Design Study for Creating Pathfinder: A Visualization Tool for Generating Software Test Plans using Model based Testing

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Abstract: Model Based Testing (MBT) is a popularly used software testing technique in the software industry. However, there still exists a gap between the awareness of benefits of MBT and its adoption in the industry, specifically in the Computer Aided Design (CAD) or Computer Aided Engineering (CAE) domains. This can be predominantly attributed to the learning curve of using many of the existing MBT tools. To address this gap in the CAD/CAE industry, we propose Pathfinder - an MBT tool, with a Graphical User Interface (GUI), for guiding a software tester in generating test plans for a system-under-test (SUT). The goal of using Pathfinder is for obtaining consistency and reproducibility in the generated test plans across a team of software testers. Our tool introduces a novel representation of the SUT as a High-level Model (HLM), and the use of graph visualization for test plan generation from the HLM. We have designed the GUI to be intuitive for the tester to generate test plans and select relevant tests, which precedes the test execution done outside of our tool. Here, we discuss the design decisions we adopted towards creating Pathfinder, and demonstrates its usage with two case studies.

1 INTRODUCTION

The current generation of software applications, which are used in mechanical design and engineering simulation, are feature-rich and generally have a graphical user interface (GUI). Owing to the complexity of the applications, the respective GUIs require very complex user interactions. Examples of such applications include HyperMesh®, HyperGraph®, SolidThinking Inspire®, HyperView®. The performance of such applications is measured by the consistency, efficiency, and conciseness in both functionality and usability.

Owing to the complexity of the software of these applications, quality assurance (QA) testing of such GUI-based tools pose several challenges to the software testers. One such challenge which we frequently face is the lack of support for collaborative QA testing. Thus, the larger question we attempt to answer is: “How will a team of software testers be able to generate or devise a consistent test plan or a set of tests that represent a feature in the software system with desirable test coverage, with an additional condition of repeatability of such a generation?”. While there are several theoretical results, many of them are not usable in real-world scenarios, predominantly owing to steep learning curves, low adaptability, and shorter cycles for development, testing and product releases. Additionally, in reality, the software testers do not have the expertise or the skills to fine-tune many of the state-of-the-art, but complex, QA testing tools. Thus, in practice, the team relies on ad-hoc practices and individual initiatives in lieu of the QA testing tools. The downside of such initiatives is that such tests are neither unique nor reproducible. This leads to the scenario where two software testers from the same team assigned with testing the same application tend to arrive at different sets of tests. Since the test generation process lacks a formal basis for determining sufficiency and code coverage of the tests, the generated test plans tend to be inconsistent with an uneven test coverage, vacillating between over- and under-testing.

Given these gaps in formalizing the test generation process in a QA team, we propose an approach of building a High-Level Model (HLM)[1] of the system-under-test (SUT) and exploring the HLM using graph visualization for test plan generation. Our approach is motivated towards adoption of model based testing (MBT) for overcoming some of the defects of manu-

[1]An HLM is a generic term used for models constructed for various purposes, which in our case is restricted to a test model.

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ally generated test plans. Our proposed visualization tool, Pathfinder enables QA testers to build HLMs which are testing models, and generate appropriate test plans. In this paper, we additionally critique our design decisions for creating Pathfinder[2]. The novelties of Pathfinder are two-fold – (a) a GUI for generating and reusing relevant HLMs for MBT of GUI applications in the Computer Aided Design (CAD) and Computer Aided Engineering (CAE) domains, and (b) use of visualization as a technique to engage the QA tester in exploring the HLMs and generating test plans, using a scientific and deterministic approach. The scientific process entails complying with the requirements of QA testing, with the goal of consistency and sufficiency in test coverage. The deterministic process enables reproducibility in the test plan generation. Thus, the advantages of Pathfinder with respect to software testing include: (a) reduction in the number of overlapping test cases, (b) consistency, reproducibility and reusability of test cases across a team of software testers, thus improving testing efficiency, and (c) the visual exploration of the HLM and the generated test plans, paths, and cases. Visualization enables the user to prioritize tests rationally. Thus, overall, Pathfinder makes the HLMs usable in every aspect of software test generation, which implicitly improves the practicality and usability of MBT in industrial settings. In this paper, we discuss the design of Pathfinder and demonstrate its usage in two different case studies.

2 RELATED WORK[3]

The usage of MBT has matured over time in the software testing community. The approach is based on building an abstract, but high-level, model of the software and using the model for generating test cases through various principles or techniques. The central idea of MBT has been to bring finite state modeling and software testing together, similar to the testing of hardware components using finite state models (Chow, 1978). Several case studies of MBT given by (Apfelbaum and Doyle, 1997) have demonstrated its advantages. Even though increase in efficiency of software testing teams had not been an intended outcome of MBT, (El-Far and Whittaker, 2001) have found strong correlation between the adoption of MBT and team efficiency.

On MBT Tools: There exist several MBT tools with varying sets of features. Several studies have provided categorization of these tools (Dias Neto et al., 2007; Utting et al., 2012), based on the approaches used for implementing MBT. (Utting and Legeard, 2010) have elaborated on various practices in all stages of the MBT workflow, such as, model creation, test generation, execution, advantages/disadvantages of the approach etc. AGEDIS (Hartman and Nagin, 2004) is one of the open-source tools available, which integrates various processes of MBT, and has been deployed in industrial environment. Other state-of-the art MBT tools are described in (Artho et al., 2015; Belinfante, 2010; Dranidis et al., 2012; Huima, 2007; Micskei,). (Chinnapongse et al., 2009) have proposed the use of graph visualization for navigating through the finite-state machine representation of the model. We have extended their work on static graph visualization by using a GUI for exploring the network with relevant user interactions for test plan generation. (Sarma et al., 2010) have compared two MBT tools, namely Confirmq's QTronic and Microsoft's SpecExplorer 2010, in an industry setting, and reported that both tools have a steep learning curve for software testers. GraphWalker (Karl, 2010) is similar to our Pathfinder, as it is an MBT tool which uses graph visualization. However, GraphWalker considers a test model with the level of granularity of function names as nodes, as opposed to the more abstract HLM (at a coarser level of granularity) that we use. GraphWalker is a tool for both test generation as well as execution, whereas our tool is for test generation exclusively. Our design decision is driven towards preserving the testing environment as it was prior to the introduction of Pathfinder, where in the QA testers write scripts corresponding to test plans and run the tests on a black box GUI test automation tool, e.g., eggplant[4].

