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A SNAPSHOT OF THE U=RISOLVE FRAMEWORK: SELF-LEARNING ELECTRIC CIRCUIT FUNDAMENTALS MADE EASIER

VISÃO GERAL DO PROJETO U=RISOLVE: FACILITANDO A (AUTO)APRENDIZAGEM DA ANÁLISE DE CIRCUITOS ELÉTRICOS

DESCRIPCIÓN GENERAL DEL PROYECTO U=RISOLVE: FACILITANDO EL (AUTO)APRENDIZAJE DEL ANÁLISIS DE CIRCUITOS ELÉCTRICOS

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Abstract

Innovative teaching and self-learning paradigms and tools have been emerging in the past decade, in a trend to boost motivation and autonomy in new generations of Electrical and Computer Engineering (ECE) students. In this context, we have been leveraging the *U=RIsolve* framework (https://urisolve.pt/app/), which aims at providing an interactive portal for teaching/self-learning the fundamentals of electric circuit analysis and simplification methods. This paper overviews the current functionalities of this web application and summarizes work-in-progress, giving a particular focus to an ongoing research line on automatic circuit schematics identification and modelling based on pictures and computer vision algorithms. Importantly, all contributions in this framework have been devised and implemented by students in the context of their undergraduate/graduate projects/thesis and are freely available to the international community.

Palavras-chave: electric circuit analysis, self-learning tools, web-app, computer vision, machine learning.

Resumo

A última década tem testemunhado o aparecimento de novas abordagens e ferramentas de ensino/autoaprendizagem, visando fomentar a motivação e a autonomia nos estudantes, nomeadamente no contexto do ensino superior. É neste sentido que temos vindo a dinamizar o projeto U=RIsolve, que se materializa num portal web com várias ferramentas para a autoaprendizagem dos fundamentos e métodos de análise e simplificação de circuitos elétricos (https://urisolve.pt/app/). Este artigo dá uma visão geral desta aplicação, resumindo as funcionalidades já implementadas e em desenvolvimento, dando um enfoque especial a uma das suas linhas de investigação: a identificação e modelização automática de circuitos elétricos a partir da imagem do seu esquema, baseando-se em técnicas de processamento de imagem e de aprendizagem computacional. Saliente-se que todas as contribuições neste projeto têm tido o envolvimento de estudantes, em vários níveis de ensino, estando a aplicação e o seu código disponíveis livremente à comunidade internacional.

Palavras-chave: análise de circuitos elétricos, ferramentas de autoaprendizagem, web-app, visão computacional, aprendizagem através da máquina.

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Resumen

En la última década uno ha sido testigo del surgimiento de nuevos enfoques y herramientas de enseñanza/autoaprendizaje, cuyo objetivo es fomentar la motivación y la autonomía de los estudiantes, particularmente en el contexto de la enseñanza superior. En este contexto hemos dinamizado el proyecto U=RIsolve, que se concreta en un portal web con varias herramientas para el autoaprendizaje de los fundamentos y métodos de análisis y simplificación de circuitos eléctricos (https://urisolve.pt/app/). Este artículo ofrece una visión general de esta aplicación, resumiendo las funcionalidades ya implementadas y en desarrollo, dando especial énfasis a una de sus líneas de investigación: la identificación y modelado automático de circuitos eléctricos a partir de la imagen de su esquema, basándose en el procesamiento de imágenes y técnicas de aprendizaje computacional. Cabe señalar que todos los aportes a este proyecto han contado con la participación de estudiantes, de los distintos niveles educativos, estando la aplicación y su código a libre disposición de la comunidad internacional.

Palabras-clave: análisis de circuitos eléctricos, herramientas de autoaprendizaje, aplicación web, visión computacional, aprendizaje a través de la máquina.

1 INTRODUCTION

Learning electrical circuit fundamentals is typically one of the introductory subject in Electrical and Computer Engineering (ECE) degrees. It involves a wide range of concepts and terminology, laws, theorems and algorithms that undergraduate students often struggle to understand, both in theory and in practice. While problem-based and project-based approaches may pave the way for an easier learning process, the fact is that the student cannot avoid building on the foundations of circuit theory, particularly in what concerns circuit analysis and simplification theorems and algorithms. This demands an intensive iterative process of understanding the methods and practice them through examples, which is already difficult by nature and is getting increasingly challenging for the new generations of students.

