An Optimization Framework for the Design of Cable Harness Layouts in Planar Interconnected Systems

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The components of complex systems such as automobiles or ships communicate via connectors, including wires, hoses, or pipes whose weight could substantially increase the total weight of the system. Hence, it is of paramount importance to lay out these connectors such that their overall weight is minimized. In this paper, a computationally efficient approach is proposed to optimize the layout of flexible connectors (e.g., cable harnesses) by minimizing their overall length while maximizing their common length. The approach provides a framework to mathematically model the cable harness layout optimization problem. A Multiobjective Genetic Algorithm (MOGA) solver is then applied to solve the optimization problem, which outputs a set of non-dominated solutions to the bi-objective problem. Finally, the effects of the workspace's geometric structure on the optimal layouts of cable harnesses are discussed using sample test cases. The overarching objective of this study is to provide insight for designers of cable harnesses when deciding on the final layout of connectors considering aspects such as accessibility to and maintainability of these connectors. [DOI: 10.1115/1.4051685]

Keywords: approximation-based optimal design, computational geometry, design automation, design for assembly, design optimization, multiobjective optimization

1 Introduction

Complex interconnected systems such as household appliances (e.g., refrigerators), electronic devices, and vehicles consist of several subsystems and components. For these components to communicate and transmit electric power or transport fluids, they must be connected via connectors such as wires, hoses, or pipes. Depending on the system's complexity, hundreds to thousands of connectors are required to make the communication among various components possible, which could adversely affect the overall weight of the system. Thus, it is often desired to minimize the weight of connectors by minimizing their corresponding lengths. However, finding the shortest routes for connectors in a limited space left at the final design stages while avoiding collisions with objects in the environment is a challenge.

This problem is known as the multipath planning problem, where multiple connectors need to be routed in a cluttered environment while collision with any of the objects (and even other connectors) is prohibited. While pipe routing and wire routing are both instances of multipath planning, the two have fundamental differences in the design requirements and the metrics defined to quantify length. The focus in this study is, however, on the wire routing in electromechanical systems where the Euclidean norm is used to quantify the lengths of wire segments. For sample studies on pipe routing problems, readers are referred to Refs. [1–4].

In addition to length minimization, these connectors should be installed and laid out such that they can be easily accessed for inspection and maintenance. To achieve this, in electromechanical systems, wires are often bundled together to form a cable harness that could branch out at a breakout point to reach a particular system component. The number and locations of these breakouts can then determine the final layout of a cable harness assembly. A cable harness makes the wiring assembly more organized and is preferred as it occupies less space than loose wires in addition to reducing the installation costs. A sample cable harness assembly is shown in Fig. 1.

Yan et al. in a survey of design of cable harness assemblies [5] and Ng et al. [6] have independently pointed out several challenges in the design of cable harnesses, such as being costly, complex, tedious, and often performed following a trial-and-error approach in the detail design stage with limited space left for installing harnesses.

The efforts in addressing the challenges mentioned above in cable harness assemblies can be directed into two channels: (1) the design process for cable harnesses in different systems and (2) the optimization of cable harness layout to satisfy various objectives, including but not limited to the length minimization.

While this study provides an overview of both approaches, the main objective is to develop an optimization framework that overcomes the limitations of current methods and can find optimal

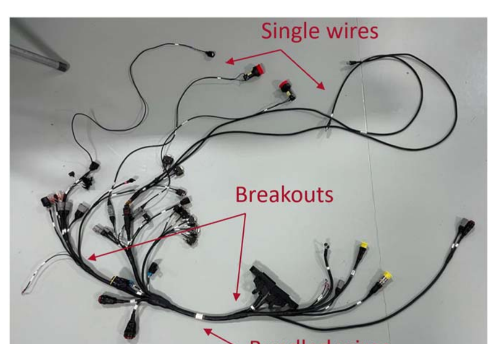

Fig. 1 Picture of a wire harness

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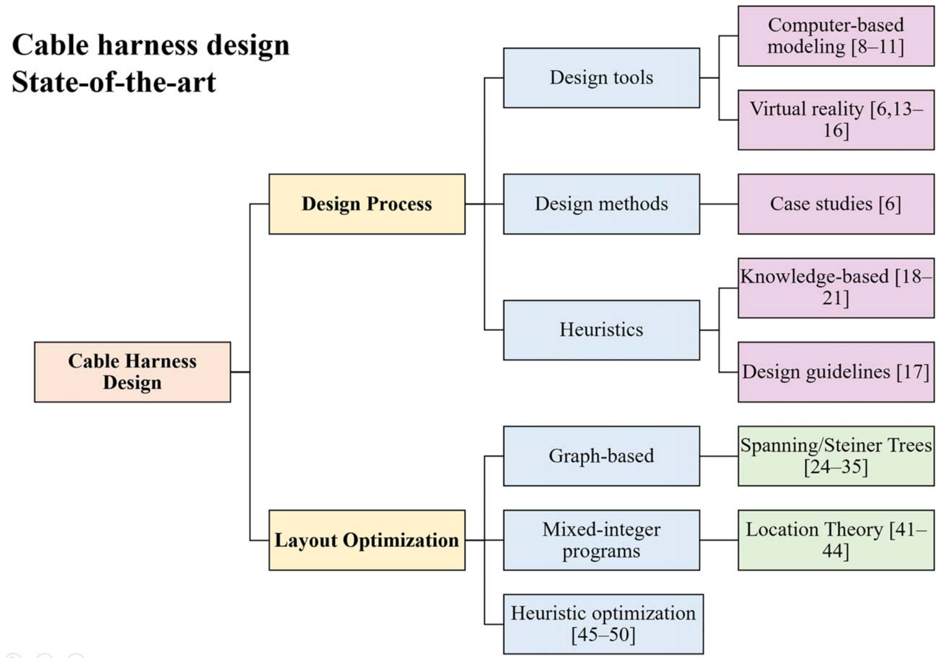

Fig. 2 Classification of the studies related to cable harness design

layouts for cable harnesses by determining the locations of their breakouts.