On MBT for Test Generation: JUMBL (Prowell, 2003) generates test cases based on the usage model and its statistical properties. The model is a finite-state machine, which is represented using a graph, where the nodes are states. A specific action is depicted by an edge, whose weight is the probability of using or performing the action. The probabilities of usage of such actions are then used in Markov chain to generate test paths. Our work is different from JUMBL as we do not use statistical testing approach. (Bernard et al., 2006) have discussed the generation of test scripts using UML and have also explored various test coverage criteria, while we use visual exploration of the HLM for arriving at test plans.

[2]Pathfinder website http://pathfinder.au-syd.mybluemix.net/ has demonstration video and high-resolution images of the case studies.

[3]To our knowledge, no dedicated visualization approaches exist for MBT.

[4]https://www.testplant.com/eggplant/testing-tools/

3 DESIGN OF PATHFINDER

We propose **Pathfinder** as a tool to explore the HLM for determining a consistent set of software tests for GUI-based application, complying with requirements of sufficient coverage of software testing and rapid cycles of agile development. While Pathfinder is usable for software pertaining to other industries, our design is based on GUI application used in the CAD/CAE industry for modeling mechanical parts.

Generally, the SUT is feature-rich, which exponentially increases the number of software test cases with addition of features. It is neither practical nor economical to execute such large sets of test cases. However, one can perform *test selection* by ranking the tests using specific criteria and choosing the highly ranked ones to give a realizable and pertinent subset of tests. In practice, test selection is the outcome of a pre-determined software model, which in our case, is the HLM. Our proposed HLM selects ~ 10 of ~ 10000 tests giving us: (a) a usable subset consisting of unique and consistent set of tests, and (b) reduction in test case variability due to perception and expertise variations across testers.

In an ideal software testing practice, the (formal) specifications used for software development drive both development and testing. However, in reality, the software testing team dedicated for a single product in a suite of products is small, and the documentation is not updated as rapidly as that of the specifications. Additionally quicker cycles of agile development and product releases require efficient ways of adding new features to existing software. Manually generating test plan for the entire software after addition of new features leads to repetitive work, which is highly error-prone and results in uneven testing. Our proposed HLM alleviates reconstruction of the test model during agile development.

Our Definition of an HLM: The HLM of a GUI-based software application is a high-level abstraction representing user interactions with the application. For instance, such applications in the CAD/CAE domains have high-level actions, such as, opening a complex geometric model, enabling certain visualization controls in the GUI, choosing an appropriate predetermined viewing orientation, and selecting a rendering style. These actions are at a high-level definition in comparison to its corresponding micro interactions, such as, radio button selections, mouse clicks, drop downs, etc. The high-level actions transform the SUT, i.e. the GUI application, from one "state" to another. For instance, action of "loading new geometry" changes the state of new session on the GUI to a state containing information of loaded geometry. The HLM captures state transitions, and we can visually represent the HLM as a state transition diagram, which is essentially a network. Thus, we represent the high-level actions and states in the HLM as a "model-based network" (MBN)[5]. In such an abstraction, the node of a MBN is a state of the application, and its edge corresponds to the corresponding high-level action for state transition. Highly descriptive networks of application behavior can be assembled using this basic technique. Thus, the HLM is an "image" of the complex application fed into the testing pipeline. The most significant contribution of HLM is in quick updates of the "image" during agile development where addition and deletion of features are involved, thus enabling quicker testing cycles.

We propose visualization of the MBN for creating, editing, and exploring the HLM, as the visual representation provides the spatial context of the MBN that demonstrates coverage of selected tests. In practice, building a HLM for user interactions of certain parts of the GUI-application is a collaborative activity among developers, testers, program managers, and even customers. Deliberate creation of the HLM help in limiting the scope of possible high-level interactions, which are essential to be captured in test cases. Just as the tester uses the HLM to generate test case definitions, other stake holders may reuse such an HLM for other specific purposes, owing to the coarse-grain abstraction of the HLM. e.g. a program manager can effectively use the HLM to convey to developers what an application can and cannot do. The developer may use the HLM to decide how best to implement the underlying code. The MBN can be algorithmically traversed under a variety of constraints. Each traversal is a sequence of visits along a path of nodes and edges, which represents a possible use case in the SUT. Thus, using such network traversals, test case definitions can be automatically discovered from a HLM. We emphasize that a naïve implementation of this idea will typically result in a combinatorial explosion of possible test case definitions. Thus, it becomes necessary to control the graph traversal intelligently with a variety of constraints.

Proposed Features of Pathfinder: We propose features of "Pathfinder," which will allow its users to create an HLM and explore it for identifying test plans and suite. The HLMs are to be built intuitively using simple user interactions, considering the skill-set of target users, namely software testers. The HLMs must be saved from a session in its graph format, so that it can be loaded in a new session. Various constraints

[5]Networks contain *nodes* and *links*, equivalent to *vertices* and *edges* of a graph data structure. In Pathfinder, they are referred to as 'nodes' and 'edges' respectively.

are to be applied to the MBN, e.g. where to start and end the traversal, what nodes to include and exclude, what nodal dependencies to specify, etc. The user must be able to assign node and edge weights, based on the importance of the node or edge in the SUT. The user must be able to then generate potential test case definitions by algorithmically traversing the graph under the user-specified constraints. The user must be further able to perform test selection to cull ($\sim$ 10000) of potential test case definitions to $\sim$ 10 per feature of the SUT. Thus, we provide options for ranking to be used for test selection, where the highly ranked tests are meaningful subsets to be retained. The user must be able to iterate through each test in the culled set to ascertain the areas of graph coverage. One must also be able to see the full coverage represented by the total subset. Finally, the chosen test definitions must be outputted in an ASCII text file, which can be co-edited by the testing team and be further post-processed to produce a variety of test plan documents. Thus, we design Pathfinder as a GUI-based application for building and preparing HLMs for feature-rich [6] end-user applications, e.g. GUI-based CAD/CAE tools. We visualize the HLM as a graph, instead of the conventionally used alternative option of matrices, as the testers need to visualize the connectivity when identifying constraints for graph traversal in the MBN.

Test Plan Generation: is the first step of the software QA process. A *test plan*, which is a text document containing test cases, is a plan of the end-to-end testing process. The test plan contains list of tests and the details of logistics, e.g. testers assigned for text execution, expected test outcomes, requirement of automation, category of test cases and testing phase, etc. Test plans are typically written by a QA Engineer (QAE)[7] by considering the specifications of a software development project and using his/her experience in the relevant domain, e.g. CAD/CAE. The MBT approach begins with the model preparation, subsequent to the test plan generation.