The academic community has been addressing the creation of self-learning-oriented computer applications for electrical circuit analysis in order to leverage students' motivation and autonomy, triggering desktop and web-based frameworks that validate electrical circuit equations (Weyten et al., 2011), create step-based tutoring systems (Skromme et al., 2015), introduce remote homework systems (Becker & Plumb, 2017) or simply generate symbolic solutions for a given analysis (Pelivan et al., 2020). In parallel, some studies opted to use existent software tools such as MATLAB (Yousuf et al., 2014) and LabView (Xu & Tao, 2015) to create applications dedicated to teaching the fundamentals of circuit theory.

However, existing tools do not offer students a centralized source of content for learning and practicing electrical circuit analysis, because they typically cover a very limited set of circuit analysis/simplification methods and exercises. This triggered the *U=RIsolve*[1] framework (Sousa et al., 2021a), a web portal aiming at guiding the students through all learning process stages, by producing straightforward, guided and step-by-step (re)solutions of different circuit analysis & simplification methods.

In this article, we outline *U=RIsolve* current functionality and ongoing work, unveiling the initial stage of the automatic identification and modelling of pre-drawn circuit schematics.

2 OUTLINE OF THE U=RISOLVE FRAMEWORK

Currently, the *U=RIsolve* web application supports three circuit analysis methods: Node Voltages, Branch Currents and Mesh Currents. Students can reuse a built-in database of example-circuits or build their own using the QUCS circuit simulator (Brinson & Kuznetsov, 2016), which serves as a schematic editor and provides the data input to the application, specifically a circuit description (netlist). As illustrated in Figure 1, users upload the circuit model (netlist) and (optionally) its schematics, select the analysis method and then get the output with all relevant circuit variables

[1] reads like "you resolve", such that with U=RIsolve the student understands & resolves by him/herself.

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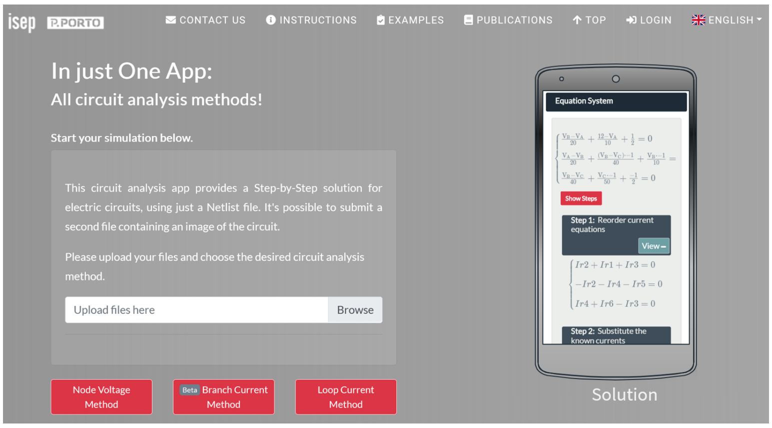
and a step-by-step analysis including (depending on the method) the node/mesh selection, the construction of the equations system and ultimately the numerical computation of all voltages/currents.

Figure 1

U=RIsolve application interface and its step-by-step solution



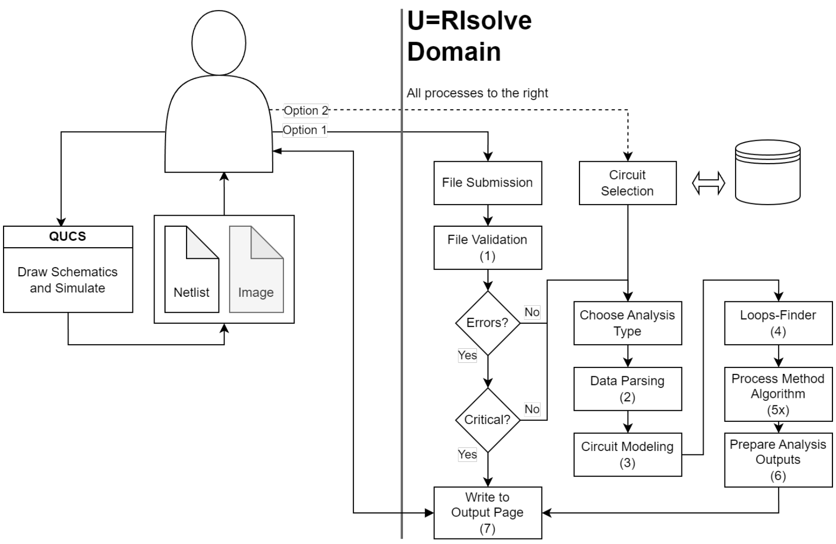
The *U=RIsolve* web-application software architecture is illustrated in Figure 2. The analysis process starts with the validation of the input, in particular netlist-based errors that include misplacement of the Ground terminal, disparities in components units/values or misidentification of circuit nodes. Upon validation, the components are parsed into objects and then the complete circuit model is created by mapping the interconnections given in the netlist. Thereafter, and depending on the selected method, circuit loops are computed, and the correspondent algorithm is processed.

