Advancements in Fault Diagnosis: A Comprehensive Review of Patented Graph-Theoretical Approaches and Future Directions

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Abstract - *Fault diagnosis plays a crucial role in guaranteeing the reliability and safety of complex systems in diverse industries, such as power systems, manufacturing, and telecommunications. With the increasing complexity and interconnectivity of technological systems, traditional fault diagnosis methods are encountering difficulties in maintaining accuracy and scalability. This document presents a thorough examination of recent patents that utilize graph theory for fault diagnosis. It focuses on identifying important patterns, novel methodologies, and areas where the current technological environment may be lacking. The analysis demonstrates an increasing inclination towards the integration of graph-theoretical techniques with advanced technologies such as machine learning and artificial intelligence. This integration has led to the creation of more advanced and precise fault detection and isolation systems. The review, however, highlights gaps in the application of graph theory to dynamic and evolving networks, as well as its underutilization in industries such as healthcare and logistics. The paper concludes by discussing future directions for research and development. It emphasizes the importance of dynamic and adaptive graph models, industry-specific solutions, and hybrid approaches that integrate graph theory with other diagnostic methodologies. This review aims to provide researchers and practitioners with a valuable resource for developing technically advanced and practically applicable fault diagnosis technologies.*

Key Words: **Fault Diagnosis, Graph Theory, Complex Systems, Patent Review, Dynamic Networks.**

1. Introduction

Fault diagnosis is a crucial element in guaranteeing the dependability and security of diverse systems, spanning from basic household appliances to intricate industrial machinery, power systems, and communication networks. Timely detection, diagnosis, and mitigation of faults can prevent minor problems from escalating into catastrophic failures, thereby protecting lives, property, and valuable resources [1]. With the increasing complexity of technological systems, fault diagnosis methods and tools have advanced, integrating sophisticated techniques from diverse fields such as machine learning, signal processing, and control theory [2].

Any anomalous state that disrupts the system's regular operation can be defined as a fault. These faults may occur because of component malfunctions, environmental influences, human mistakes, or design deficiencies. Fault diagnosis is a multi-step process that includes fault detection, fault isolation, fault identification, and fault recovery [3]. Fault detection is the process of identifying an anomalous state in the system. Fault isolation aims to identify the precise location or component where the fault has occurred. Fault identification entails the process of determining the characteristics and extent of a fault, while fault recovery is concerned with restoring the system to its usual operational condition or minimizing the consequences of the fault. Fault diagnosis is of utmost importance, particularly in critical systems where failures can result in substantial financial losses, environmental harm, or the loss of human life. Undetected faults in power systems have the potential to trigger blackouts that can impact many individuals, potentially reaching millions of people. A malfunction or defect in an aircraft's control system in aviation has the potential to lead to a catastrophic crash resulting in death. Hence, the development of resilient and effective fault diagnosis techniques is of utmost importance in diverse sectors.

1.1. Introduction to Graph Theory

Graph theory is a mathematical discipline that focuses on analyzing graphs characteristics and practical applications. A graph is a mathematical construct that consists of a collection of nodes (or vertices) connected by edges (or links). Graphs are a useful tool for representing various real-world systems. In this representation, the nodes represent entities, such as components, devices, or states, while the edges represent the relationships or interactions between these entities. The study of graphs originated in the 18th century, with the contributions of Swiss mathematician Leonhard Euler [4]. Euler's solution to the renowned Königsberg bridge problem has widely recognized him as the founder of graph theory. Subsequently, graph theory has expanded into a multifaceted and extensive discipline with practical implementations in a range of fields, such as computer science, biology, social sciences, and engineering.

Graph theory is a valuable tool for representing and studying the connections and interactions between components in a system when it comes to diagnosing faults. By depicting a system as a graph, one can utilize diverse graph-theoretical principles and algorithms to efficiently identify and analyse faults [5]. For instance, in a power grid, nodes could symbolize substations, while edges could symbolize transmission lines. A system fault can be represented as a disturbance in the connectivity of the graph, and algorithms based on graphs can be employed to isolate and identify the fault. An important benefit of employing graph theory in fault diagnosis is its capacity to effectively manage intricate and interrelated systems. Modern systems, such as communication networks and power grids, have complex structures with many components and interactions. Graph theory gives us a clear and accurate way to show these systems, which lets us use advanced analytical methods to find hidden patterns, figure out what parts are important, and guess where they might break.

1.2. Objective of the Review

The main goal of this review is to provide a thorough analysis of current patents that use graph theory for fault diagnosis. Due to the increasing complexity of modern systems, there is a rising interest in creating innovative techniques to accurately detect faults in these systems. Graph theory, due to its capacity to represent intricate connections and interactions, has become a promising tool in this context. This review aims to analyse and classify the primary patents approved in the field of fault diagnosis using graph theory. Through the analysis of these patents, our objective is to reveal patterns in the advancement of fault diagnosis methods based on graphs, emphasize inventive techniques, and pinpoint any deficiencies in the existing body of knowledge. In addition, the review will examine the utilization of these patented technologies in various sectors, such as power systems, telecommunications, and manufacturing.

This review aims to serve as a valuable resource for researchers, engineers, and practitioners by summarizing the current state of graph-based fault diagnosis and providing insights into potential future developments. Through a comprehensive analysis of the current patent landscape, individuals involved in the field can more effectively navigate and comprehend the existing patents. This enables them to identify potential areas for innovation and make valuable contributions to the development of fault diagnosis technologies.

1.3. Significance of the Review

This review's significance stems from its ability to synthesize and evaluate the vast amount of knowledge documented in patents. Patents are a distinctive and valuable reservoir of knowledge, as they embody the tangible and business-oriented implementations of scientific and engineering progress. Patents prioritize practical applications and solutions, in contrast to academic publications that typically emphasize theoretical advancements. Hence, by examining patents related to fault diagnosis using graph theory, we can gain a deeper understanding of the practical application of these concepts and their influence on diverse industries.