The remainder of this article is organized as follows. Section 2 presents an overview of the related work on the design and optimization of cable harnesses. After the limitations of the existing approaches are identified, in Sec. 3, the problem addressed in this research is defined along with an explanation of the assumptions made and a mathematical formulation. Next, the method to address the defined problem and its relevant computational requirements are described in Sec. 4. The computational performance of the proposed method is further evaluated and discussed in Sec. 5. Finally, and in Sec. 6, closing remarks and future research directions are presented.

2 Review of the Related Work

A summarized classification of the relevant studies reviewed in this research is shown in Fig. 2. It is noteworthy that the two main classes (design process or layout optimization) are not mutually exclusive. For example, in some design-based studies, the optimization of cable routes is also considered a step in the design process. The optimization approaches, on the other hand, mainly focus on developing or deploying a mathematical framework to achieve the set objectives. Therefore, these efforts often overlook the actual design process that leads to the development of the final layout.

2.1 Design Process for Cable Harnesses. Cable harnesses are designed to meet electrical, geometric, and environmental requirements [7]. Meeting such design requirements that are varied across multiple domains in a limited space available for the installation and routing of cables is a complex task. Therefore, design tools and guidelines have been developed to assist the designer throughout the design process from modeling at early design stages to deciding the final routes/sizes of cables. Additionally, design methods such as case studies were followed to further investigate the industrial design of such systems and provide recommendations to improve the processes being practiced [6].

A body of research has focused on developing modeling capabilities for cable harness design. The objective of this class of research efforts is to remove the costly need for developing and testing the outcome of design on physical prototypes. Examples include, but are not limited to, computer-aided design systems (for example, see Refs. [8–11]) and virtual reality environments, where designers, as well as users, can interact with the virtual prototype (for example, see Ref. [12]) to make design-related decisions. Readers are referred to a series of works by Ritchie et al. [6,13–16] for further details on virtual reality applications in cable harness design.

Others, on the other hand, have focused on design heuristics, including the development of design guidelines [17] and knowledge-based or artificial intelligence design approaches. Advocates of knowledge-based design of cable harnesses argue that the full automation of the cable harness design process is infeasible, and human knowledge must be the foundation of this dynamic and iterative activity [18]. In Refs. [18–21], different knowledge-based as well as AI techniques are employed for the cable design problem. Notwithstanding the efforts, following these heuristics, there is no guarantee that the final solution is optimal since it solely relies on human experience [17].

2.2 Optimization of Cable Harness Layout. The focus of design-based studies is mainly on the design process of cable harnesses which requires different levels of human intervention and thus lacks automation. More importantly, the design-based methods may not yield a final optimal layout which could bear significant costs for the manufacturing and maintenance of the cables [6]. Hence, optimization methods are developed and applied to overcome the limitation of manually (and often sub-optimally) determining routes of cables and locations of breakouts.

Of the relevant studies in the optimization domain, tree-based methods have gained popularity in designing interconnected networks. Minimum Spanning Tree (MST) and Steiner Minimal Tree (SMT) are the two common types of optimal tree networks. Given a set of nodes, MST is the minimum-length tree that spans all the nodes [22]. SMT, in particular, is extensively employed to address problems where adding extra nodes to a network is allowed to further minimize the total length [23]. Due to the intrinsic advantages of minimizing the length of a network while spanning all or specified nodes, Steiner (and spanning) trees are natural candidates for cable harness layout optimization. For sample studies on the application of MST and SMT, readers can refer to Refs. [24–29].

The original Steiner/spanning tree, however, does not deal with obstacle-avoiding constraints; hence, researchers have to make modifications to adopt the method for cable routing in the presence of obstacles. In fact, adding obstacles to the environment significantly increases the complexity of the problem [30]. Therefore, the research to address this constraint is limited to the use of approximations [31,32] and/or heuristic workarounds [33–35]. Hence, the obstacle-avoiding Steiner tree may not be a computationally efficient solution to the general cable layout optimization problem.

Apart from tree-based methods, when the focus is on the determination of optimal locations for the harness breakouts, methods developed for facility location problems (known as the Weber problem [36]) become relevant. Location problems in the presence of obstacles have been among the challenging NP-hard problems in operations research [37]. Even though different methods are presented over the past four decades, they still cannot address the problem in its entirety. For example, the available methods can only deal with convex obstacles [38–40]—since the objective function is non-convex, the discretization of the workspace is used [37], which results in locally optimal solutions. In addition, the multiobjective multi-facility problem in the presence of freeform objects, which can model the cable harness layout optimization, remains unsolved. Hence, this class of solution methods may too be computationally expensive to apply to the harness layout optimization problem.

Lastly, due to its computational efficiency in solving NP-hard problems, the class of heuristic methods is widely applied to solve different instances of multipath planning problems with branches [41–46], although the solutions found are not necessarily globally optimal.

This review of the literature shows a scarcity of research efforts in developing computationally efficient methods to tackle the optimization of cable harness layout in the presence of freeform objects without approximating the length of wires. Based on the existing limitations, this study aims to bridge the gap by presenting a framework to mathematically model and solve layout optimization for cable harnesses in cluttered environments without approximating the lengths of wire segments. The overarching goal is to provide an insight for the designers and decision-makers of cable harness layouts at any stage of design by running a computationally efficient optimizer.

3 Problem Definition and Assumptions

Before the optimization method is described, an explicit definition of the problem is required. In this research, an optimization algorithm is sought to address the following problem:

For a given number of start and goal nodes representing different system components in a cluttered environment, an optimal layout for a cable harness spanning the required nodes is to be found, characterized by the routes of cables and the locations of a finite number of breakouts. The connectors are not allowed to cross any object, and the breakouts must not be placed inside an occupied area. The optimization objectives are (1) to minimize the cost of the cable connectors as a function of their total length and (2) to maximize the common length of the connectors (or bundle as many connectors as possible for the longest possible distance), providing more accessibility and traceability of connectors for maintenance purposes.