Even though the analysis methods require different computational operations, they have all been developed with the same rationale: perform a symbolic manipulation of variables to strategically integrate them into a step-based output along with helpful tips. The application supports multiple output formats (HTML, PDF, TEX, and JSON), providing seamless integration with Overleaf.

The *U=RIsolve* app functionalities are summarized in the following sections.

Figure 2

U=RIsolve software architecture



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2.1 Analysis/Simplification Methods

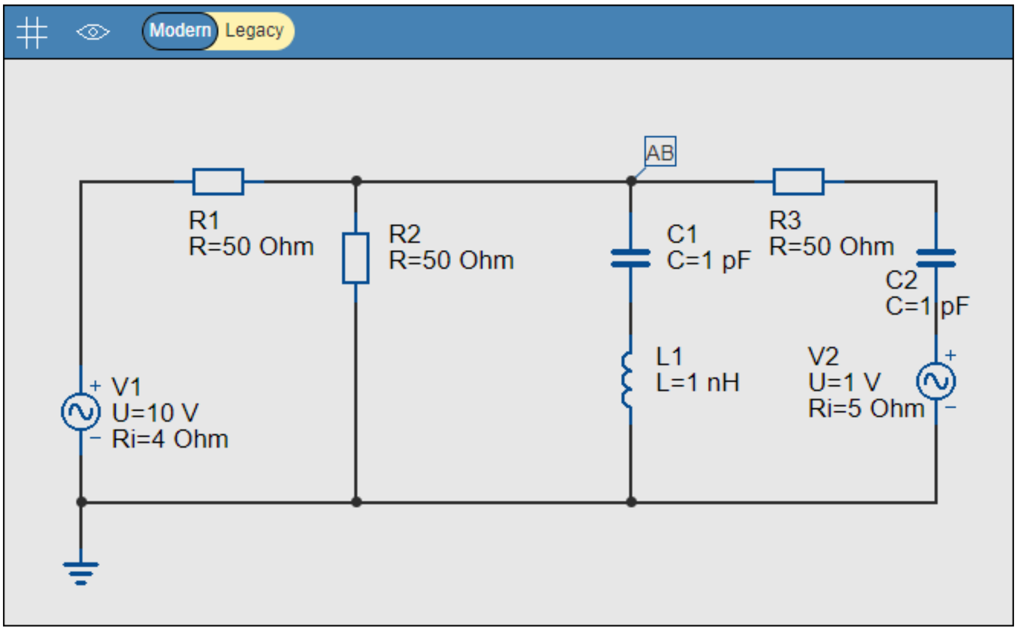
As already mentioned, the *U=RIsolve* application currently supports the Node Voltage Method (Sousa et al., 2021b), the Mesh/Loop Current Method (Pinheiro, 2021), and the Branch Current Method (Carvalho, 2023). The former follows the super-node approach, and the two latter are based on the Meshes-Finder function (Rocha, 2022), an heuristic and algorithm specifically designed to efficiently find and return all loops in a circuit, using a representative graph or node/branches references as input.

Other modules under development include the following:

- Superposition Theorem analysis method, which will enable users to interact with the circuit in real-time, producing operations like modifying component properties, select the order of circuit source analysis and choose a resolution method for each sub-analysis. Given the intrinsic need of manipulating the original circuit, this module required the implementation and design of a widget for displaying and interfacing with the circuit, as in Figure 3.
- Thévenin's and Norton's Theorems simplification methods, which will include interactive features involving the selection of the dipole of interest and the "direction" of the analysis, e.g., determining the equivalent circuit from dipole {A, B} to the "left" of the circuit.
- Equivalent Resistance/Impedance determination, which will provide students with a step-by-step solution of the equivalent resistance (DC) or impedance (AC) in the perspective of a chosen dipole, sequentially applying the required series, parallel and star-delta equivalents.

