An Automatic Hypothesis of Electrical Lines from Range Scans and Photographs

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Abstract:

Building information modeling (BIM) with high level of detail and semantic information on buildings throughout their lifetime are getting more and more important for stakeholders in the building domain. Currently, such models are not yet present for the majority of today’s building stock. With increasing speed and precision of laser scans or photogrammetry, geometric data can be acquired at reasonable costs. Unfortunately, these data are unstructured and do not provide high-level semantic information, which stakeholder require for non-trivial workflows.

A current research topic are methods to extract non-visible structures from visible geometric entities. This work uses domain specific geometric and semantic constraints to automatically deduce information that is not directly observable in architectural objects: electrical power supply lines. It utilizes as-built BIM data from scans of indoor spaces in order to provide a hypothesis of paths of electrical lines. The system assumes that legal requirements and standards exist for defining the placement of power supply lines. This prior knowledge is formalized in a set of rules, using a 2D shape grammar that yields installation zones for a given room.

Observable endpoints (sockets and switches) are detected in indoor scenes of buildings using methods from computer vision. The information from the reconstructed BIM model, as well as the detections and the generated installation zones are combined in a graph that represents all likely paths the power lines could take. Using this graph and a discrete optimization approach, the subgraph is generated that corresponds to a probable hypothesis.

Our approach has been tested against synthetic and measured data and shows promising first results. Application possibilities include generation of a probable wiring for as-built / optically acquired building model, or suggesting cable ducts for a building reorganization or during planning of a new building.

Keywords: BIM, as-built BIM, semantic enrichment, formal grammar

1. INTRODUCTION

A study conducted on the productivity of the construction industry in North America (Hanna et al., 2014) shows that the industry is struggling with a lack of coordination, in particular the electrical construction companies. The study points at the implementation of Building Information Modeling (BIM) in these fields as a solution for this problem. Its application in this field would reduce conflicts and improve coordination. The study simultaneously points at little actual implementation of BIM in the electrical construction field. This is supported by the finding that 59% of the companies, who actually use BIM, have only three or less years of experience with this technique.

Another survey conducted in the USA (Azhar, 2009) gives a ranking of BIM features for this field, e.g. clash detections, visualization of electrical design or space utilization. Out of the participating companies, 79% responded that they are not using BIM, with the main reasons being not knowing about BIM, lack of technological experience, software incompatibility, and implementation costs. However, the 21% that use BIM reported positive savings in time and cost.

While these studies show that there is an interest in the utilization of BIM for electrical construction, this interest is currently not fulfilled in the area of as-built documentation and renovation projects - which makes for 75% of the EU building market share (Atanasin et al., 2011).
Past and current work practices of companies installing the electrical wiring of buildings use 2D drawings as a base for the work on site (Figure 1). These drawings contain the necessary information for workers to execute the work in the building, such as the position of switches, fuse boxes, as well as the principal connection between these. The workers themselves know about the height, that switches are to be mounted in the walls and the way that cables shall be laid. These rules are setup by national authorities and today harmonized on the European level. Technical standards, as the DIN 18015 in Germany (see also Figure 2), or the “Stærkstromsbekendtgørelsen” in Denmark, specify so called installation zones, which should be preferred for routing of cables. Workers might adapt the routing to special features on local level, but will generally follow the concept of the norms.

This current situation is challenging, as the documentation of the electrical system of a legacy building is, if at all, only present as 2D drawing that does not provide information about the concrete position of cables in three dimensions. The general compliance of the electrical installation to the framework built by norms provides a relatively secure ground for professionals to estimate where wires could be routed, but assured data are usually not available. This situation provides the base scenario of this paper and other recent research, where the location of sockets in 2D floorplans of buildings were used to estimate the amount of copper wire in the walls – a valuable resource and a real asset in the evaluation of a buildings value before demolition (Petkova 2014). This method integrates the prior knowledge of wiring placement directly into the algorithm, however, the norms may differ between countries, or may be revised. In contrast, the method presented in this paper proposes to encode this knowledge in a set of rules using a formal grammar system. Such grammar systems were originally developed in formal language theory, and are commonly used in compiler construction. They are also a common tool used by generative modeling techniques (Thaller, 2013), and have been used in inverse problems e.g. for specifying prior knowledge in façade reconstruction (Riemenschneider, 2012). For a review on generative modeling techniques we refer to (Krispel, 2015a). The grammar ruleset can be adapted to reflect changes in norms, or encode different norms, typically by a domain expert. The method is implemented by a pipeline that uses indoor 3D scans of buildings as a starting point. These scans consist of range scans and image information. From this data, a 3D representation of the scanned spaces is generated via a preprocessing step, and is further processed to determine the configuration of installation zones and a possible wiring hypothesis for the acquired data.