Additionally, the review will enhance the overall understanding of fault diagnosis by emphasizing the significance of graph theory in tackling key challenges within this field. As systems become increasingly complex and interconnected, traditional fault diagnosis methods may lose effectiveness or become more challenging to implement. Graph theory provides a versatile and scalable framework for modelling and analysing complex systems, allowing us to overcome these challenges. This review will primarily focus on identifying inventive methodologies that have received legal protection through patents in their respective fields. Patenting is centred around innovation, and the patents discussed in this article are expected to include original methods and techniques that expand the limits of current fault diagnosis capabilities. Through the analysis of these advancements, we can gain valuable knowledge about the discipline's future trajectory and pinpoint areas that require further investigation and progress.

2.Overview of Graph Theory in Fault Diagnosis

2.1. Basic Concepts of Graph Theory

Graph theory is a mathematical discipline that focuses on the analysis of graphs, which are conceptual models representing a collection of objects connected by links. These entities are commonly known as vertices or nodes, while the connections connecting them are referred to as edges. Graphs are versatile tools for representing various real-world systems and structures, such as networks, pathways, relationships, and flows. The key principles of graph theory that are especially pertinent to fault diagnosis encompass nodes, edges, paths, cycles, connectivity, and subgraphs.

- **Nodes and Edges**: The basic elements of a graph are nodes (also called vertices) and edges (also called arcs). Nodes represent entities, while edges represent the relationships or interactions between them. In the context of fault diagnosis, nodes might represent components of a system, while edges represent the functional or physical connections between these components.
- **Paths and Cycles**: A path in a graph is a sequence of edges that connect a sequence of distinct nodes. A cycle is a path that starts and ends at the same node without traversing any edge more than once. In fault diagnosis, paths might represent potential fault propagation routes, while cycles could indicate feedback loops or redundant connections that could complicate fault detection.
- **Connectivity**: A graph is said to be connected if there is a path between every pair of nodes. In fault diagnosis, connectivity is crucial because it can indicate whether a fault in one part of the system

can propagate to other parts. Strongly connected components (subgraphs where any node is reachable from any other node within the subgraph) are particularly important in understanding fault dynamics in complex systems.

2.2 Application of Graph Theory in Fault Diagnosis

Fault diagnosis refers to the systematic procedure of detecting, isolating, and identifying faults within a given system. Faults are atypical circumstances that can lead to the deterioration or breakdown of a system, and it is critical to promptly identify them to maintain the system's dependability, security, and effectiveness. Graph theory provides effective techniques for representing and examining the intricate connections and interdependencies within systems, making it a valuable method for diagnosing faults in different domains [6].

In various physical systems, such as electrical grids, mechanical assemblies, and process plants, the different parts can be represented as nodes, while their interactions, such as power flow, mechanical coupling, or fluid transport, can be depicted as edges. The use of a graph-based representation facilitates the visual examination and examination of the system's structure, thereby simplifying the identification of critical elements and potential paths for fault spread.

Cyber-physical systems (CPS) combine computation with physical processes, such as smart grids and autonomous vehicles. Graph theory can represent both the physical and cyber components in CPS. Nodes can be used to represent various components, such as sensors, actuators, controllers, and communication devices. On the other hand, edges are used to represent the flow of data, control signals, and physical interactions. Graph theory facilitates understanding the interplay between faults in the cyber layer, such as sensor failures and communication delays, and their impact on physical processes, and vice versa.

The process of identifying patterns in a graph that deviate from expectations is known as anomaly detection. In communication networks, one can detect abnormal traffic patterns by analysing alterations in the flow properties of the graph, such as edge capacities and node centralities. Cybersecurity commonly employs graph-based anomaly detection to identify intrusions or attacks that disrupt regular network activities.

Fault propagation analysis entails examining how faults disperse throughout the system's graph. One way to represent cause-and-effect relationships between components is by using directed graphs, where edges have a direction. For example, in process control systems, a malfunction in one sensor could spread through control loops, impact actuators, and subsequent processes. Comprehending fault propagation is beneficial for creating resilient fault-tolerant systems and efficient fault management strategies.

To summarize, graph theory provides a robust and adaptable framework for fault diagnosis in various systems. The tool is essential for ensuring system reliability and safety due to its capacity to simulate intricate interactions, facilitate real-time analysis, and seamlessly integrate with other diagnostic methods. Nevertheless, there are still notable obstacles that need to be addressed, specifically regarding the speed and effectiveness of computations, the accuracy and reliability of data, and the seamless incorporation of graph-based techniques with other methodologies. As research progresses, graph theory is expected to have growing significance in the future of fault diagnosis.

3. Methodology

The patent search strategy is an essential element of this review paper, as it guarantees that the analysis is thorough and encompasses the most pertinent and up-to-date advancements in the use of graph theory for fault diagnosis. We meticulously crafted the patent search methodology to encompass a diverse array of patents from various industries and applications, with a particular emphasis on the utilization of graph theory in fault diagnosis.

3.1 Databases Utilized

To gather the relevant patents, multiple patent databases were used to ensure broad coverage and comprehensive results. The primary databases included:

Google Patents: Google Patents is a free and easy-to use tool for searching patents, including those from multiple patent offices around the world. The platform provides sophisticated search functionalities, such as Boolean operators, enabling users to conduct accurate searches by selecting specific keywords.

United States Patent and Trademark Office (USPTO) Database: The extensive collection of patents filed in the United States led to the selection of the USPTO database. Due to the significant amount of innovation in the United States, this database is essential for identifying notable patents in the field.

World Intellectual Property Organization (WIPO) – Patentscope: We used the WIPO-provided Patentscope database to gather global patents, focusing on those that might not be in national databases like the USPTO or EPO.