The underlying assumptions based on which the problem needs to be formulated and solved are the following:

- The problem is modeled on a *2D plane.*
- Since the wiring connectors are flexible, the *Euclidean* distance metric is used to calculate the lengths of cables.
- Obstacles are *arbitrary convex or non-convex polygons* scattered on the plane with known topology, dimensions, and locations.
- All obstacles are *stationary.*
- The Cartesian coordinates of the nodes (points on components) that need to be connected are given.
- The number of required breakouts is prespecified.

The mathematical formulation of this bi-objective constrained optimization problem is given in Sec. 3.1.

3.1 Mathematical Model.

Suppose a cable harness assembly needs to be laid out to connect n components from a list of *Start* components to a *Goal* list of m components. For simplicity, it is assumed that only two breakouts are required for this harness; the first is to bundle n wires from the *Start* list and extend the bundle to reach the second breakout, where the bundled cables branch out to reach the m components in the *Goal* list. The general mathematical formulation of this problem with two breakouts is provided in problem 1.

Problem 1

$$\min_{B_1,B_1\in\mathbb{R}^2} Z_1=\left(\left[\sum_{i=1}^{n}D(S_i,B_1)\right]+n_wD(B_1,B_2)+\left[\sum_{j=1}^{m}D(B_2,G_j)\right]\right),$$

$$\max_{B_1,B_1\in\mathbb{R}^2} Z_2=[D(B_1,B_2)]$$

$$\text{S.t.}\, B_1,B_2\notin\bigcup_{k=1}^{l}\operatorname{int}(P_k)$$

where

B_1, B_2: the two breakouts of the cable harness,
S_i: ith start point, $i=1, 2, \ldots, n$,
G_j: jth goal point, $j=1, 2, \ldots, m$,
P_k: kth polygonal obstacle, $k=1, 2, \ldots, l$, and
n_w: the number of wires passing through the length covered between B_1 and B_2.

$$D(a,b)=\begin{cases}\|a,b\| & \overline{ab}\cap(\operatorname{int}\bigcup_{k=1}^{l}P_k)=\varnothing\\ D(a,b) & \text{otherwise}\end{cases}$$

■

In problem 1, the minimization objective function has three terms: (1) the sum of the distances between each start terminal and the first breakout, (2) the distance between the two breakouts multiplied by the number of wires, n_w, passing from B_1 to B_2, and (3) the sum of the distances between the second breakout and each of the goal terminals. The number of wires is estimated by $n_w=max\{|S|, |G|\}$, where $|\bullet|$ is the cardinality of the set. The second objective function looks at maximizing the common length of wires between the two breakouts. The decision variables are the (x, y) coordinates of the breakouts in $\mathbb{R}^2$. The constraints are to avoid placing a breakout inside the union of all polygonal obstacles. It is, however, permitted to place a breakout on the boundary of an obstacle. It is also noteworthy that the constraint of having cables not crossing the interior of any obstacles is implicitly addressed by calling the distance function, $D(\bullet, \bullet)$, which calculates the length of collision-free routes as explained in Sec. 3.2.

3.2 Distance Function Definition.

The distance function, $D(\bullet, \bullet)$ shown in problem 1 outputs the Euclidean distance, $\|\bullet, \bullet\|$, between any two points of a plane that are visible to each other. Any pair of nodes are visible if they can be connected by a line segment not intersecting any obstacles. If the line of sight of the points is blocked by one or more obstacles, a modified distance function, $\tilde{D}(\bullet, \bullet)$, is called to calculate the length of the shortest collision-free path connecting them.

Different optimal routing methods exist that find the shortest collision-free path between points in a cluttered environment. Among these methods, only visibility graphs are both exact and capable of obtaining the globally optimal solution [47]. A more computationally efficient variant of the visibility method that is based on the convex hulls of the intersecting obstacles and is proven to generate the globally optimal solution is introduced in Ref. [47]. Using such convex hulls, the proposed method reduces the complete visibility graph to a local graph, without loss of generality, and therefore improves the computational efficiency of the graph construction phase. As shown in Ref. [47], the method applies to the generalized path-planning problems on a plane, including routing through narrow passages between obstacles which are relevant to the specific problem of cable harness layout design.

3.2.1 An Overview of the Convex Hull-Based Routing Algorithm. The convex hull-based routing algorithm explained in Ref. [47] starts with detecting the intersections with the obstacles. Upon intersection detection, the intersecting objects are ordered from the closest to the path start point to the farthest. Next, a series of convex hulls are generated using an initial point and an intersecting object. At the onset, the initial point is the path start point, and at each $(i+1)$th iteration, two initial points are introduced, being the extreme points of the convex hull generated at the ith iteration. The extreme points are points on the hull with the maximum distance from the line connecting the start and goal points of the path. By this definition, for each convex hull, two extreme points are identifiable, one per each side of the start-goal line.

Upon arrival at each initial point identified, the algorithm checks for a direct collision-free path between that initial point and the goal. If one exists, the algorithm finalizes the path and adds it to the graph; otherwise, a new set of intersecting objects are identified and ordered, and a convex hull is created using that initial point and the closest newly identified intersecting object. This process is iteratively and recursively continued until a complete collision-free graph is formed. The nodes of this graph are vertices of the objects on the series of convex hulls, and the graph edges are non-intersecting edges of the convex hulls. After the graph is completed, Dijkstra's search algorithm [48] is applied to output the shortest route from the start to the goal. Figure 3 depicts the graph construction steps on a sample workspace. For further details of the method and its computational performance, readers are referred to Ref. [47].

The modified distance function in problem 1, $\tilde{D}(\bullet, \bullet)$, outputs the length of the shortest route found following the convex hull-based approach. Previously, the efficiency of this method in finding the shortest path between any two points in a cluttered planar environment has been shown [47]. In this effort, its extension and application to cable harness layout as a multipath planning problem with more than one optimization criterion are further investigated.