Figure 1. Typical electrical plan for a small one family house. Image was retrieved from (BuildingGuidelines, 2001).

Figure 2. Installation zones for electrical installations based on DIN18015. Zones are defined by a minimum and maximum distance from elements like floors, doors, windows, etc. Image from (InstallationZones 2014).
2. AN AUTOMATIC HYPOTHESIS

The proposed approach is divided into the main concepts data acquisition, data preprocessing, the detection of visible endpoints of electrical installations (sockets and switches), and eventually the hypothesis of installation zones and a possible wiring inside the walls.

2.1 Pipeline Overview

Figure 3, on the right, shows a visual overview over the whole pipeline. The first part, data acquisition, is concerned with the acquisition of measurements in the form of range scans and image information, i.e. photographs.

In the preprocessing stage, a coarse room layout and geometric model is reconstructed from the point cloud. Furthermore, orthographic projections of the picture information of each wall are generated.

In these orthophotos, visible points of electrical lines, e.g. sockets or switches, are detected using a classification algorithm that has been pre-trained on a set of exemplar images of sockets and switches.

From these detections and additional information that were extracted from the reconstructed model, i.e. the adjacency of walls and the location of openings (windows and doors), the location of preferred installation zones for electrical wirings are generated in consideration of norms and requirements. By means of the extracted wall adjacency, the installation zones inside all walls are connected to one graph that represents all possible routes along preferred zones. From this graph, a final hypothesis of wall wirings is extracted under the assumption that all detected points should be connected using the least amount of resources, i.e. cable length. The following sub-chapters describe each part of the pipeline in greater detail.

2.2 Data Acquisition

The input for the pipeline consists of range scan information (point clouds) in E57 format (Huber, 2011), accompanied with spherical panoramas, i.e. equirectangular projections of the sphere around the scanner. For bigger datasets, e.g. a whole building floor, several scans might be required and registered. The E57 file stores metadata for each scan, and additionally one panorama per scan has to be supplied. Our test datasets were acquired using a FARO Focus 3D scanner. In some cases the scanner-mounted camera yields too low resolution for the details that should be detected in photographs, and some lighting conditions were challenging. In these cases, a high-resolution panoramic image was used that was taken with a Canon 500D DSLR and a Nodal Ninja 3 panoramic head. These panoramas were acquired at the scanners’ position, immediately after the scan.

2.3 Preprocessing

If multiple scans have been acquired, they need to be registered into one coordinate system before further processing. After registration, all point clouds and meta data (e.g. position or orientation of each scan) are stored in E57 format. We utilize the approach presented by (Ochmann et al., 2016) to obtain the room layout and a coarse geometric representation that contains information about walls and their openings, see also Figure 4.

Figure 3. Pipeline Overview
Figure 4. Geometric preprocessing of range scans (a) was carried out using the method of (Ochmann et al., 2016). The method estimates a room layout (b), and the configuration of walls (c) and openings, e.g. windows and doors (d).

The resulting data is stored in an intermediate JSON format that encodes the position of each wall, the adjacencies of walls, and the position of windows and doors inside walls. After the extraction of rooms and walls, a projection of the spherical panorama onto each wall is generated to obtain orthophotos for each wall (Krispel, 2015), as shown in Figure 5. If several scans are available, each pixel of an orthophoto is generated using the nearest scan, i.e. the scan with shortest distance from scanning position to the pixel.

Figure 5. Orthophotos (right) generated from the panoramic views and coarse wall geometry (left).