Indian Patent Journal: To capture patents filed in India, a region renowned for its burgeoning technological innovation, the search strategy also encompassed the Indian Patent Journal. This journal provides access to patents specifically designed for the Indian context or innovations that address unique challenges in the region. The incorporation of the Indian Patent Journal broadened the review to include patents from diverse geographical locations, including innovations that may not receive widespread recognition in Western databases.

Patent Lens: This database provided an extra layer of verification and confirmation for the patents sourced from other databases, ensuring the presence of any significant patents.

3.2 Keywords and Search Terms

Choosing the appropriate keywords was a crucial component of the search strategy. We selected the keywords to ensure the search would include patents specifically related to the use of graph theory in fault diagnosis. The subsequent keywords and phrases were employed:

Primary Keywords:

- "Graph Theory"
- "Fault Diagnosis"
- "Fault Detection"
- "Graph-Based Fault Diagnosis"
- "Graph Algorithms"
- "Fault Isolation"

Secondary Keywords:

- "System Reliability"
- "Network Analysis"
- "Fault Propagation"
- "Fault-Tolerant Systems"
- "Graph-Based Modeling"
- "Cyber-Physical Systems"

The keywords were effectively combined using Boolean operators (AND, OR, NOT). Patent searches were performed using search terms such as "Graph Theory AND Fault Diagnosis" and "Graph-Based AND Fault Detection" to find patents that specifically addressed the combination of these concepts. In addition, proximity operators were employed to further refine the search, specifically by ensuring that the terms "graph theory" and "fault diagnosis" appeared together within the same patent claim or description.

3.3 Time Frame Considered

The patent search was limited to a time period of 20 years, specifically from 2004 to 2024, in order to include patents that were filed or granted during that time. Over the past twenty years, there have been notable progressions in graph theory and its utilization in fault diagnosis, specifically in relation to the emergence of intricate systems such as cyber-physical systems and extensive networks. By concentrating on this specific time frame, the review guarantees that it encompasses the most pertinent and cutting-edge patents. By considering patents within this time frame, we can encompass both recently developed innovations and well-established technologies that have undergone testing and practical implementation. This equilibrium offers a comprehensive perspective on the current state of the art. Examining patents spanning a 20-year duration enables the detection of patterns and changes in the utilization of graph theory for fault diagnosis. This analysis provides a valuable understanding of the field's development and potential future directions.

3.4 Review and Documentation

Following the search process, each patent underwent a thorough review to evaluate its relevance to the review. Essential details, such as the patent number, title, assignee, filing date, and a concise overview of the innovation, were recorded. The information was subsequently categorized according to the system or application domain, the specific graph-theoretical methods employed, and the types of faults targeted. By employing a methodical approach to patent searching and analysis, a comprehensive examination of patents pertaining to fault diagnosis using graph theory was conducted. This ensured that the resulting article offered a thorough and perceptive overview of the subject matter.

4. Review of Key Patents

4.1. Patent 1: “Fault diagnosis and pre-warning system in oil refining production process and establishment method thereof”, CN104238545B, China University of Petroleum Beijing.

The reviewed invention is a sophisticated system for diagnosing faults and providing early warnings in the petroleum refining production process. The main goal of this invention is to overcome the limitations of current fault diagnosis methods, particularly in terms of fault spread and diagnosis accuracy. The intricate and perilous setting of petroleum refining places the utmost importance on safety, uninterrupted flow, and steadfastness of operations. The patent proposes a system that introduces a method to create a comprehensive fault diagnosis framework. This framework utilizes a multi-stage flow model and integrates both static and dynamic nodes. As a result, it enhances the capability to detect, predict, and respond to faults. The method uses a mix of complex methods, like HAZOP analysis to find possible dangers, dynamic Bayesian networks to set up fault relationships, and Bayesian inference and hidden Markov models for real-time data analysis. This invention greatly improves the safety and efficiency of the petroleum refining process by addressing the complex dependencies and interactions within refining systems.

Innovative Aspects

This invention's essential innovation is the use of a multi-stage flow model that accurately charts the intricate interconnections within the petroleum refining process. The model incorporates both stationary nodes, symbolizing the variables under observation, and dynamic nodes, representing the functional components of the system. By incorporating these nodes into a cohesive fault diagnosis framework, a comprehensive comprehension of fault propagation is achieved. Furthermore, the invention employs a dynamic Bayesian network structure for evaluating different models. This methodology enables the identification of the most precise fault multi-stage association model, which is subsequently employed for fault diagnosis and early warning provision. Expert knowledge and historical data combine to make the conditional probability relationships between nodes realistic and reliable, thereby enhancing the accuracy of fault detection. Another notable advancement is the incorporation of Bayesian inference and hidden Markov algorithms in the fault diagnosis and early warning module. These techniques facilitate immediate analysis of monitoring data, allowing the system to not only identify current faults but also anticipate potential future faults based on observed patterns. The ability to make accurate predictions is essential in an industry where even small disruptions can result in substantial safety hazards and financial damages.

Applications

The petroleum refining industry primarily uses this invention to significantly improve the safety and efficiency of production processes. The system is specifically engineered to seamlessly integrate into current refinery operations, offering instantaneous monitoring and identification of faults across a diverse array of equipment and processes. The system's precise identification and prediction of faults aids in accident prevention, decreases downtime, and minimizes production losses, rendering it indispensable for refinery operators.

4.2. Patent 2: “A kind of diagnosing faults of numerical control machine method”, CN106406229B, Jilin University.

The patent outlines a systematic approach for identifying malfunctions in numerically controlled machine tools by utilizing both graph theory and data-driven techniques. This approach tackles the intricacy and interconnectedness that naturally exist in contemporary machine tools, which incorporate various technologies such as mechanical, electrical, and hydraulic systems. The patent describes a process that includes several important steps: breaking the system down into its parts, looking into why things fail and how faults spread, figuring out how bad the fault is, making models to guess how often faults happen by using time correlation, and finally figuring out what caused the fault.