4 Computational Framework and Solution Method

In this section, first, the computational framework to algorithmically describe the constraints in problem 1 is outlined. Then, the optimization method proposed to yield optimal harness layouts is explained.

4.1 Bounding the Feasible Domain Via a Convex Hull—Linear Constraints. The formulation shown in problem 1 requires the optimization solver to search the entire feasible domain, which is the $\mathbb{R}^2$ plane excluding the areas occupied by the obstacles to find the optimal locations for the breakouts. This exhaustive search could significantly slow down the optimization process, especially in large-scale problems. Instead, Klamroth [49] has proposed using an iterative convex hull approach to limit the feasible domain. The notion of an iterative convex hull is based on the results of Kuhn's work [50], which asserts that the location of a new node (here, the breakout) in a tree network should be inside the convex hull of the existing nodes. Klamroth in Ref. [49] suggests that when obstacles are present in an environment, the boundary of Kuhn's described convex hull should be extended to also include any obstacle that crosses the convex hull's boundary. The expansion of the convex hull's boundary continues iteratively until no further crossing can be found.

It is noteworthy that the collision between the convex hull's boundary and the polygonal obstacles is detected following an intersection detection algorithm outlined in Ref. [47]. For additional algorithmic details in creating this convex hull, readers can refer to Ref. [51].

Using the idea of an iterative convex hull, we add a new constraint to problem 1, and the problem is reformulated as problem 2. A set of linear inequalities is added to problem 2 to model the new constraint of enforcing the location of the breakouts inside the convex hull. After the convex hull is created, its edges are extracted to define the linear constraints of the problem.

Problem 2

$$\min_{B_1, B_1 \in \mathbb{R}^2} Z_1 = \left(\left[\sum_{i=1}^{n} D(S_i, B_1) \right] + n_w D(B_1, B_2) + \left[\sum_{j=1}^{m} D(B_2, G_j) \right] \right),$$

$$\max_{B_1, B_1 \in \mathbb{R}^2} Z_2 = [D(B_1, B_2)]$$

$$\text{S.t.}\, B_1, B_2 \notin \bigcup_{k=1}^{l} \text{int}(P_k)$$

$$B_1, B_2 \in C$$

Where

C: the convex hull of the setpoints S, G, and the intersecting obstacles.

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4.2 The Point-in-Polygon Problem—Nonlinear Constraints. In addition to the linear constraints resulting from the convex region, the nonlinear constraints are required to model the feasible region for placing the breakouts inside the convex hull. For every polygonal obstacle bounded inside the convex hull of nodes in S and G and intersecting objects, a nonlinear constraint checks whether the breakout is placed inside this polygon. This problem is known as the point-in-polygon (PIP) problem in computational geometry.

In this study, the *even-odd rule* based on ray crossing [52] is used for its simplicity in determining the location of a point relative to an arbitrary yet closed polygon. Based on this rule, the point P is inside a closed polygon, Q, if a horizontal ray originated from P crosses the edges of Q an odd number of times; otherwise, P is outside Q (see Fig. 4 for example).

An algorithm can be developed to count the number of ray crossings to determine whether the breakout is outside an obstacle. An example algorithm with MATLAB implementation used in this research can be found in Ref. [53].

4.3 Multiobjective Genetic Algorithm. Problem 2 is a bi-objective non-convex constrained optimization problem of the NP-hard type. The objectives are functions of the distances between the nodes. Even though the distances eventually come down to Euclidean norms (which are differentiable), when solving for the optimal layout of the harness, it is not known a priori which path is taken to connect every *Start* node to its corresponding G*oal*. Thus, not knowing the path, the mathematical function describing the path length is also unknown. Therefore, the derivatives of the objective functions cannot be found, making the problem hardly solvable with gradient-based methods. Consequently, a heuristic, gradient-free solution method needs to be sought. Although heuristics cannot guarantee to find the global optimum, their computational efficiency in addressing NP-hard problems outweighs their capability in converging to the global optimum.

Genetic Algorithm (GA) is among the widely used heuristic methods, relying on two main operations of mutation and crossover

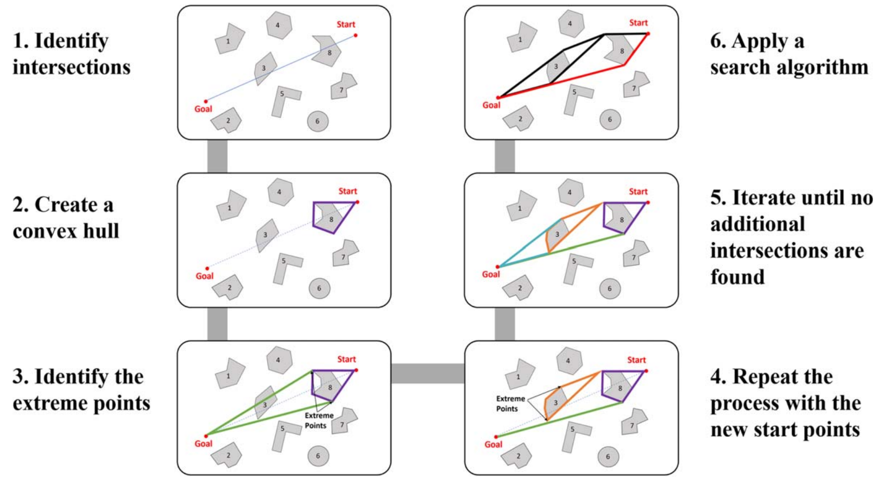

Fig. 3 Example of the convex hull-based routing applied to a sample workspace

to evolve the found solutions (population) toward optimality. At the onset, an initial random population is considered, and after the fitness of individuals in the population is evaluated using the objective function(s), the fitters are selected to create the next generation using crossover and mutation operations [54]. Some termination criteria of GA include reaching the maximum number of generations, reaching the time limit, or insignificant improvement to the fitness of individuals from one generation to the next. Additional details of the GA theory and applications can be found in Refs. [54–56].