3.1 Testing using High-level Model

When using MBT, the steps in the testing workflow, that sequentially follow the test plan generation are: *model preparation*, *test generation*, *test selection*, and *test saving*. We follow design principles specific to each step, in Pathfinder.

Model Preparation: is the step when the HLM is constructed for a specific functionality of the SUT, e.g. the Contacts or the Fasteners (in Section 4). A *test suite* is a set of all tests to be performed on a certain section of the software of the SUT. This software section can be logically defined as a finite, but inclusive, set of states, $\mathcal{S}$. Thus, a test suite can be identified as a set of states and their corresponding transitions. Narrowing down, a "test case" of the SUT refers to a set of tests performed on a part of the section of the software of the SUT, where the tests are based on certain constraints, e.g. specific start and end states of the SUT during the test. Thus, the HLM is created of $\mathcal{S}$ and a test suite corresponds to the entire network in its MBN. A test case corresponds to one of the *paths* between chosen source and destination nodes in the MBN. The weights[8] of the nodes and edges of the MBN are specified in this stage, based on the QAE's estimation of their respective significance. The edge weights could be optionally computed from the node weights in the current stage using user-defined values, or preferably, automatically during the test generation step.

Test Generation: is the step of generating individual test cases in a test plan. In our case, a *test case* of the HLM is represented by a path, called as *test path*, in the MBN, and is executed as a *test*. The path traversal is equivalent to the code coverage in the test case. The *length of the test path* is the number of edges in the path; and its *weight* is the sum of the edge weights. The constraints we use in this step as well as in the test selection step pertain to restricting the number of tests and the length of test paths. In this, we use specific constraints on the number of nodes per test (NPT) and *model search* type, namely, exhaustive or sampled. Using minimum and maximum values for NPT ensure sufficiently long test paths, thus avoiding *trivially* short and *inefficient* long tests. The exhaustive model search on the HLM returns all possible test cases, from the *walks* through the entire network. The sampled model search on the HLM returns a set of random samples of paths, making it more efficient than the exhaustive search. Sampled model search is preferable in the case of large complex HLMs, whereas, exhaustive search is desirable for smaller HLMs. The automatic computation of edge weights from node weights, if chosen over manual assignment, occurs in this stage.

[6]Henceforth, to disambiguate the "feature" of the SUT from the "feature" of Pathfinder, we refer to the former as "functionality" of the SUT.

[7]One of the authors, who also participated in the case study, is a QAE with 15+ years of QA testing experience in the CAD/CAE industry.

[8]In MBN, node- and edge-*weights* are values used for steering the path traversal in desired direction. Their *coverage* refer to inclusion of nodes and edges, respectively, for a specific test path.

Test Selection: is the step to select highly relevant steps, which *efficiently* and *sufficiently* test a single functionality, such as the Fasteners (Section 4). The culling is performed either automatically or manually. Automatic test selection is done using either sampling, namely uniform and random, or coverage criteria, namely, node-coverage and edge-coverage options. Sampling does not ensure test coverage of critical or other important sections of the software. Hence, specific code coverage criteria, which corresponds to node- or edge-coverage in the MBN, give more control for desired testing. Node-coverage implies an optimally minimal test path where every node in the path is visited at least once, and edge-coverage is the same for every edge in the path. Edge-coverage gives more number of tests than node-coverage, by design. Pathfinder offers flexible options for coverage criteria, namely "fewest tests", "weighted tests", and "stated tests". "Fewest tests," which is the default setting, tightens the set of tests returned by the chosen coverage type (node- or edge-) with the least number of tests that visit all the nodes or edges at least once, respectively. "Weighted tests" expand the set from "fewest tests" to include the test paths which are of higher weights. "Stated tests" allows users to interactively set the number of tests, which the engineer considers is sufficient for testing a specific functionality, based on the design specification of the functionality of the SUT as well as his/her experience. This number should be between the number of tests given by the "fewest tests," and the total number of tests that the coverage type can return. e.g. in our case study of the Contacts (Section 4), we get 16 and 5 test paths using weighted and fewest tests, respectively, for node-coverage based test selection.

Test Saving: For sharing and reusability, the selected tests can be saved and reused across the team. The test cases, chosen using Pathfinder, are written into an ASCII text file, in the format of a detailed test plan. The file is then processed offline generate a Microsoft Excel file, for readability and identifying the sequence of actions for executing a test case.

3.2 Visual Exploration of the HLM

One of the ways of engaging software testers in actively generating test plans from the HLM is by visual exploration with the help of a GUI. The MBN of the HLM is best visualized as a node-link diagram than its alternative matrix visualization, as the node-link diagram provides the spatial context of connectivity. Connectivity visualization is important for the QAE to choose appropriate criteria for test selection.

Graph Visualization: The visualization enables the user, who is the QA tester, to perform both a summarization of the HLM as well as model exploration. Node-link diagram of the MBN gives better overview of the spatial context of the path in the HLM, compared to the traditional way of viewing the test paths provided in a list in text. Pathfinder allows the user to exploring the model by selecting test paths in the tests pruned in the test selection set. This visualization, however, requires that the tests are sorted so that the user prioritizes these paths. We use two-levels of sorting, similar to a dictionary, which takes into consideration both the length and weight of the path. Sorting of the length of the paths is done in increasing order, and sorting of weight of the paths in decreasing order. Hence, in Pathfinder, the "*length-then-weight*" sorting gives the heaviest of the shortest paths; whereas the "*weight-then-length*" one gives the shortest of the heaviest paths.