This approach starts by dividing the numerically controlled machine tool system into distinct components and then conducting a thorough examination of fault propagation using graph theory. A directed graph represents the system components as nodes, with edges indicating the relationships of fault propagation between the components. The patent describes new ways to do analysis, such as the PageRank algorithm for figuring out how faults affect the system and Interpretive Structural Modeling (ISM) for turning the fault propagation diagram into a hierarchical model.

Innovative Aspects

The methodology combines graph theory and data-driven analysis to model fault propagation and impact in a distinctive manner. This hybrid approach utilizes the advantages of both methods, enabling a more precise and realistic identification of faults in intricate and interconnected systems. The methodology overcomes a common limitation in traditional fault diagnosis methods by incorporating time-based correlation in fault rate modelling. These methods typically assume static or time-independent failure rates. This temporal aspect is included to improve the fault diagnosis process's precision, allowing it to better adapt to real-world conditions. The use of algorithms such as PageRank for fault impact assessment and ISM for hierarchical fault modelling demonstrates this approach's sophisticated analytical capabilities. Various contexts commonly employ these algorithms, including the use of PageRank in web search. Their application in fault diagnosis for machine tools is new and effective.

Applications

The patent's methodology can be implemented in diverse fields that utilize numerically controlled machine tools, such as manufacturing, aerospace, automotive, and robotics. This approach is especially beneficial in settings where machine dependability is crucial, and the amount of time that machines are out of operation due to malfunctions must be kept to a minimum.

4.3. Patent 3: “Industrial equipment fault diagnosis method based on knowledge graph”, CN113723632B, Beijing University of Posts and Telecommunications

The patent describes an innovative technique for identifying faults in industrial equipment by using a knowledge graph-based method. When it comes to industrial equipment, where large-scale machinery is critical for production, the ability to rapidly and precisely identify faults is of utmost importance. This approach combines conventional fault diagnosis with sophisticated data structures, such as knowledge graphs, to improve the effectiveness and precision of detecting faults and determining their root causes. This approach utilizes historical maintenance records and sensor data to create a comprehensive knowledge graph that captures the connections between equipment components, fault phenomena, causes, and solutions. Deep learning models enhance fault diagnosis by integrating semantic analysis of text data with real-time sensor inputs. This approach overcomes the constraints of current fault diagnosis methods by offering a more methodical and automated approach to detecting and examining equipment faults. As a result, it reduces the need for expert judgment and improves the overall fault management process in industrial environments.

Innovative Aspects

The novelty of this approach resides in its smooth incorporation of knowledge graphs and AI-powered fault diagnosis models. An important innovation is the creation of a triple structure that accurately represents the relationships between different elements of the fault diagnosis process, including equipment components, fault types, and sensor data. The systematic method of organizing data makes fault identification and separation more efficient. This is achieved by utilizing a comprehensive database of past fault information. Another important step forward is the use of semantic similarity calculations to combine different explanations for faults. This effectively fixes the common problem of using the wrong words in maintenance records. Standardizing the representation of faults and their causes enables the system to make more accurate comparisons between new fault occurrences and historical data. This ultimately results in more precise diagnostic outcomes.

Applications

The patent's methodology can be implemented in diverse fields that utilize numerically controlled machine tools, such as manufacturing, aerospace, automotive, and robotics. This approach is especially beneficial in settings where machine dependability is crucial, and the amount of time that machines are out of operation due to malfunctions must be kept to a minimum.

4.4. Patent 4: "Driving motor fault diagnosis model construction method based on intra-class feature transfer learning and multi-source information fusion", CN112036301B, China University of Mining and Technology CUMT

The invention proposes a technique for creating a fault diagnosis model for driving motors. This technique combines intra-class feature transfer learning and multi-source information fusion to improve the accuracy of diagnosis in different operational conditions. This approach addresses the challenges posed by the nonlinear and non-stationary nature of vibration signals used in fault diagnosis, as well as the complex and high-dimensional feature sets obtained from time-frequency analysis methods. The suggested method utilizes ensemble empirical mode decomposition (EEMD) to break down vibration or current signals into intrinsic mode functions (IMFs). Subsequently, statistical parameters are extracted to create a comprehensive set of features. The method also utilizes dimensionality reduction techniques, such as principal component analysis (PCA), to enhance the efficiency and accuracy of fault diagnosis by reducing the impact of redundant and irrelevant features.

Innovative Aspects

An important innovation of this invention is the use of intra-class feature transfer learning, which improves fault diagnosis performance in a variety of complex operating conditions. The method improves the model's ability to generalize across different scenarios by transferring relevant features within the same class. This helps to address the common problem of distribution differences between the training and testing data. Moreover, the method's incorporation of multi-source information fusion is exceptionally groundbreaking, as it merges data from various sensors to offer a more resilient and precise diagnosis. This method reduces the constraints associated with relying on a single sensor, which could be susceptible to interference, measurement inaccuracies, or inconsistent sensitivities. The use of EEMD in the signal decomposition method, along with the subsequent extraction of statistical features, enhances its novelty by providing a thorough and all-encompassing depiction of the driving motor's condition.

Applications

The primary use of this invention is to diagnose faults in driving motors, which are essential components in various types of rotating mechanical equipment. Industries like manufacturing, energy production, and transportation, where equipment dependability and safety are crucial, find this approach especially valuable. This method's capacity to precisely identify malfunctions in diverse operational circumstances makes it well-suited for deployment in environments characterized by intricate and fluctuating working conditions, such as industrial plants, mining operations, and transportation systems. Moreover, the method's focus on combining information from multiple sources and transferring features within the same class indicates its potential usefulness in other industries that demand reliable fault diagnosis, such as aerospace, automotive, and renewable energy systems. This method can enhance overall operational efficiency by improving the accuracy and reliability of fault diagnosis, thereby reducing maintenance costs and preventing unexpected equipment failures.