2.4 Endpoint Detection

The system was trained using a database of images of fixed size, in three classes (sockets, switches and background) and a random forest classifier (Breiman, 2001). The descriptor used for training is a combination of a slightly modified Histogram of oriented gradients descriptor (Dalal and Triggs, 2005) and Haar-like features (Viola and Jones, 2001) as also described in (Krispel, 2015b). The results of the detection are bounding boxes around each detected endpoint, associated to a specific orthophoto, or wall.

2.5 Electrical Line Hypothesis

The input to generate an electrical line hypothesis is based on a JSON file that contains wall information, i.e. wall openings (e.g. doors and windows) and adjacency relations to neighbouring walls. Furthermore, the file contains the position of detected sockets and switches, see also Figure 7 (a). An installation zone grammar JSON file is supplied that contains the rules that specify the prior knowledge of the applying standards for the creation of installation zones. The rules are encoded in a formal grammar. The system evaluates the grammar, which yields horizontal and vertical installation zones per wall, their centerlines are represented by dashed lines in Figure 7 (b).
Figure 6. The detection system has been trained with various examples of switches (a) and sockets (b). Detections on an orthophoto are shown on the right (c), the violet rectangles.

After grammar evaluation, a graph is built that encodes all possible routings: crossing installation zones yield vertices, and detections (blue and green rectangles in Figure 7) are either placed as vertex on an existing edge, or connected by the shortest path to an adjacent edge. Adjacent zones from adjacent walls are connected together. Furthermore, at least one power root (orange rectangle in Figure 7) has to be specified.

Figure 7. The Hypothesis generation starts from the input that specifies walls, openings (yellow), detections (green and blue), and roots (purple) as seen in (a), by generating installation zones according to a given set of rules (b). From these zones, a graph is extracted that connects all given end points (c), and a final hypothesis is extracted that approximately minimizes the total wire length (d).

Finally, a subgraph (specifically a forest) is extracted from this graph that connects all marked endpoints (detections) to a power root, with the assumption that the overall length of power lines, which equals to material costs, is minimized.

**Installation Zone Grammar**

As has been observed from the standard specifications of installation zones, these zones are placed with respect to wall boundaries or “forbidden” zones, e.g. windows or doors. We define the installation zone grammar as an attribute grammar,

\[ G_{IG} = (N, T, P, S) \]

that consists of the set of nonterminal symbols \( N \), the set of terminal symbols \( T \), the set of production rules \( P \) and the start symbol \( S \). Nonterminal symbols are written in uppercase letters (e.g. WINDOW) and terminals are written in lowercase (e.g. hzone). A production rule is written

\[ \text{NONTERMINAL} \rightarrow \text{terminal|NONTERMINAL}\{\text{attribute definitions}\} \ldots \]  

The left side of a production rule contains exactly one nonterminal, the right side can consist of any number of nonterminal and terminal symbols, together with attribute definitions in curly brackets. All symbols on the right hand side automatically inherit all attributes from the left hand side, additional attribute definitions are carried out afterwards.
The starting production rule produces nonterminal symbols according to all elements that influence installation zone placement (walls, doors, windows, detections). All positional information is stored in attributes, with respect to wall coordinates (see also Figure 8) that are defined for each wall segment. The terminal symbols of this grammar correspond to horizontal and vertical installation zones, as well as forbidden zones, e.g. doors or windows, for the placement of wirings.

The nonterminals produced by the starting rule are expected to contain the following default attributes: a bounding box specified by the attributes left, top, width, height. Furthermore each wall has a unique identifier, called id. Each terminal is expected to contain an attribute wallid that references the wall this symbol belongs to. Given the starting rule that contains the wall detection semantics from a dataset, the production rules are evaluated until the list of nonterminal symbols is consumed and only terminal symbols are left. The terminals with a special meaning for the optimization system are hzone, vzone, root, the others are treated as an endpoint if it contains the attribute endpoint that is set to true. Using this mechanism, users can manually add points that should be contained in the routing hypothesis, e.g. if there are known positions of wirings that could not be detected by the automatic endpoint detection.