Figure 3

Schematic design widget



2.2 *U=RIsolve* Academy

U=RIsolve Academy (Castedo, 2023) is a web portal in a higher abstraction level, for a different approach to user interaction and activity data storage. Future plans include using this data to train machine learning algorithms so that the app is able to customize dynamic content according to student's needs and difficulties. This feature will enable them to practice exercises and access additional information (videos, tutorials, written material), as shown in Figure 4, depending on their score/level. The Academy portal will also implement basic administration features, allowing educators to create lectures' content.

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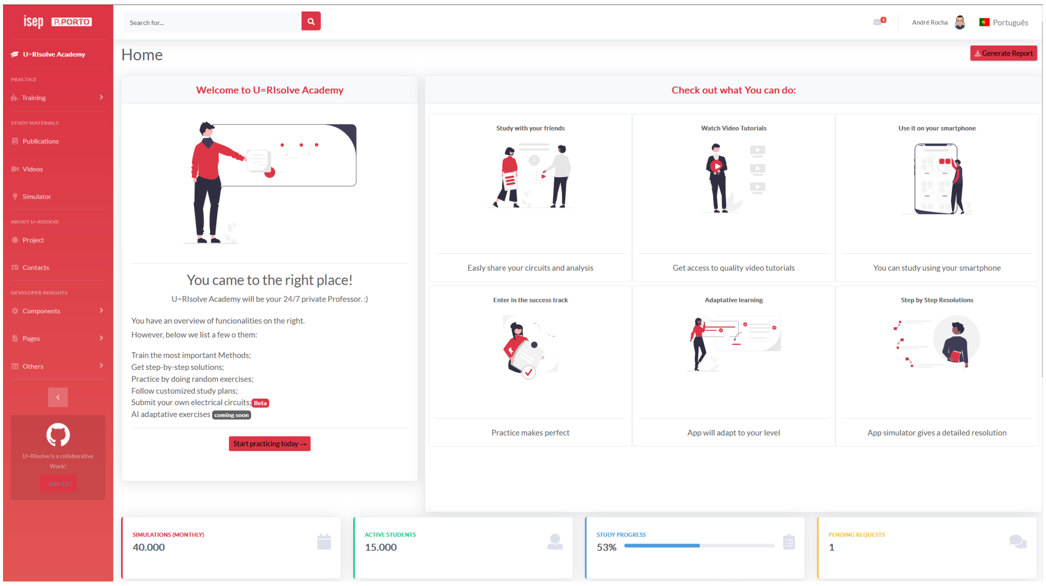
Figure 4

U=RIsolve Academy app preview

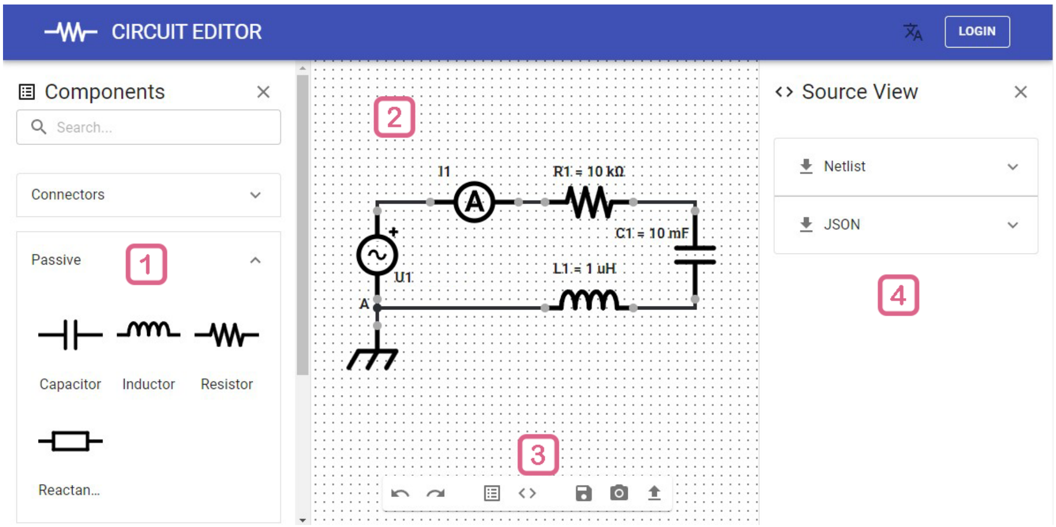


2.3 Circuit Editor

The *Circuit Editor* (Morim, 2022) project focused on designing an open-source web application to enable users to import, edit, and export circuit schematics based on a custom-made JSON data model, extending the need to depend on QUCS to generate the circuit model/schematics and enabling a whole new dimension of graphical manipulation and meta-information in the circuit schematics. Although this project output is not yet ready for integration, it has provided significant contributions such as the JSON model for storing circuit schematic data, as well as the creation of an intuitive editing interface, shown in Figure 5, providing seamless animation and interactivity for the circuit schematics.