4.5. Patent 5: "Equipment fault diagnosis and maintenance knowledge recommendation system based on knowledge graph", CN114579875B, University of Chinese Academy of Sciences

The patent describes an advanced system for diagnosing equipment faults and recommending maintenance knowledge. This system utilizes the cutting-edge technology of knowledge graphs. The system tackles various obstacles in contemporary equipment health management, specifically the requirement for an astute and adaptable approach to fault diagnosis and maintenance. Conventional fault diagnosis systems have primarily focused on analyzing and maintaining faults after they occur, often disregarding the possibility of predictive diagnostics and comprehensive knowledge management. This patent presents a system that combines different artificial intelligence methods, such as knowledge graphs, link prediction, and recommendation algorithms, to develop a comprehensive and proactive framework for fault diagnosis and maintenance. Engineers specifically engineered the system to gather, arrange, and employ information from various origins, including expert input, equipment records, and sensor data. This results in a tailored and intelligent recommendation system for identifying faults and making maintenance decisions.

Innovative Aspects

The novelty of this patent resides in its extensive utilization of knowledge graphs to augment fault diagnosis and maintenance procedures. This system differs from traditional systems in that it not only focuses on monitoring and diagnosing after a fault has occurred, but it is also capable of predictive and real-time fault diagnosis. An important innovation is the use of link prediction in the knowledge graph, which enables automatic deduction of missing data and detection of potential errors before they become apparent. This approach enhances fault diagnosis accuracy and facilitates maintenance planning by utilizing historical data and expert knowledge to predict future issues.

Applications

The system has a wide range of significant applications, particularly in industries that heavily rely on the dependability and continuous operation of intricate machinery. These sectors encompass manufacturing, energy production, transportation, and aerospace, where equipment failure can lead to substantial periods of inactivity and economic detriment. The system's ability to provide prognostic maintenance suggestions can assist organizations in minimizing unforeseen malfunctions, optimizing maintenance timetables, and reducing overall equipment ownership expenses.

4.6. Patent 6: "Integrated Hierarchical Process for Fault Detection and Isolation", WO/2009/148984, GM Global Technology Operations, INC.

The invention introduces an advanced system and method for identifying and isolating malfunctions in vehicle systems, with a specific emphasis on the challenges posed by the integration of various subsystems, including braking, steering, and powertrain systems. The technique utilizes a hierarchical tree structure to combine diagnostic trouble codes from different subsystems and components, resulting in a confidence assessment of the origin of a fault. Using models and observations, the system improves fault detection and isolation accuracy. This is especially helpful when there are interrelated subsystem operations that make it difficult to identify the main cause of a problem. The innovation also includes a graph-based diagnosis system that can handle the dynamic and interconnected nature of modern vehicle subsystems. This system allows for real-time analysis and effective fault management.

Innovative Aspects

This invention presents multiple groundbreaking features that greatly enhance the process of identifying faults in vehicle systems. Using a hierarchical tree structure makes it easier to combine diagnostic data from different subsystems, which lets you get a full picture of the vehicle's condition. This methodology guarantees the ability to identify faults with a high level of certainty, specifically within individual components or subsystems. This is critical to avoiding failures that affect the entire system. Furthermore, the integration of hierarchical and graph-based models offers a versatile and scalable framework capable of accommodating intricate and ever-changing interactions among vehicle subsystems. Another crucial innovation is the use of confidence estimates generated by local decision-making algorithms at different levels of the hierarchy. This enables a more nuanced and precise diagnosis process. Furthermore, the system's capacity to modify information in response to vehicle conditions, such as speed, provides an additional level of adaptability that improves its practical use in real-life situations.

Applications

The proposed system has extensive applications in the automotive industry, specifically in the realm of vehicle stability control systems, where accurate and timely fault detection is of utmost importance. The system is capable of monitoring and diagnosing faults in crucial subsystems, including braking, steering, and powertrain systems, to promptly identify and resolve any issues in order to uphold vehicle safety and performance. Moreover, the graph-based diagnostic system is especially valuable in cyber-physical systems characterized by close interactions between multiple subsystems, as faults in one area can have a cascading effect on others. The proposed method's hierarchical and distributed nature makes it well-suited for real-time diagnostics in autonomous vehicles. In this context, on-board systems must consistently monitor and manage their own health to ensure safe operation.

4.7. Patent 7: "Intelligent model-based diagnostics for system monitoring, diagnosis and maintenance", US20060064291, University of Connecticut

The patent pertains to sophisticated systems and techniques for monitoring, diagnosing, and conducting condition-based maintenance of intricate mechanical systems. It specifically focuses on integrating intelligent, model-based diagnostic methodologies that combine quantitative (analytical) models with graph-based dependency models. These methodologies are specifically developed to improve diagnostic accuracy, especially in the context of contemporary computer-controlled systems like automobiles, aircraft, power systems, and industrial machinery. The progress in sensor technology, remote communication, and computational capabilities has required more advanced diagnostic methods to handle the growing complexity and interconnectivity of these systems. The development, validation, and maintenance of traditional rule-based diagnostic systems have become more challenging due to their increased complexity. The text emphasizes the necessity for advanced diagnostic systems that can consistently monitor the health of a system, identify abnormalities, pinpoint the underlying causes of malfunctions, and aid in implementing the appropriate corrective measures.

Innovative Aspects

The novel features of the disclosed systems and methods reside in the hybrid approach, which effortlessly combines quantitative simulation models with graph-based dependency models. This integration is innovative because it enables a more precise and consistent diagnosis in contrast to conventional systems that solely depend on graph-based models or rule-based approaches. The system can enhance the precision of fault detection and isolation processes by utilizing validated knowledge from established diagnostic methodologies and integrating it with sophisticated simulation tools such as MATLAB and Simulink. Another novel feature is the use of a multi-agent system, in which individual agents at the local level use subsystem-level data to make diagnostic decisions, while a central agent at the vehicle level combines these determinations to provide a comprehensive diagnosis. The implementation of this hierarchical diagnostic structure allows for efficient remote diagnosis, simplifies system maintenance, and improves the overall resilience of the system.