Due to the conflicting objectives in Problem 2, a multiobjective optimization approach must be taken, which generates a set of Pareto optimal solutions (rather than a single solution) reflecting the tradeoff between the objectives. For this research, a Multiobjective Genetic Algorithm (MOGA) approach known as Nondominated Sorting Genetic Algorithm II (NSGA-II) [57] is adopted, which serves two purposes: (1) finding a diverse set of solutions and (2) converging toward the true Pareto optimal front.

4.3.1 A Numerical Example. To demonstrate the capability of the proposed computational framework, an example workspace, shown in Fig. 5, is created with 12 scattered obstacles, three *Start* nodes, four *Goal* nodes, and two breakouts, the locations of which are to be decided. Also shown in this figure is the convex hull of the nodes and intersecting objects (aka the linear constraints).

The problem is solved using MATLAB's MOGA solver with 100 generations and a population size of 50. Separate MATLAB functions are created for nonlinear constraints and objective functions following the framework presented in Secs. 4.1–4.3. The final set of nondominated solutions to this problem can be seen in Fig. 6.

It should be reminded that due to the use of a heuristic solver, at each execution of the GA, a new set of non-dominated solutions is generated, and the non-dominated solutions at the last generation may not necessarily reflect the true Pareto front.

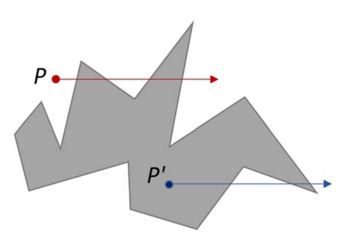

Fig. 4 Example of ray crossing test for the PIP problem

For every point in the non-dominated or eventual Pareto set, there is an associated optimal layout for the cable harness found by locating the breakouts. Two of these layouts are shown in Fig. 7.

Layout 18 is a special case where the two breakouts coincide, zeroing the total common length. While this layout may not provide any commonality for wire bundles, it can still bring insight to the designer when deciding about the final layout.

In addition, it would be relevant to compare this special layout with zero commonality to a layout where no breakout exists—the single criterion problem of minimizing the total wire lengths. For the example workspace shown in Fig. 5, the optimal no-breakout layout is presented in Fig. 8. By having all these different layouts, the decision-maker can finalize the routes of cable harnesses based on his/her priorities of the competing objectives.

5 Computational Performance of the Method

In this section, we further explore how the final optimal solution set can be affected by the geometric structure of the workspace. Since the optimal solution is not unique, to make the comparison of different layouts more meaningful, three solutions are selected from the Pareto set: the layout with the maximum distance between the two breakouts, the layout with the minimum total lengths of wires, and the optimal no-breakout layout. The tests are

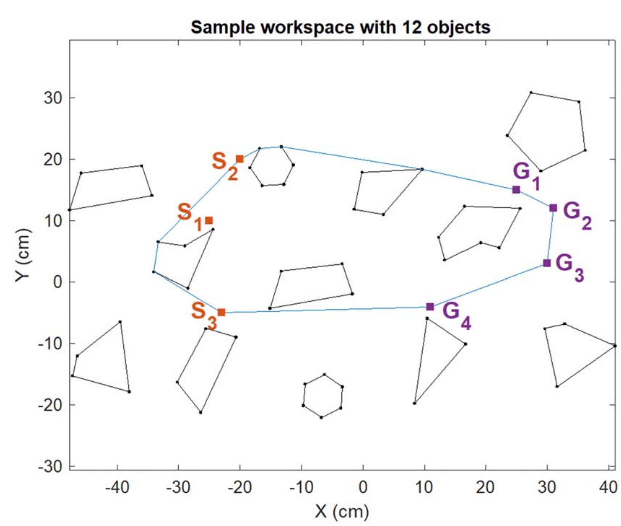

Fig. 5 Sample workspace of a cable harness layout problem

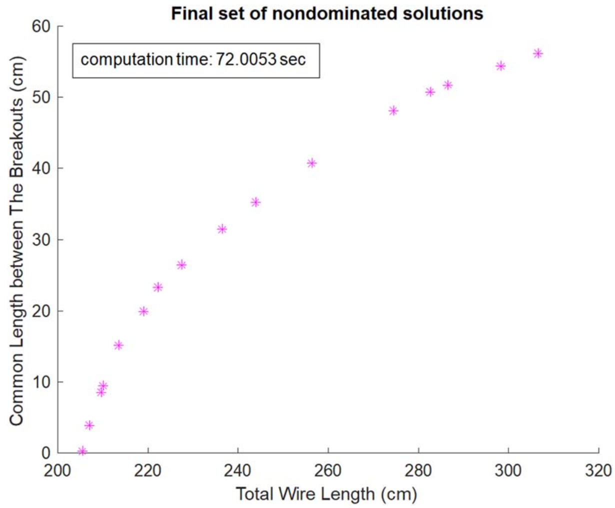

Fig. 6 Non-dominated solutions set for workspace in Fig. 5

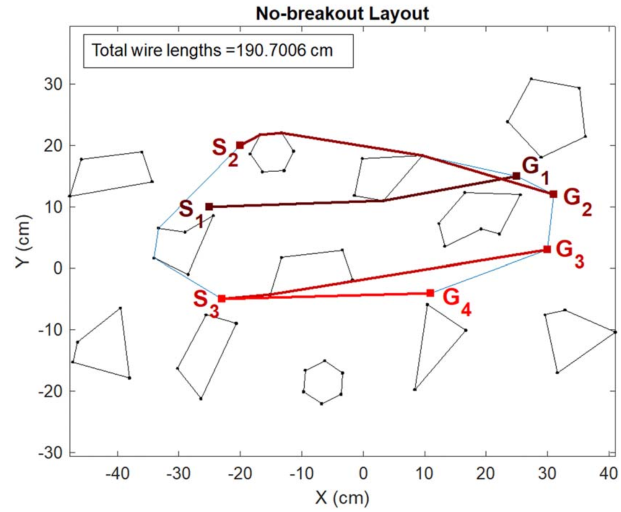

Fig. 8 No-breakout layout for workspace in Fig. 5

run on a system with an Intel Core i7-6500U CPU, 2.50 GHz, and 8.00 GB RAM.