Proposed GUI for Visualization: The interface of Pathfinder has been carefully designed for ease of use. The GUI consists of four parts, as shown in Figure 1: "*Control-panel*," "*Display-area*," "*Console-output*," and "*Status-bar*." The **Control-panel** consists of "Dropdown-menus" for file access, view settings and help; "Functional-control-widgets" which are required for interacting with the model-based network; and "Shortcut-widgets", which are a group of widgets with custom-built icons. The Shortcut-widgets are for easy access to few of the frequently used widgets, such as choices in the Dropdown-menus as well as some of the Functional-control-widgets. The Functional-control-widgets are further logically and physically grouped as visibility settings, and as a stack of tabbed widgets for stages in MBT, namely, model preparation, test generation, test selection, and cluster selection. *"Visibility-group"* is a group of widgets to enable and disable rendering of different parts of the graph, e.g. nodes, edges, etc. *"Model-preparation-tab"* includes widgets for building the MBN interactively and editing it, e.g. adding and deleting nodes, and edges. *"Test-generation-tab"* includes widgets for applying constraints and generating tests. *"Test-selection-tab"* is for culling relevant subsets of tests, for instance, based on the coverage type. *"Cluster-selection-tab"* is a group of widgets to enable clustering of tests to enable better management of tests. However, test clustering is complex and needs a separate study of its own, and hence, is beyond the scope of this paper. The **Display-area** is the area dedicated for the node-link diagram of the MBN. The **Console-output** displays output messages of state of Pathfinder, relevant for each interaction of user with application. The **Status-bar** shows messages which guides next actions of the users, e.g. screen coordinates of last left-mouse-button click on

Display-area, etc. The Console-output and the Status-bar make the Pathfinder GUI responsive. We have built the software for Pathfinder has been implemented in C++ with OpenGL and QT libraries.

GUI Design Patterns: For improving adoptability of MBT, we incorporate four different design patterns in our Pathfinder. *Firstly*, depending on the usage style of each user, the configuration settings of Pathfinder GUI for selections in the widgets in each of these groups can be saved and reloaded in the subsequent session of Pathfinder. The configuration *remembers* the states of checkboxes, radio buttons, or values, e.g. minimum or maximum values of NPT. For model creation and editing, the last entered labels of nodes and edges are saved and automatically reloaded in subsequent sessions. Multiple nodes with specific settings, used previously, can be quickly created on the screen one after another without having to activate "Create node" checkbox each time. *Secondly*, the widget groups, including the tabs, in the Control-panel are expanded (or maximized), by default, and can be contracted (or minimized) in order to *maximize screen space to the Display-area*. Pathfinder is designed to run on screens with large resolutions (which is usually the case in industrial projects). This feature has improved the visual experience, particularly for HLMs with more than 20 nodes. *Thirdly*, the model creation and editing functions are made *responsive* through the use of prompt messages on the Status-bar for guiding user actions. We additionally keep the UI design *minimal, light-weight, and crisp*, e.g. requiring an "OK" button for confirmation has been eliminated, as the "Enter" key for entering values can double up for confirmations.

Fourthly, the overriding principle governing the design of Pathfinder is *the realization of abilities and limitations of target users*. Constructs and concepts commonly used in the research community of software testing, e.g. MBT, are often not familiar to and inaccessible to the software testing professionals. Hence, the design of Pathfinder reflects the limitation of working knowledge of MBT, not only in what features it provides as well as what features it avoids. Intuitive color coding and visual feedback are provided in Pathfinder, for better understanding, in the form of intuitive colors and two-dimensional rendering. Similarly, we avoid features that require extensive programming knowledge-base in Pathfinder. e.g., conditionals, and Boolean logic have been consciously avoided throughout the GUI. One of the significant feature of Pathfinder is the graph traversal. We intentionally de-couple graph traversal and application data dependency in the GUI using appropriate abstractions in the back-end. An example of the intuitive color coding is that the start and end nodes for a node traversal for test paths are colored green and red, respectively[9]. For visually representing dependencies of the model, specific color combinations have been used. e.g., two-color combinations are used for indicating two constraints on states for selection nodes in a test path; and nodes in the path are given the specific color that corresponds to the constraint they fulfil, such as constraints could be specific to the geometric model that has been loaded, e.g. "use bolts invoked with single hole" and "auto fastener", as used in our case study (Section 4).

Visualization Design Study: Following the design study methodology prescribed in (Sedlmair et al., 2012), we have conducted design studies, validation, reflection, and design iterations. We first enumerated the requirements of the visualization as a guiding tool for QA testers for exploring and using HLMs for test plan generation. The Pathfinder GUI went through two development cycles after feedback from targeted users. The changes made in the GUI were on logical grouping of widgets and workflows for logical sequences of user interactions. While the node-link diagram is the mainstay of the visualization, we iterated through the design of the nodes, edges, and glyphs for weights (Figure 2(Left)). Since most graphs are skewed (i.e. lean and long) and screen displays are wider than longer, horizontal layout has been preferred over vertical layouts. Our initial visualization included three-dimensional rotation and rendering for encoding coverage and weights for both nodes and edges. Coverage was visually represented as "stack ribbons" in the y-z plane, and weights as "bars" in the x-z plane. Since the human visual system has higher accuracy in judgements pertaining to comparisons of numerical values, in length perception than in planar position perception, and even lesser in depth perception (Ware, 2010; Munzner, 2014), we have changed from using stack ribbons and bars to triangular icons and then, finally to rectangular icons with linear fill. The final choice of rectangular over triangular shape was done based on user feedback.

[9]To accommodate issues of the color palette for color vision deficiency or color blindness, we have used different values of the color hue, e.g. (0,255,0) and (215,48,39) as RGB values for green and red, respectively, as per the tip on using red-green hues together:
http://tinyurl.com/red-green-workaround