Applications

The disclosed systems and methods have extensive applications in diverse industries. Automotive systems are the primary focus of the discussed methodologies, but they can also find application in various other domains like aerospace, power generation, manufacturing, chemical processing, transportation, and industrial machinery. The hybrid model-based approach is especially advantageous in automotive applications for monitoring the condition of vehicles equipped with advanced electronic control systems. Remote monitoring and diagnosis of vehicle systems can effectively minimize downtime, optimize maintenance schedules, and reduce operational costs. In addition to automotive systems, this approach can be modified to oversee and sustain other intricate, interconnected systems, guaranteeing their dependable functioning and prolonging their lifespan. Centralized data analysis has the potential to assist manufacturers in effectively managing the health of entire fleets of vehicles or specific classes of machinery. This can be beneficial for tasks such as parts management, recalls, and continuous product improvement.

4.8. Patent 8: "Scheduler, Substrate Processing Apparatus, and Substrate Conveyance Method", US 2019/0271970 A1, Ebara Corporation

The patent introduces an innovative method for managing the timing of substrate movement in substrate processing devices, which are utilized in diverse sectors, including semiconductor production. The conventional approaches for scheduling substrate conveyance heavily depend on simulation techniques, which entail intricate computations and are frequently time-consuming, rendering them less feasible for real-time operations. This invention aims to improve the inefficiencies of current systems by integrating graph network theory into the scheduling process. The system optimizes the schedule for substrate conveyance by representing the processing conditions, time, and constraints as nodes and edges in a graph network. It determines the longest route length to each node to make the schedule more efficient. This approach greatly decreases the amount of computational work required and enables more effective and adaptable operations, even when dealing with changing processing conditions or nonstationary states.

Innovative Aspects

The main breakthrough of this invention is its utilization of graph network theory to address the issue of scheduling substrate conveyance. This approach differs from traditional methods that involve complex simulations with multiple parameters. Instead, it represents the system as a graph network and determines the longest route length to each node to calculate the schedule for transporting the substrate. This minimizes the requirement for prior calculation and parameter restriction, which conventionally consumed a substantial amount of time and computational resources. In addition, the invention presents a method of preparing a graph network using a modular approach. This involves grouping a specific number of substrates into mini batches, which enables the graph network to be optimized and fixed gradually. This modular approach not only streamlines the optimization process but also allows for the inclusion of new substrates introduced during ongoing operations. The system's robustness and flexibility are further enhanced by its ability to adapt to nonstationary states through real-time recalculation of the graph network.

Applications

This invention has important ramifications for industries that depend on substrate processing apparatuses, especially in semiconductor manufacturing, where achieving high throughput and maintaining strict process control are crucial. The graph-based scheduling method can be used for many substrate processing tasks, such as plating to make bumps, creating TSVs (through-silicon vias), and rewiring. The ability to quickly and effectively compute optimized conveyance schedules, even when faced with nonstationary conditions or unforeseen alterations, ensures that production processes can maintain high efficiency and output. Additionally, this method's modular approach to preparing graph networks makes it especially suitable for environments that process substrates in batches or require continuous processing. Various industries, frequently involving intricate processing sequences and strict time limitations, have the potential to apply this technology's flexibility and adaptability.

4.9. Patent 9: "System and Method for Detecting And/or Diagnosing Faults in Multi-Variable Systems", US 2012/0185728 A1, Commonwealth Scientific and Industrial Research Organisation

By utilizing dynamic machine learning models, the method described addresses the challenges of identifying faults in systems with multiple variables. This approach emphasizes the analysis of operational data from different components within a system, such as HVAC systems, to detect both normal and faulty operations. Contrary to conventional rule-based or qualitative model-based systems, which are frequently inflexible and challenging to modify, this approach employs multiple machine learning models to offer a more adaptable and expandable solution. The method improves the dependability and precision of fault detection by incorporating dynamic models that consider the intricate interactions within a multi-variable system. Utilizing a data fusion process enhances the detection outcomes, resulting in a more thorough comprehension of potential faults. This method represents a significant advancement in fault detection, offering a more robust solution that extends beyond HVAC to include energy distribution and security systems.

Innovative Aspects

The novelty of this approach resides in its utilization of dynamic machine learning models to identify defects in systems with multiple variables. This approach differs from traditional methods that depend on fixed rules or intricate, computationally demanding models. Instead, it adapts dynamically to the unique operational conditions of each component in the system. An important innovation is the hierarchical organization of fault detection models, where overarching models oversee the overall health of the system while more specialized models concentrate on individual components. This stratified approach enables more accurate identification and examination of faults. In addition, the method utilizes a data fusion process that applies Dempster-Shafer theory to combine outcomes from multiple models. This enhances the dependability of fault detection by considering the confidence levels of each individual model, fault detection is more reliable. The capacity to alter and retrain models using real-time data also brings about a degree of flexibility that is especially advantageous in settings where system conditions are consistently evolving.

Applications

This method is highly versatile and can be applied to a wide range of industries that depend on intricate systems with multiple variables. Within HVAC systems, it serves the purpose of identifying malfunctions in real-time, thereby enhancing the effectiveness of heating, ventilation, and air-conditioning operations. This, in turn, leads to decreased energy usage and a longer lifespan for the equipment. Energy distribution systems can also employ this approach to identify and rectify faults that could lead to power outages or inefficiencies. This approach enhances the reliability of fault detection in security and alarm systems, guaranteeing the prompt and accurate identification of potential threats. The method's versatility also renders it appropriate for implementation in environments characterized by frequent changes in conditions, such as automated lighting systems or smart buildings, where operational parameters may fluctuate based on occupancy and other dynamic factors. In summary, this method serves as a flexible and potent instrument for preserving the functional soundness of intricate systems across various fields.