5.1 Effects of the Number of Nodes and the Number of Breakouts.

While having more components to be connected obviously requires more wires and increases the total length of the wire harness, other factors such as the locations of the nodes (components) highly affect the total and common lengths. Hence, it is inconclusive as to how increasing the number of nodes alone could affect the optimal layout of the harness without knowing where the new nodes are located.

Further, analyzing the effects of the number of breakouts on the optimal solutions requires knowledge of the topology of the harness. The harness topology shows that nodes are connected to each breakout and how the breakouts are connected to one

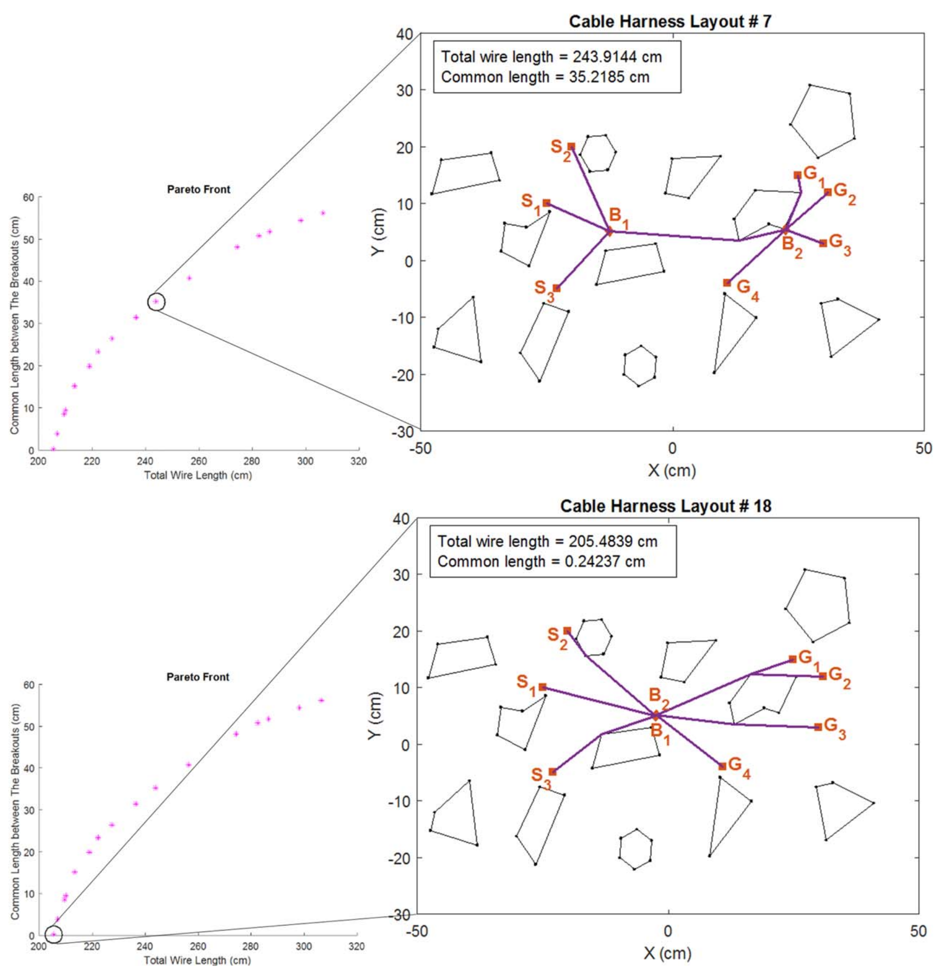

Fig. 7 Example optimal layouts for workspace in Fig. 5

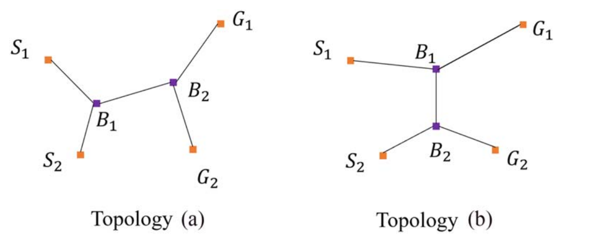

Fig. 9 Different harness topologies for spanning the same nodes with two breakouts

another. For example, Fig. 9 shows two different topologies for the case with the same number of nodes and breakouts. Thus, to analyze the effects the number of breakouts has on the final layout, it should accompany the topological information of that harness. Sample harness layouts with more than two breakouts found by applying the proposed method are shown in the Appendix.

5.2 Effects of the Workspace Density. One of the challenges the designer of a cable harness layout faces is the limited feasible space remaining to route all the wires in the detail design stage. Adding more objects to the same workspace results in a more densely populated environment. Therefore, the knowledge of the effects of the environment density on the optimal layout of a cable harness can help the designer observe the effects of adding or removing one or more components from the system.

The density of the workspace, in this study, is defined as the ratio of the area occupied by the obstacles inside Klamroth's defined convex hull over the area of the convex hull:

$$\text{density } (\%) = \frac{\text{area(obstacles)}}{\text{area(Conv hull)}} \times 100 \tag{1}$$

To evaluate the effects of density on the optimal solutions, 11 different test cases are generated by varying the density from 14.25% to 52.36% in the feasible region of the workspace (these numbers result from the addition of obstacles in the space bounded by the convex hull). The density is increased by adding objects inside the hull until the run-time passes a threshold of 1 h (for the density of 54.5%, which did not yield a solution within the 1-h run-time of the algorithm). To make the comparison of the test cases possible, two *Start* and two *Goal* nodes are used with fixed locations across all the tests. For this topology, two breakouts are required to organize the wires efficiently. By keeping the topology simple with two breakouts, we can avoid extensively allocating computational resources to the complex topology and focus more effectively on analyzing the impacts of increasing the workspace density. The workspaces of these test cases can be found in Appendix A of Ref. [51], and the results are shown in the graphs of Fig. 10.