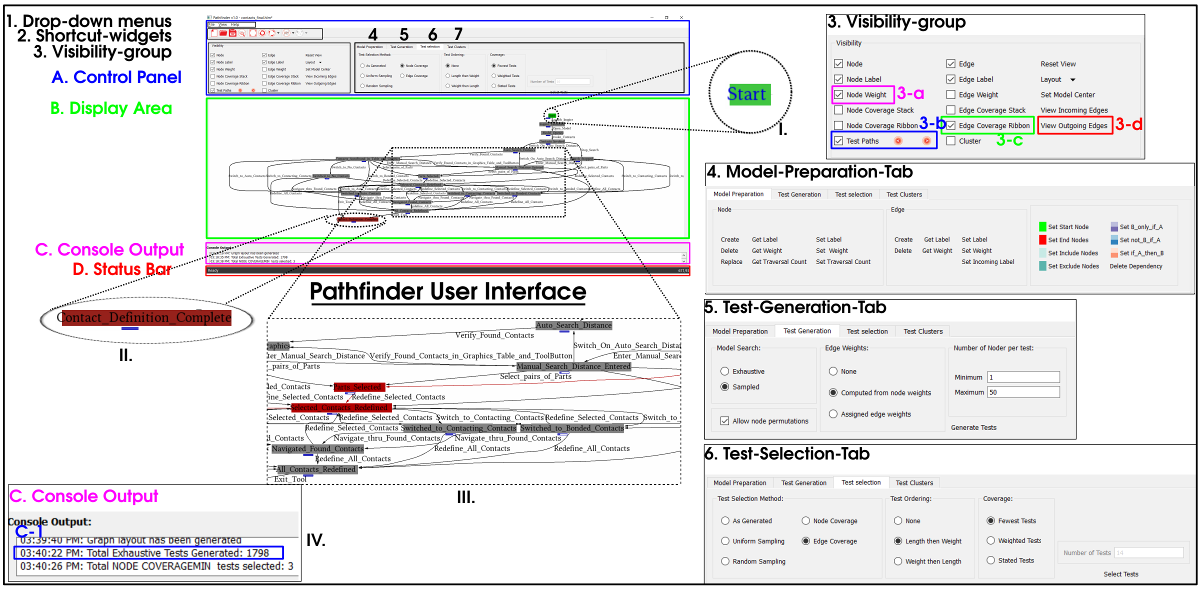


Figure 1: Overview of the GUI of Pathfinder displaying its four components (A-D): Control-panel, Display-area, Console-output, and Status-bar. The Display-area shows the visualization of the MBN (19 nodes, 19 edges) of the HLM of the Contacts (Section 4). (1-2) show dropdown menus, and (3-7) show groups of widgets, namely, Visibility-group, Model-preparation-tab, Test-generation-tab, Test-selection-tab, and Cluster-selection tab, where (4-7) are stackable tabs. The settings in the widget groups and the highlighted widgets 3-a, 3-b, 3-c, and 3-d are used in our case-study of Contacts. The start and end nodes for test paths are selected (insets in I. and II.) and rendered as green and red nodes, respectively. III. shows inset of a subnetwork in the MBN. IV. shows the console output for choice of exhaustive search during test generation step (highlighted in C-1).

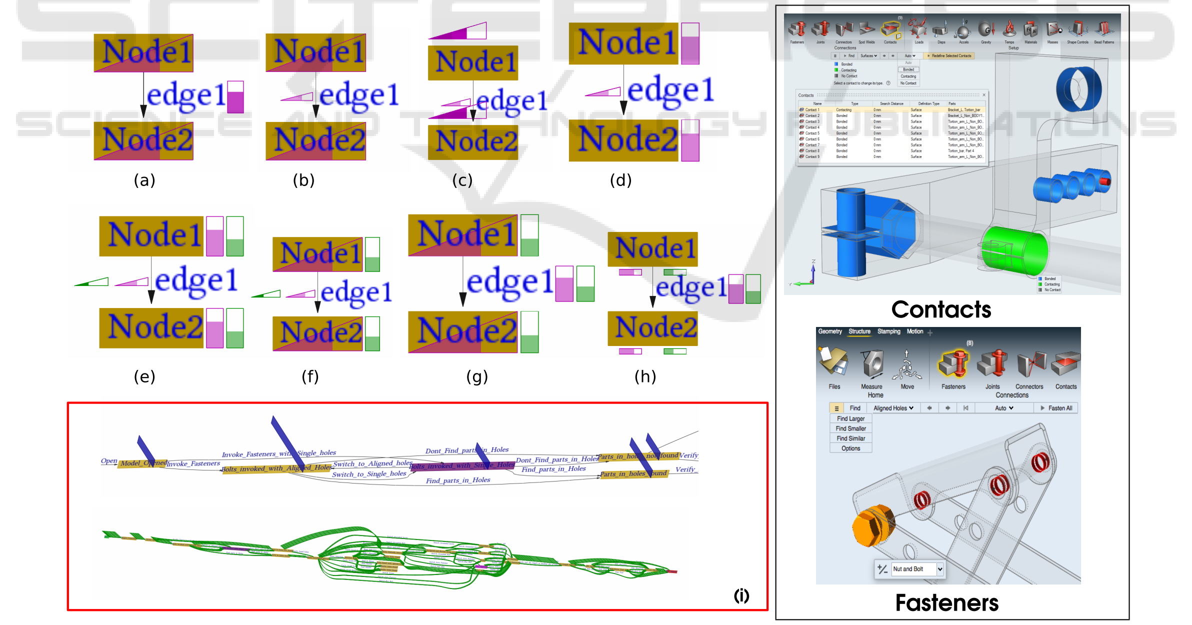


Figure 2: (Left) Different design iterations we performed for representation of edge and node weights, including a 3-dimensional rendering of the same (shown in (i)). For (a)-(h), the magenta glyphs represent the weights of nodes and edges, respectively; and the green glyphs show the coverage of the nodes and edges. Similarly, in (i), the blue “bars” show weights and the green “stack ribbons” show coverage. (Right) Screenshots of GUI of Solid Thinking Inspire®, showing Contacts and Fasteners functionalities, which are our case studies.

4 CASE STUDIES

Here, we demonstrate how Pathfinder is used in the software testing workflow or a software quality assurance (QA) process in the case of a GUI-based software product, solidThinking Inspire® (STI)[10]. This case study highlights the improvement in the workflow due to the use of Pathfinder, based on the inputs for this case study has been provided by a QA Engineer (QAE), who is one of the authors of the paper. We study two functionalities here, namely the **Contacts** and the **Fasteners**. Figure 2 shows the mechanical parts loaded in STI, where these functionalities are used, as well as the parts/modules of the GUI of STI for using these functionalities. We use Pathfinder to generate test plan for these GUI modules. In our case study, we extract an HLM of the states STI will reach due to the user interactions related to either functionality on the given geometrical model, i.e., the mechanical part. The goal here for the **test plan generation** is to test the various workflows, which are specifically for (a) detection of possible contacts in the mechanical part, and (b) creation or modification of fasteners in the mechanical part.

We have not compared our work with existing techniques primarily because of the differences of the models used in those methods and ours. e.g. if our SUT is modeled using GraphWalker (Karl, 2010), the graph grows exponentially when using function names as nodes of the graph, and it is not compatible with the rest of the software testing workflow in our case studies (e.g. test execution). In a different vein, comparison with JUMBL (Prowell, 2003) is not accurate for our work since the MBT is based on usage in the former, whereas ours focuses on both usage as well as behavior, owing to the dependencies involved in the CAD/CAE domain.