4.10. Patent 10: "System and method for maintenance recommendation in industrial networks", US 11693924 B2, Hitachi Ltd

The patent introduces an innovative method for identifying and isolating faults in industrial networks by utilizing graph theory and machine learning methods. The fundamental concept involves viewing the elements of an industrial network as nodes in a graph, and representing the relationships between these elements as edges with varying weights. This approach mitigates the constraints of conventional fault detection methods, which frequently overlook the interdependencies among various components. The patent proposes a data-driven solution that can effectively detect and isolate faults in industrial networks by representing them as graphs and analysing them as node classification problems. This approach not only increases the precision of identifying faults, but also enhances the effectiveness of maintenance suggestions by considering the spatial connections between network elements.

Innovative Aspects

The patent's most groundbreaking feature is its utilization of graph theory to address the issue of fault detection and isolation in intricate industrial networks. Conventional methods for identifying faults typically involve examining individual components separately, which can produce less-than-optimal outcomes because they fail to take into account the interconnectedness of the components. The patent's methodology, on the other hand, defines the issue as the task of classifying nodes based on a graph structure, enabling a comprehensive analysis of the network. Furthermore, the patent presents the concept of community detection in the graph structure, organizing interconnected elements into clusters according to their relationships. By prioritizing these communities, the system can enhance its ability to detect faults that may otherwise remain undetected if components were analysed separately. The system significantly amplifies its capacity to learn from past data and progressively enhance fault detection accuracy by incorporating machine learning, specifically deep learning methods like graph convolutional neural networks (Graph-CNNs).

Applications

The patent's methodology has extensive applications in diverse industries that depend on intricate, interconnected systems. In electrical grids, the ability to rapidly identify and isolate faults is crucial for ensuring the reliability of the network. This capability can effectively prevent large-scale power outages and minimize the amount of time that the system is not operational. This method can detect leaks or other malfunctions in a specific section of water supply networks, potentially impacting the functioning of other elements. Manufacturing systems with interconnected machinery and equipment can also benefit from this method. In such systems, if there is a fault in one machine, it can have a domino effect on the entire production line. When this method is used in maintenance recommendation systems, it makes sure that problems are found quickly and the right fixes are made. This lowers the chance of more damage happening and makes the maintenance process more efficient. It can work with a variety of industrial networks and can get better by itself through machine learning. This makes the system a useful tool for improving the dependability and efficiency of many important infrastructure systems.

5. Comparative Analysis

The preceding section's analysis of the patents reveals several significant observations about the patterns, shortcomings, and potential advancements in the use of graph theory for fault diagnosis across diverse industries.

5.1. Trends in Patented Technologies

i. Increasing Use of Graph-Theoretical Methods

An evident pattern that can be observed from the patents is the extensive utilization of graph theory as a fundamental tool for fault diagnosis. Traditional fault diagnosis methods commonly relied on conducting isolated analyses of individual components or systems, frequently failing to consider the interconnected nature of modern industrial networks. The reviewed patents emphasize the trend of considering systems as interconnected networks, with nodes representing individual components and edges representing the relationships or dependencies between these components. The patent from Hitachi Ltd. (US 11693924 B2) highlights the application of graph theory in representing industrial networks as graphs. This approach formulates fault detection and isolation as node classification problems. The patent from Beijing University of Posts and Telecommunications (CN113723632B) utilizes knowledge graphs to enhance fault diagnosis in industrial equipment. The patent captures and analyses the relationships between various components and their operational data to achieve this.

ii. Integration with Machine Learning and AI

The integration of graph theory with ML and AI is a notable trend. The combination described in this statement utilizes the advantages of both graph theory and ML/AI. Graph theory offers a reliable framework for representing intricate relationships within systems, while ML and AI techniques facilitate the examination and forecasting of faults by utilizing historical and real-time data. The utilization of Graph-CNNs in the Hitachi patent (US 11693924 B2) serves as a prime example of this prevailing pattern. Deep learning techniques on graph-structured data can enhance the fault detection accuracy of the system over time. The patent CN114579875B from the Chinese Academy of Sciences employs knowledge graphs and AI-driven link prediction algorithms to improve both predictive and real-time fault diagnosis capabilities.

iii. Focus on Complex and Interconnected Systems

The identified patents demonstrate a particular emphasis on intricate and interdependent systems, wherein malfunctions in a single component can result in a chain reaction affecting the entire system. The importance of promptly and precisely identifying malfunctions is especially apparent in industries like power grids, industrial machinery, and vehicle systems. In these sectors, the capability to rapidly and accurately diagnose faults is crucial for upholding operational efficiency and ensuring safety. The patent from GM Global Technology Operations (WO/2009/148984) proposes a solution to the problem of fault detection in vehicle systems. It suggests using a hierarchical tree structure along with graph-based models to effectively handle the intricate interactions among subsystems such as braking, steering, and powertrain. This approach allows for more sophisticated and precise fault diagnosis, even in systems with extensive interdependency.

iv. Emphasis on Real-Time and Predictive Maintenance

One emerging trend in the field is the increasing focus on real-time fault detection and predictive maintenance. The reviewed patents emphasize the significance of not only detecting faults after they have occurred but also predicting potential issues before they result in major system failures. The correlation between this trend and the utilization of machine learning and AI is significant, as these technologies empower systems to acquire knowledge from past data and enhance their ability to make accurate predictions as time progresses. The system, as described in the patent from the Commonwealth Scientific and Industrial Research Organisation (US 2012/0185728 A1), exemplifies the trend by employing dynamic machine learning models for real-time fault detection in multi-variable systems such as HVAC systems. The proactive maintenance approach implemented in this system effectively reduces downtime by promptly addressing faults before they have a chance to escalate.