The proposed grammar is not context free, as it was discovered that a context free grammar will not be able to suggest installation zones when specific arrangements of symbols (e.g. vertical or horizontal arrays of sockets and switches) suggest an additional installation zone which is not specified by governing norms (i.e. the norm specifies only a typical distance from walls and windows/doors). Figure 6 (c) shows an example of such an arrangement (left column). Therefore, our approach implements a context sensitive grammar that allows pairs of nonterminal symbols on the left side of a production rule (written “NT1: NT2”) with an optional attribute condition expression that matches if the condition on the attributes of the pair of symbols evaluates to true. Pair rules are always prioritized until no pair of symbols matches anymore, context free rules are matched and executed afterwards. This allows us to formulate rules that group horizontal and vertical arrangements together; groups that exceed a specific size will generate an additional installation zone.

**Wire Routing Hypothesis**

A wire routing is represented by a graph \( G_w = (V, E) \), that contains a number of vertices \( v \in V \) and a number of edges \( e \in E \), where a vertex is associated to a position inside a wall segment, and an edge connects two vertices. Vertices can also be associated to either an endpoint (sockets, switches) or a power root. The graph of all possible routings is created from the list of terminal symbols as follows: For each wall, the graph is built from the arrangement of lines formed by the horizontal and vertical installation zones. Then, any edges that intersect terminal symbols that are marked as forbidden are removed. Symbols that are marked as an endpoint are connected to the arrangement by connecting the midpoint point of the symbol rectangle to the nearest arrangement line using a horizontal or vertical connection. After this step, graphs from adjacent walls are connected together at corresponding nodes.

Under the assumption that the wire route planning was carried out minimizing material costs, creating a hypothesis for actual routing is extracted from this graph by the following optimization: We want to extract the hypothesis subgraph \( G_H \subseteq G_w \), where \( G_H \) is a forest that connects all vertices that are marked as endpoints to a power root. If no root is defined, an arbitrary endpoint is selected as root. This graph is minimal with respect to the sum of edge costs, with a cost function defined for each edge of \( G_w \) that corresponds to the Euclidean length of the edge. This problem is also called the minimum Steiner tree problem in graphs, and is known to be NP-complete (Hwang and Richards 1992). However, there exist approximation algorithms that run in polynomial time. Our current solution implements a local search algorithm similar to (Kou et al., 1981), which runs in \( O(n^2 \cdot m) \), where \( n \) is the number of edges and \( m \) is the number of endpoints.
3. RESULTS AND DISCUSSION

The approach was evaluated on a few single room scans, and a larger dataset that consists of several rooms on one floor. The room shown in Figure 9 was evaluated on a Core i7-4930K with 3.40GHz and 6 cores. The orthophoto generation took 2.4s, the endpoint detection 575.2s and the wire hypothesis (inclusive grammar evaluation) 0.44s.

The endpoint detection is based on a statistical, machine learning approach, which can be improved using a comprehensive training set. With the reduced training set used in these demonstration examples, the endpoint detection already yields very good results. These results are further improved by the pipeline in a step that removes elements inside forbidden regions, i.e. windows or doors, which have been extracted from the range scans, see also Figure 9 (b) and Figure 9 (c). The grammar that was used places vertical installation zones near doors and windows, and creates zones from vertical or horizontal groupings, as seen in Figure 9 (b).

4. CONCLUSIONS

This work presents an approach that synthesizes a hypothesis of electrical lines from range scans and photographs using a new method that utilizes a formal grammar to represent the guidelines that govern the placement of electrical lines. This enables the adaption of rules to different norms, up to specifics that concern only one building. The labeling of detected sockets with confidence values from the detection stage proved to be a viable approach in this project. Practitioners which evaluated our solution remarked that it would be necessary to show users that the generated data is an estimate and not the sole truth, to counter the blind believe, which stakeholders often demonstrate in the face of external data. The representation of an installation zone probability as a heat map would be a way to present this information. Practitioners also stated that this feature would be helpful in the design of new buildings. In later BIM based planning stages, the number and locations of sockets and switches per room are known, but no automated means to estimate the cable length and the attached costs are available.

Source code for the proposed pipeline for the modules orthophoto generation, electric endpoint detection and installation zone generation as well as wiring hypothesis is freely available at the GitHub repository https://github.com/DURAARK/ in Modules orthogen, elecdetect and wiregen.
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InstallationZones (2014). Verlegezonen Wohnräume. By Fabian (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons.