Contacts[11]: is a functionality that determines if two neighboring surfaces in a mechanical part(s) are bonding, in contact, or not in contact. STI automatically detects possible contacts in the model. The Contacts functionality allows the user to manipulate the current state of presence or absence of contacts and to create different types of contacts.

Fasteners[12]:is a relatively new functionality in STI to connect different mechanical parts using screws and bolts. After loading a three-dimensional model of the mechanical parts in the application, the "Fasteners" functionality is used to automatically find the "geometry," which refers to holes, slots, etc., and its corresponding (solid) fasteners that physically *fit in* the geometries subsequently. The functionality entails user interactions for selecting or deselecting the geometry, and finding other geometry which satisfy specific criteria. These criteria include specific range of dimensions of the selected geometry; comparisons with the selected geometry, such as similar to or smaller/larger than; or other relevant properties, e.g. single or aligned holes. In addition to specifications based on properties of the geometry, STI provides choices of different types of Fasteners, such as "bolt and nut" or "screw." The tool can also automatically choose the best Fastener type that fits the hole, which is referred to as "auto."

4.1 MBT Workflow for Case Studies

We have created the HLM from the MBN, e.g. for creating the MBN for the Fasteners functionality, we start by adding nodes that represent states in the creation or modification of Fasteners in the chosen mechanical part. We then add relevant edges connecting the nodes. This model is created using the specification of the functionality (e.g. Fastener or Contact) of the SUT (e.g. STI), which is of interest for development and testing. The nodes and edges are created in Pathfinder using the Model-preparation-tab. The MBN for Contacts has 19 nodes and 19 edges (Figure 1-(B) and (III.)), and Fasteners has 29 nodes and 67 edges (Figure 3-(a) and (c)).

Model Preparation for Fasteners: Here, we start with a single state to build a HLM, for which we use the state of "Holes_Auto-found_Selected" (H-A-S). H-A-S corresponds to the state of STI when all the holes automatically found are selected. The HLM nodes include all the states that STI can reach from H-A-S by user interactions. The QAE identifies these states based on the specifications as well as his/her experience of using STI. As per the design of STI, the actions we can perform on the selected holes are, namely, "Reset Selection," "Switch to Nut and Bolt," "Switch to Auto Fastener," "Switch to Screw," "Navigate the Found Holes." Hence, in the HLM, these edges are outgoing from the node H-A-S, highlighted as red edges. These outgoing edges are rendered by clicking on the corresponding button in the Visibility-group (Figure 1-(3)). Once the outgoing edges are in place, we add the nodes at the other end of these edges, as well as other relevant edges to complete the model-based network.

Once the MBN is constructed completely, we generate test cases by specifying constraints and dependencies on the network. These constraints and depen-

[10]http://www.solidthinking.com/Inspire2017.html

[11]http://www.solidthinking.com/help//Inspire/2017.3/win/en_us/index.html?contacts.htm

[12]http://www.solidthinking.com/help//Inspire/2017.3/win/en_us/index.html?fasteners.htm

dencies are characteristic of the functionality being tested. For Fasteners, we select the constraints on the start and the end nodes, for test paths, where "Start" and "Bolts_Created" (B-C) are selected, respectively. The start and end nodes are colored green and red, respectively, (Figure 1-(I) and (II), respectively). During the model preparation step, we further specify a dependency based on the type of holes, for which the following conditions exist, namely, "single" and "aligned" holes, and the selection of Fastener type, namely, "auto," "nut and bolt," and "screw." In our example, we use the specific dependency that if the hole is "single," then Fastener selection cannot be automatic, i.e. "auto." We select the dependency type "Set_not_B_if_A" in the Model-preparation-tab (Figure 1-(4)), and further select nodes, "Bolts_ Invoked_With_Single_Holes" (B-I-W-S-H) and "Auto_Fastener" as A and B, respectively. The rendering of the dependency uses two-color combination to show A and B.

The QAE then assigns node weights, interactively on Pathfinder GUI, by clicking on the widget for "Set node weights" in the Model-preparation-tab (Figure 1-(4)). Here, we set weights for nodes, B-I-W-S-H and "Bolts_Invoked _With_Aligned_Holes" (B-I-W-A-H), using a higher weight for the latter than the former, as, in practice in industry, B-I-W-A-H is considered more important than B-I-W-S-H. Similarly, the node Parts_In_Holes_Found (P-I-H-F) has higher importance than the node Parts_In_Holes_Not_Found, and hence, is assigned a higher weight. We use the default automatic computation of the edge weights during the test generation step.

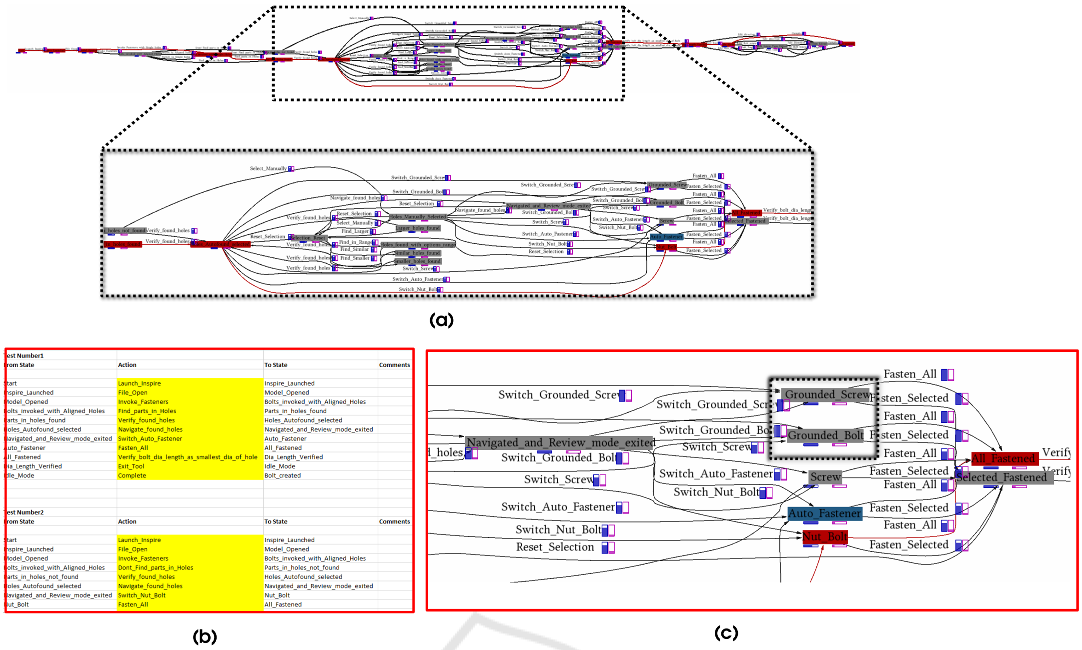
Test Generation, Selection and Saving for Fasteners: Once the HLM is prepared using the user-defined MBN, we start generating test cases. In the Test-generation-tab in the Control-panel, we select appropriate options for the sampled search of the model, automatic computation of edge weights, as well as input values for the user-defined minimum and maximum NPT, for which we choose 1 and 50, respectively. This action is finalized by clicking on the "Generate Tests" button (Figure 1- (5)). Selecting exhaustive search would have led to an explosion in the number of test cases, which is indicated in the Console-output (Figure 1 (C-1)). Hence, we keep the number of test cases more tractable by choosing the sampled search, which is 5000 in our case, as shown in message in Console-output.