5.2. Gaps and Opportunities

i. Limited Application in Certain Industries

The reviewed patents encompass various industries; however, there are discernible deficiencies in the utilization of graph theory for fault diagnosis in certain sectors. The patents reviewed indicate an underrepresentation of sectors such as healthcare, logistics, and consumer electronics. The use of graph-theoretical methods has the potential to benefit a wide range of industries. These methods can be particularly useful in areas such as predictive maintenance of medical equipment, fault detection in logistics networks, and diagnostics in consumer electronics.

ii. Challenges with Dynamic and Evolving Networks

The patents reveal a gap in the ability to effectively utilize graph-theoretical methods for dynamic and evolving networks. Most existing patents assume of static network structures, in which the number of components and their relationships remain relatively unchanged over time. In real-world applications, particularly in sectors such as telecommunications and smart grids, networks undergo constant evolution. This entails the addition or removal of components, as well as dynamic changes in relationships. An opportunity exists to develop new methods that can effectively handle dynamic networks. Future patents may investigate the utilization of dynamic graph theory. In this approach, algorithms constantly update the structure of the graph as the network changes over time. This enables more precise and timely detection of faults.

iii. Underutilization of Advanced Graph Algorithms

Node classification and community detection are commonly employed techniques in graph theory. However, more advanced graph algorithms, including spectral clustering, graph embeddings, and traversal algorithms like Dijkstra's and A*, are not as widely utilized for fault detection. The use of these advanced methods has the potential to significantly improve fault diagnosis precision and effectiveness, particularly in complex and large-scale networks. Future research and patent filings may prioritize the integration of these advanced algorithms into fault diagnosis systems, which could result in the development of more robust and flexible solutions.

5.3. Future Directions

i. Development of Dynamic and Adaptive Graph Models

One potential area for future advancement is the creation of dynamic and adaptive graph models capable of evolving to accurately represent network changes over time. The utilization of these models would prove to be highly advantageous in industries characterized by frequent network modifications, such as telecommunications, smart cities, and IoT networks. The models can enhance real-time fault detection and isolation by consistently updating the graph structure.

ii. Enhanced Integration of Graph Theory with AI and ML

In the future, we expect significant advancements in the integration of graph theory with AI and ML. One possible approach involves utilizing graph neural networks (GNNs) and their variations, such as graph attention networks (GATs). These networks can capture intricate dependencies within graph-structured data, leading to enhanced accuracy in fault diagnosis. Furthermore, we can leverage diagnosis information to optimize maintenance actions through the integration of reinforcement learning and graph theory. This integration may lead to the development of more effective and efficient maintenance strategies.

iii. Application in Emerging Technologies

The application of graph theory to emerging technologies, such as autonomous vehicles, drones, and smart manufacturing, presents a promising area with considerable potential. The ability to diagnose faults quickly and accurately will be critical as these technologies become more complex and interconnected. Autonomous vehicles can utilize graph-based models to perform real-time fault diagnosis across various subsystems, thereby ensuring safety and reliability.

iv. Development of Industry-Specific Graph-Based Solution

Future advancements may include the development of industry-specific solutions that address the unique needs and challenges of various sectors. For example, the healthcare industry can benefit from graph-based models for diagnosing faults in medical devices and equipment. Similarly, the logistics industry can employ these models to effectively manage and predict failures in supply chain networks. Adapting graph-theoretical methods to the unique needs of various industries has the potential to enhance the efficiency and precision of fault diagnosis solutions.

v. Exploration of Hybrid Approaches

Exploring hybrid approaches that combine graph theory with other methodologies, such as statistical analysis, probabilistic modelling, and system dynamics, holds significant potential. The use of hybrid approaches has the potential to provide a more comprehensive understanding of system behaviour and improve fault diagnosis accuracy. An example of how to improve the ability to model uncertainties and dependencies in complex systems is by combining graph theory with Bayesian networks.

The implementation of graph-theoretical methods in fault diagnosis involves several technical challenges, such as dealing with computational complexity, scalability issues, and the need to ensure accuracy. To effectively tackle these challenges, it is necessary to develop innovative solutions that are both technologically advanced and easily applicable in practice. For these innovations to be eligible for patent protection, they must satisfy the requirements of novelty, non-obviousness, and practical applicability. This ensures that they constitute substantial advancements in the relevant field and provide tangible benefits to industries that rely on fault diagnosis technologies.

6. Conclusion

The review of patents pertaining to fault diagnosis using graph theory highlights the increasing significance of this mathematical framework in improving the dependability and effectiveness of intricate systems in diverse industries. With the growing complexity and interconnectivity of systems, traditional fault diagnosis methods are encountering considerable difficulties in maintaining accuracy and scalability. Graph theory provides a robust solution to these challenges by utilizing its capability to model and analyse the relationships and dependencies within these systems. One of the key trends in the patents is the integration of graph-theoretical methods with advanced technologies like machine learning and artificial intelligence. When you put these things together, you can make advanced fault diagnosis systems that can learn from data, change based on circumstances, and spot potential problems before they become big problems. The reviewed patents showcase several innovative approaches, including the utilization of Graph-CNNs and knowledge graphs. These approaches are leading to improved fault detection and isolation, with higher levels of accuracy and timeliness.

However, upon analysis, it becomes evident that there are several gaps present in the current landscape. Graph theory finds applications in various sectors, such as power grids, manufacturing, and telecommunications. However, industries such as healthcare, logistics, and consumer electronics currently restrict its utilization. Furthermore, the issue of effectively implementing graph-theoretical techniques in dynamic and evolving networks remains unresolved. Most current patents primarily address static network structures, which may not be well-suited for real-world applications that involve dynamic network changes. The future of fault diagnosis utilizing graph theory is dependent on the resolution of these gaps and the exploration of novel avenues. One promising area of research is the development of dynamic and adaptive graph models that can evolve with changing network conditions. Furthermore, we expect more robust fault diagnosis systems because of the increased integration of graph theory with AI and ML, specifically through advanced algorithms like graph neural networks (GNNs). Additionally, there is considerable potential in the development of industry-specific solutions that address the distinct challenges faced by various sectors. Furthermore, exploring hybrid approaches that integrate graph theory with other methodologies is also a promising avenue.

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