Figure 5

Circuit editor interface



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2.4 Oscilloscope Interface and Simulation App

Ongoing work on an oscilloscope simulator aims at developing a web application and Graphical User Interface (GUI) for real-time oscilloscope simulation (self/remote learning) and interfacing with a real Oscilloscope (for high-level control and data acquisition). The back-end module is being designed to support different oscilloscope models, while the front-end module targets simulation/control of a specific Oscilloscope model (the one prevalent in one of our labs). Key contributions will include a versatile data model for digital oscilloscopes and an efficient Application Programming Interface (API) for reading data and transmitting commands.

2.5 Circuit Automatic Generation

This module is being designed to automatically generate example-circuits, using (passive and linear) components such as resistors, capacitors, inductors, as well as AC/DC voltage and current sources. The circuits can be either generated randomly or based on users' input, by specifying a set of rules such as the type and number of components they want to use, the number of nodes and branches, or simply a "complexity" level. Users will be also able to modify component labels and values, *a posteriori*.

3 AUTOMATIC RECOGNITION OF CIRCUIT SCHEMATICS

While learning and practicing circuit analysis methods, students typically start by drawing the schematics on paper and proceed to their analytical resolution. Simulating that same circuit may be interesting, both to validate the analytical results, or to feed *U=RIsolve*. Moreover, there are plenty of circuit schematics already drawn in paper or in digital format (e.g. exercise books, manuals, books), for which a circuit model does not exist, which would be helpful to have in their mathematical model, saving the fastidious and time-consuming task of implementing them in the circuit editor/simulator.

In this context, we recently started a research line targeting the automatic recognition of circuit schematics (Barbosa, 2022), whose ultimate objective is for a student to take a picture of a circuit schematic and the software to automatically recognize and model it (JSON). This software module is based on computer vision algorithms to detect and extract components, nodes, interconnections, and associated labels from a circuit image, whether hand-drawn or computer-generated, as summarized next.

3.1 Preprocessing stage

The preprocessing is the first step of the schematics recognition module, whose purpose is to adapt image data in order to obtain the best possible result out of the subsequent computer vision algorithms. The preprocessing starts with grey scale conversion to reduce the pixel matrix complexity, then a gaussian filter is applied to reduce noise and preserve circuit contours.

The image is further transformed into a binary matrix using an adaptive threshold method, which is less vulnerable to luminosity variations than regular thresholding. Finally, morphological operations such as dilation and erosion are applied to the image in order to obtain the skeleton of the circuit, reducing pixel density to one pixel and allowing easier detection of segments for the next phase.

These transformations constitute the preprocessing stage and are illustrated in the example of Figure 6, where a "raw" schematics goes through several operations until its skeleton is obtained.

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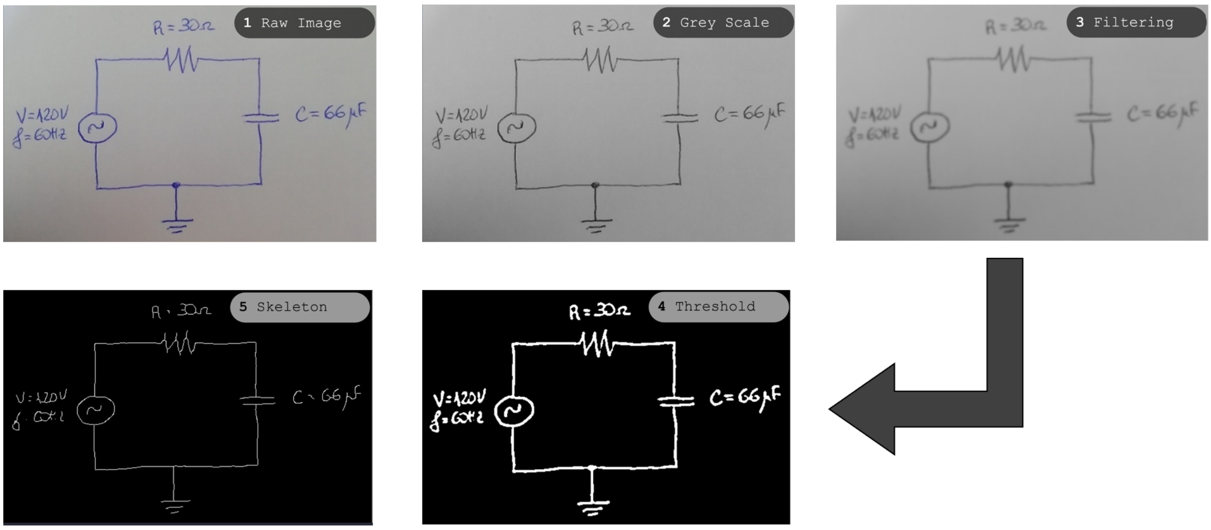
Figure 6