We decide to apply coverage criteria to further reduce the number of test cases. Within the coverage criteria, we decide to use the option for "fewest tests" to ensure the optimal minimum number of tests, for which we get 8 in edge-coverage and 5 in node-coverage. We set these criteria in widgets of the Test-selection-tab for Fasteners (Figure 1- (6)). The amount of node-coverage and edge-coverage can be visualized using glyphs where filling indicates the weights, as shown in Figure 2 (see (Left) and (h)). Here, we opt for edge coverage to get a tractable set of 8 cases. We sort the paths using length-then-weight option, and visualize each path using the "test-path" widgets, which are arrow buttons given both in the Visibility-group as well as Shortcut-widgets. The arrow buttons, which allow the user to go backward and forward in the sorted list of selected test cases (Figure 1- (3-b)). The graph of the final outcome of our selections in the Pathfinder GUI is rendered in the Display-area (Figure 3- (a)).

Once we complete test selection, we save the tests by clicking on the "Save tests" option in the "File" drop-down menu, that outputs a text file in ASCII format. The highlighted cells, in the Microsoft Excel file generated from the text file, show the sequence of actions for executing a test case, as shown in Figure 3 (see (b)). Thus, we have shown how a QAE uses Pathfinder to obtain tests using MBT of the Fasteners functionality in STI, which has taken ($\sim 3-4$) hours for a QAE. While there is a slight benefit in terms of total time taken, the true benefit is in using a deterministic reproducible process by the use of Pathfinder.

Comparing Pathfinder and Manual Test Generation for Contacts: An experienced QAE generates 47 test cases, which is a mix of high- and low-level test cases. The time taken to write down all the cases by considering various documents like specifications and tickets was 8 hours, of which the time taken for writing down the test cases under the "Workflow Testing" header was 4 hours.

On the other hand, the cases generated by Pathfinder are based on the paths through which the QAE should traverse to execute a test case. Each path contains several start states, actions and end states. The QAE must perform the actions in the sequence and verify the subsequent end states (after each action). With the use of Pathfinder, one can get 1798 high-level test cases for the Contacts functionality, which is further reduced to 13, based on "the fewest number of tests" with "edge coverage" criterion. The time taken for preparing the model in Pathfinder was less than 6 hrs. The QAE has more control and certainty in generating the cases and selecting them using Pathfinder The total time taken for generating the document is $\sim$ 6 hours.



est Number1			
rom State	Action	To State	Comments
tart	Launch_Inspire	Inspire_Launched	
nspire_Launched	File_Open	Model_Opened	
Model_Opened	Invoke_Fasteners	Bolts_invoked_with_Aligned_Holes	
olts_invoked_with_Aligned_Holes	Find_parts_in_Holes	Parts_in_holes_found	
arts_in_holes_found	Verify_found_holes	Holes_Autofound_selected	
oles_Autofound_selected	Navigate_found_holes	Navigated_and_Review_mode_exited	
avigated_and_Review_mode_exited	Switch_Auto_Fastener	Auto_Fastener	
uto_Fastener	Fasten_All	All_Fastened	
ll_Fastened	Verify_bolt_dia_length_as_smallest_dia_of_hole	Dia_Length_Verified	
ia_Length_Verified	Exit_Tool	Idle_Mode	
dle_Mode	Complete	Bolt_created	
est Number2			
rom State	Action	To State	Comments
tart	Launch_Inspire	Inspire_Launched	
nspire_Launched	File_Open	Model_Opened	
Model_Opened	Invoke_Fasteners	Bolts_invoked_with_Aligned_Holes	
olts_invoked_with_Aligned_Holes	Dont_Find_parts_in_Holes	Parts_in_holes_not_found	
arts_in_holes_not_found	Verify_found_holes	Holes_Autofound_selected	
oles_Autofound_selected	Navigate_found_holes	Navigated_and_Review_mode_exited	
avigated_and_Review_mode_exited	Switch_Nut_Bolt	Nut_Bolt	
ut_Bolt	Fasten_All	All_Fastened	

Figure 3: Use of Pathfinder for our case study of Fasteners in solidThinking Inspire®: (a) Display of MBN (29 nodes, 67 edges) (b) Microsoft Excel file, which is processed from the ASCII text output file from Pathfinder; and (c) Showing the flexibility of Pathfinder in adding two nodes on-the-fly to the model-based network of Fasteners, where the two nodes are new Fastener types, "Grounded Bolts" and "Grounded Screws." In (a) and (c), gray nodes are generic nodes, the blue glyphs represent node weights, and magenta glyphs represent node coverages.

5 DISCUSSIONS

We discuss about how Pathfinder has improved the usability of MBT in a QA team, based on the case-study discussed in Section 4. This can be considered as a first step towards an increase in adoption or use of Pathfinder and MBT by QAEs and other stakeholders. Here, we also discuss about the limitations of Pathfinder. In comparison with the current (traditional) method of test plan creation and test generation, we have observed that in our case-study, the method using Pathfinder offers more efficiency in terms of both time and effort, thus improving the flexibility of usage of the generated tests and overall productivity of the QA team.

Efficiency in MBT: The traditional method involves creating test plan creation for a specific functionality using Microsoft Excel application, and data entry of test cases by a QAE, which is not automated. Thus, there is room for relatively more human error in the traditional method, compared to our method.

