-examined.

### 7.1. Approach

The matching and merging of electrically and optically determined netlists results in several steps:

- Uniform alignment and scaling of coordinate systems of the two netlists
- Comparison of pin to pin connections of optical and electrical netlists
- Involvement of a component library to complete the component list
- Logical examination of pin connections based on the pin assignment of the PCB parts

One of the main challenges is to integrate the information obtained from the optical and electrical netlists into a consistently compatible data format, without violating the data format on the one hand and without significant loss of information on the other hand. The combined reconstruction of optical and electrical netlists requires an extended data format which permits the storage of additional information like prioritization and weighting of partial results.

The method of combining optical and electrical netlists should be tested with a known "golden pattern" in order to ensure the faultlessness of this new approach.

### 7.2. Findings

The combination of optical and electrical netlists represents a new way of the recovery of PCB netlists. The result is a new type of netlist which is physically based on two different methods. This kind of result verification allows the assumption that twice confirmed results are accurate and only the deviations must be reviewed manually. The overall result is an error-free netlist.

However, development of extended data format which meets specific requirements of the reconstruction of netlists and of the described procedure is needed.

## 8. Summary and outlook

A concept for an innovative process for destruction- and error-free automated reconstruction of PCB schematics, BOMs and layout plans has been proposed. Sub-processes were experimentally tested for a feasibility proof. Focus lay on development of new computer vision analysis methods of 3D scan data. A computer tomography of a complex PCB was used to test image quality and identify relevant 3D scanning parameters. CT image quality could be improved with voxel rotation and filter methods. Benefits of combination of CT

and 3D scan were identified. Segmentation principles for extraction of parts, pins and PCB tracks were analysed and tested. Part identification principles by use of geometric similarity search and OCR were tested. A concept for recognition of pin connections based on region growing algorithm as well as for netlist building was developed. Finally an error detection and solving concept for netlists which were created redundantly by electrical and optical sub-processes was proposed.

Recent results promise high automation potential in PCB information and data retrieval and proof feasibility of a non-destructive principle for schematics and layout reconstruction. Further research has to show possibilities of error reduction in reconstructed netlists without using comparative samples. The next step will be to implement the whole process in cooperation with industry partners. Therefore a consortium has been set up with partners in the field of 3D and CT scanning, flying probe testing, netlist building and drawing as well as layout modelling.

## Acknowledgements

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