Circuit schematics recognition – preprocessing phase



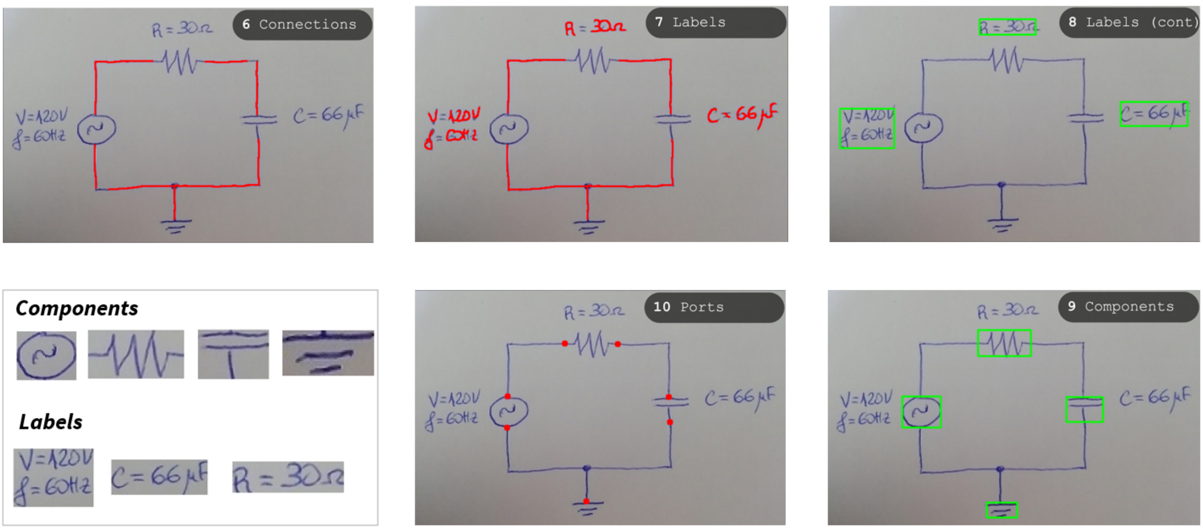
3.2 Segmentation stage

The segmentation process involves the detection and extraction of topology data from the schematic, to construct the circuit model. Our approach is to begin with the detection of interconnections between circuit elements, applying morphological operations to isolate the connections from the rest of the circuit. The resulting images are bounding boxes containing not only the components, but also their labels, which need to be disaggregated.

This is accomplished through the detection of junction points between the box elements and the circuit connections previously extracted. Nodes are then obtained by the intersection of the segmented connections, and finally the components ports are also extracted. The segmentation substages are displayed in Figure 7.

Figure 7

Circuit schematics recognition – segmentation phase



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3.3 Module output

The output of the recognition module is a segmentation map structured according to the JSON model (already used in other *U=RIsolve* modules): the schematic circuit model. The components are linked with their respective interconnections with unique IDs, which allow external other *U=RIsolve* (or external) applications to parse the circuit information output from this software package. However, the circuit model data is not complete yet, as the classification of each component and the decoding of the information contained in each label are still missing. A classification module will subsequently fill in the missing data which represents the final stage of the image-to-model conversion.

CONCLUSIONS

This paper overviews the *U=RIsolve* framework and the most relevant ongoing research lines, aiming at an interactive portal for supporting self-learning & teaching electric circuit analysis and simplification fundamentals. We particularly focus on the circuit recognition module, outlining the transformations carried out on the original circuit images (drawn schematic) in order to get its circuit model (JSON). Although full circuit modeling cannot yet be achieved, we will build on Artificial Intelligence methodologies to enable the classification of the segmented data. From that point on, users would be able to edit the schematics and perform circuit analysis and simulations. A good example of how useful this can be is a student taking a photograph of their class notebook and immediately having augmented information concerning the circuit analysis.

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