Towards quantum-based graph matching for IoT systems (extended abstract)

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Context. Heterogeneous, large, and complex federations of Internet of Things (IoT) systems pose ever-increasing challenges to current computing paradigms. Especially the continuous changes in the system structure make planning tedious. Taking a smart city as an example, the system experiences (de-)activations of individual devices and subsystems, device roaming, the movement of people and infrastructure, and volatile traffic and communication scenarios due to mass events (e.g., concerts).

Graph-based Representation. It is common to abstract large Cyber-Physical System (CPS) and IoT federations, such as smart cities, logistics management systems, and large production plants, as heterogeneous graphs, whose nodes and edges can be added, altered, and removed dynamically at runtime. This dynamic adaptability requires several computational problems to be addressed, among others, the so-called graph isomorphism problem, or its generalization, the Sub-Graph Isomorphism (SGI) problem [1]. The latter refers to the task of finding occurrences of a smaller template graph in a larger target graph. The SGI problem (a.k.a. *graph (pattern) matching*) is known to be NP-complete.

Quantum Computing for Graph Isomorphism. Recently, quantum algorithms have also been proposed to tackle the SGI problem suggesting significant advantages in terms of computational speed-up. Specifically, implementations of such algorithms in prominent quantum programming languages have been suggested for *homogeneous* graphs $G = (V, E)$, where V denotes the finite set of vertices and E denotes the finite set of edges (see [2] and references therein). They require as input the adjacency matrices of the respective graphs and directly enable the use of Quantum Computing (QC) to tackle the SGI problem and, thus, real-world problems related to dynamic adaptations of complex systems such as IoT systems.

Vehicle Platooning Use Case. To make us of the advantages of QC-based (sub-)graph matching for IoT systems, we suggest using common MDE techniques such as abstraction, graph transformation and code generation to extract the necessary graph structure. One direct use case would be in applications where all nodes represent the same object type. For instance, in logistics we may use SGI to identify potential for *vehicle platooning*. For this, a global road network view might identify vehicles (e.g., trucks) and suggest their joining. Similar applications can be used for identifying certain subgroups (e.g., people, devices) in smart cities.

Extension to Heterogeneous Models. The drawback of the current quantum SGI is its limitation to homogeneous graphs. In CPS and IoT contexts, models usually contain typed

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nodes and edges, thus requiring heterogeneous graphs that support node types and edge labels. We thus propose using a transformation method to encode the information of a heterogeneous graph $G_{het} = (V, E, L_V, L_E)$ in a specific form of a homogeneous graph, thus, enabling the use of QC for solving the SGI problem. Here, L_V denotes the finite set of vertex type labels and L_E denotes the finite set of edge labels. To encode the information of L_E, we propose a mapping to the integer weights of the edges connecting the respective nodes, i.e., $F_E : L_E \rightarrow \mathbb{N}_{>0}$. The encoding for L_V is less straightforward. First, we propose to introduce a new *label node*. Thus, the number of nodes in the generated homogeneous graph is $|V_{hom}| = |V| + 1$, where V denotes the set of vertices of the heterogeneous graph. Next, we propose a mapping between L_V and the weights of the edges that connect the original nodes in V and the new *label node*. To further be able to discriminate the *label node* in the homogeneous graph, the edge weights have to be adapted. Our proposal enables different strategies, e.g., working with negative numbers or shifting the integer weights by a non-integer constant (e.g., 0.5).

Note, that these mappings are in general injective and may even be bijective in cases where $|L_E|$ and $|L_V|$ can be restricted a-priori, i.e., when domain knowledge allows limiting the number of occurring labels in advance. Furthermore, $|L_E|$ and $|L_V|$ are usually much smaller than $|V|$ and $|E|$, thus, no focus is laid on the semantic distances of the labels in the original transformation. However, setting and adjusting scaling factors for the edge weights and working with predefined orders of labels also allows encoding this information qualitatively in the generated homogeneous graphs.

From the resulting homogeneous graphs, adjacency matrices can be generated as input for the quantum algorithms as stated above. The quantum algorithm [2] outputs the permutation of the adjacency matrix of the target graph such that the similarity between the top-left submatrix and the adjacency matrix of the template graph is maximized. This permutation represents a bijective mapping for the target graph vertices which is transformed back to the heterogeneous graph model.

Vision. Overall, our approach foresees the following steps: (1) extraction of a heterogeneous domain model, (2) model transformation to support a homogeneous graph representation, (3) generation of quantum algorithm code that can be run on modern QC frameworks, and (4) backtransformation of the QC results into the modeling framework.

Based on the vision outlined here, our next steps include the development of a prototypical implementation and performing a set of benchmarking experiments to prove the validity of our approach and highlight the potential for advantages.

References

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