Since increasing the density beyond 52.36% in the same workspace results in the exponential growth of the computation time, cases with densities greater than 52.36% are not further explored.

As seen in Fig. 10, a denser workspace results in longer run-time of the algorithm to find a set of optimal layouts for the harness. Further, it is obvious that the more obstacles are present in an environment, the more likely it is for the harness to cross them, hence, increasing the total length of the wires (whether or not breakouts are used). Nevertheless, general conclusions cannot be drawn regarding the effects of density on the common length between the breakouts.

6 Closing Remarks and Future Works

The multi-faceted problem of deciding the optimal layout of cable harness assemblies in complex systems is studied in this paper. The cable harnesses are used to bundle wiring connectors together for ease of installation and maintenance. The challenges of optimally locating the harness breakouts and routing the wires while avoiding collisions with system components are addressed by proposing an efficient framework to mathematically model the problem for planar environments and then apply an optimizer.

To ensure the length of wires is minimized, a distance function is defined that benefits from the convex-hull-based routing, a computationally efficient method to find the shortest routes on a cluttered plane. A gradient-free Multiobjective Genetic Algorithm (MOGA) solver is selected to solve sample problems with known harness topologies. Final non-dominated sets of solutions are generated,

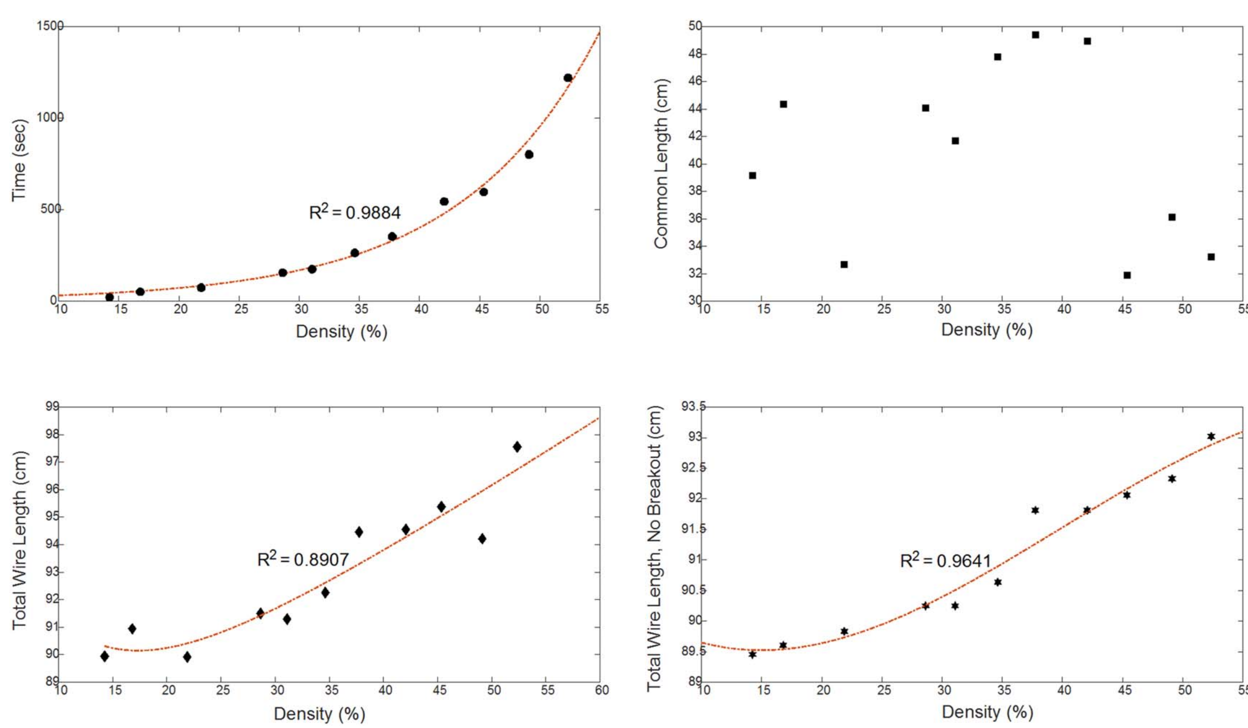

Fig. 10 Effects of workspace's geometric structure on computation time and optimal solution

reflecting the competition between the objectives of maximizing the common length of wires and minimizing the total wire length. Every point on the non-dominated solution set associates with an optimal harness layout defined by the locations of breakouts and routes of wires in the form of a graph. Along with the optimal solutions, the case with no breakouts is also provided to the designer to be able to compare different layouts and decide on the most favorable depending on their design priorities.

The computational performance of the method is evaluated by varying the workspace density and analyzing its effects on the optimal solutions. The results show that while increasing the density in an environment clearly increases the computation time and the total lengths of wires (with or without breakouts), a trend of its impact on the common length of wires is not observable, as confirmed in Fig. 10. In what follows, we further discuss some of the challenges of the proposed method, provide ideas to address the challenges, and present potential research directions to further this study.

Application to higher dimensions—Since the convex-hull-based algorithm used to calculate the shortest length for a wire applies to 2D environments, the proposed framework may not directly be applicable to 3D problems. However, for applications such as electric circuit design or wiring of refrigeration systems which are 2.5D problems and where the wires lie on a flat surface, the method can be similarly applied. Moreover, this method can also be useful in developing wiring diagrams on boards or in software tools which is a step in the design of a 3D wire harness (e.g., in automotive systems) and could provide insight for the designers in planning the final layout. As a future direction, the use of the 3D version of the convex-hull-based routing [51] in addressing the 3D harness layout design can be further studied.