The set of tests, which is obtained through Pathfinder, has been obtained through a rigorous process of thorough examination of each stage of the MBT workflow and subsequent decision making. Hence, the tests are not generated ad-hoc, as is often the case with the traditional method. Saving the tests from Pathfinder makes these tests usable across a team, and repeatable, as the workflow for generating these tests in Pathfinder is definite. Redundancy and duplication of tests are reduced when using our method; e.g. for our case study on Fasteners, traditional method generates 50 tests, whereas using Pathfinder, we are able to use 8 tests, with the same coverage for end-to-end scenarios. The preprocessing for the test plan generation and model preparation in Pathfinder is a one-time investment, as it opens up several flexible options, downstream. e.g. there is flexibility to change constraints in start and end states in the MBT by re-assigning the start- and end-nodes in the network interactively on Pathfinder. At the same time, in the traditional method, the QAE has to re-generate the test cases from the Excel file, which is not automated, and hence is inefficient.

Flexibility in MBT: Pathfinder makes test generation flexible with respect to modifications in five different aspects. Firstly, in practice, the test plan is generated in the beginning of the software development cycle. As the development matures, changes in the specifications and implementations are bound to happen. Pathfinder is flexible in adopting these changes in the test plan, as the MBN of the HLM can be modified with minimal user interactions. On the other hand, in the traditional method, the test plan has to be thoroughly scrutinized and modified, and subsequent changes must be done in each test case. The entire process in the traditional method is not automated, which makes it inefficient and inflexible to changes. e.g. in our case-study, two more different Fasteners, namely "Grounded Bolts" and "Grounded Screws," have been added in a later release. When using Pathfinder, this addition modifies the MBN by addition of two nodes and relevant incoming and outgoing edges of the nodes. The edited MBN can be visualized in (Figure 3- (c)). Secondly, Pathfinder requires the QAE to have thorough understanding of the application or the functionality being tested, during model preparation unto test generation, however, that is not the case for a QAE who has to execute these tests. This is because the testing methodology and workflow is re-usable and repeatable using Pathfinder. This in turn allows different testers to contribute to the workflow, leading to an overall efficiency of the QA team. Thirdly, MBT using Pathfinder can also be performed by a program manager who would be writing the specification of a functionality/product. In this case, the motivation for generating test cases is different, as, here the test cases are used for conveying the use cases and all possible scenarios of specific functionality/product to the concerned teams like development, QA, documentation and the application engineers in the field. Fourthly, since the HLM is constructed at a coarse level, the HLM is unaffected by changes in the low-level workflows, such as change in type of button or user interaction for an action. Fifthly, MBT using Pathfinder fits well with the flexibility of adding new modules corresponding to different components and their corresponding processes to the functionality. Just like Fasteners, we can create HLMs for models for different functionalities and flexibly assemble them together, sometimes, leading to the complete application. This gives the combinations of cases and interaction between features at a higher level. The modularity of the HLM itself makes Pathfinder suitable for testing components, sub-systems, as well as larger systems. However, this assembly is currently outside the scope of this paper. Overall, the flexibility due to Pathfinder improves productivity of the QA team.

Completeness in MBT: The visualization of the MBN in Pathfinder allows the QAE to see the various paths that the software can take starting from a state of interest. This is not guaranteed in the traditional method, as there is the danger of the engineer overlooking a state or action when manually constructing the test plan. Each Pathfinder test case is a combination of several test cases of the manual test case document. With the use of Pathfinder, the sequence of actions to be performed and their combinations can be published in the document, unlike in the manual case. An experienced QAE usually goes through these sequences while executing the test cases using his/her own experience. This implies that the documentation of the sequences is necessary for a less experienced QAE to execute the tests. When using Pathfinder, the document is easier to be followed by other QA team members since each action, state and the sequence of actions are documented.

Limitations of Pathfinder: Since Pathfinder is a novel addition to existing software testing process, there is no specific standard for the HLM. This leads to variability in relevance of abstraction of different parts of the functionality or application. It is assumed that there is a consensus in the team on the HLM definition, before using Pathfinder. However, this assumption is not guaranteed. Even though case-studies have shown improvement in efficiency and flexibility of usability of MBT with the use of Pathfinder, this concept is ridden with resistance of adoption in the QA team, owing to its novelty. However, this hesitation has been often observed to be misplaced, as it stems from the fear of automation. Several experienced QAEs feel that they would be spending lesser time in manual creation of the test plans than a semi-automated one, such as Pathfinder, and they would be equally accurate. However, these statements are fraught with insufficient data to prove the point. Overall, Pathfinder has a steep slope to climb towards larger adoption in workflow, which is a reality that we are aware of. Additionally, in the current implementation of Pathfinder, the QAE cannot make notes in the test plan while it is being created, which is convenient in the traditional method. The workaround is to put in the test plan after its creation.

6 CONCLUSIONS

In this paper, we have demonstrated how visualization can bring about a difference in the adoption of good practices in software testing of complex applications. We have motivated the need for adoption of MBT to automate test generation and selection in a software QA team, in order to improve the productivity of the team. We have proposed the use of a HLM of the specific functionality of a GUI application, which is to be tested, and a model-based network to represent the HLM. The model-based network is visually represented as a node-link diagram which allows the user to summarize as well as explore the network. Our proposed GUI-based tool, Pathfinder, is built on the network visualization along with several intuitive features. These features are designed to improve the usability of the tool, and eventually lead to larger adoption of MBT in the CAD/CAE industry.

With gradual increase in adoption, it is hoped that the use of Pathfinder will provide a higher level of rationale and consistency in the selection of test cases for GUI-based applications, and thus, reduce the variability inherent in the perception of multiple testers. Thinking beyond this, Pathfinder can evolve to a consistent and clear means of describing software application behavior. This usage takes Pathfinder significantly upstream in the software design lifecycle to the stage of application design where actors such as program managers and developers can increasingly utilize these behavior description models to improve communication and understanding. Much care has gone into the design and functionality of Pathfinder for ensuring that it is comprehensible and easy-to-use for our community of software testers. In this respect, more powerful capabilities were rejected if they could not be presented with sufficient ease of use. Notwithstanding that we have demonstrated its effectiveness for GUI-based applications, Pathfinder can be extended for test-generation in other interactive object-oriented software systems. An immediate improvement to the tool will be the use of graph-theoretic algorithms to provide default settings for several options available on Pathfinder. A natural extension to our tool would be to seamlessly integrate other processes in a software testing workflow, which are downstream of test generation, e.g. verification of software requirements and test execution.

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