Obstacle shapes—The proposed method applies to planar environments regardless of the shapes of the obstacles since the tessellated models of obstacles are used for shortest length computations. For obstacles with curved surfaces, to achieve accurate results, it is recommended that the resolution of the tessellation be increased. The designer should, however, note that increasing the tessellation resolution could adversely affect the computational cost of the solution method.

Design constraints and criteria—The two main design objectives considered in this study are the minimum length of each wire and the maximum length of the bundled section and the main constraint is to avoid intersecting the obstacles. In addition to the considered constraint, other factors such as closeness to sharp edges and hot zones could affect the final decision of harness layout. These prohibited regions of the space can be modeled as additional polygonal obstacles or through offsetting the existing obstacles. Other physical constraints that need to be accounted for, so that the method provides more instrumental insight for designers, include the turn radius of the cables and the voltage/current constraints for wires. Turn radius, in particular, can be a critical constraint for larger wire harnesses. As more wires are added to a cable, the allowable turn radius must be larger, further limiting the feasible space. Thus, the turn radius constraint needs to be modeled as a function of the number of passing wires.

It is also noted that workspace density is not the only factor affecting the optimal solutions and computational performance of the method. As future avenues of research, the effects of factors such as the number and locations of nodes and the topology of the harness could also be studied to gain a better understanding of how an optimal layout may change by varying the workspace structure. As the harness topology depends on the number of the breakouts and their connection to the nodes, which are treated as given in this method, it would be of interest to address the question of "what is the optimal number of breakouts for a known set of nodes?"

Other future directions—Since the choice of cable harness layout affects other decisions throughout the design of an interconnected system, the problem can be modeled as a multidisciplinary optimization problem. For example, the layout of system components needs to be optimized simultaneously with cable harness layout optimization as a bi-level optimization problem. Researchers have conducted extensive studies on addressing the problem of finding the optimal layout for a number of components in a system, known as the packaging problem, considering multiple objectives such as maximizing compactness, survivability, accessibility, and maintainability of components [58–63]. In the future, the capability of our proposed approach in furthering the state-of-the-art in addressing the concurrent optimization of packaging and routing [64,65] can be explored. Further, it would be relevant to the engineering design field to look at how best the knowledge of expert wire harness designers and engineers can be incorporated into the developed methodologies to automate the process of finding the optimal layouts.

Conflict of Interest

There are no conflicts of interest

Appendix

The proposed optimization framework can be applied to different harness design cases as long as the topology of the harness indicating the connections between breakouts and nodes (terminals) is known. For example, additional wire harness layouts with three and four breakouts are found by applying the proposed method and sample solutions are shown in Figs. 11 and 12.

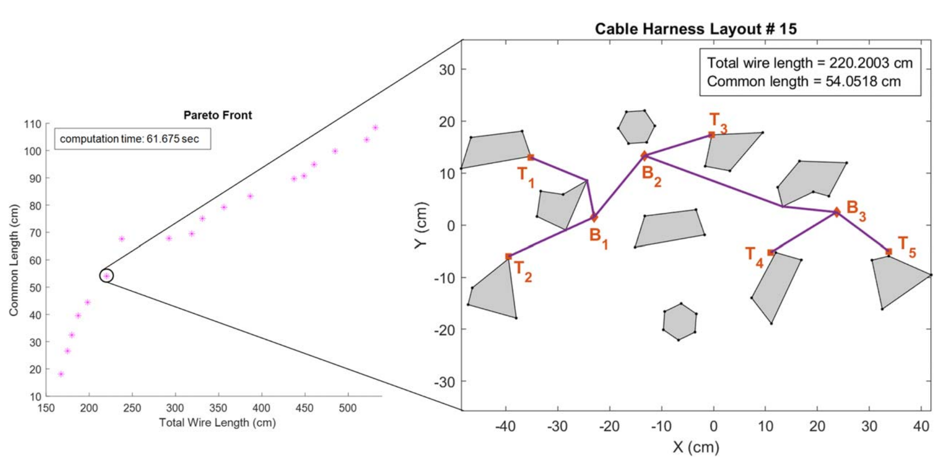

Fig. 11 Sample cable harness layout with three breakouts

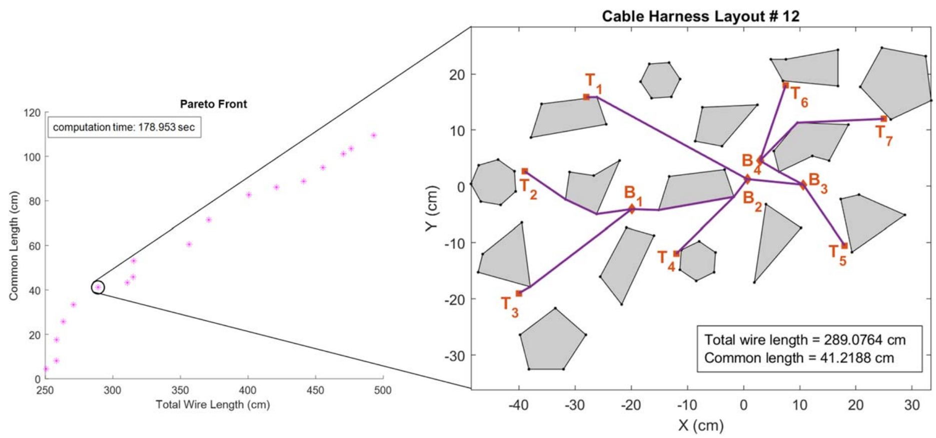

Fig. 12 Sample cable harness layout with four breakouts

References

[1] Qu, Y., Jiang, D., Gao, G., and Huo, Y., 2016, "Pipe Routing Approach for Aircraft Engines Based on Ant Colony Optimization," J. Aerosp. Eng., **29**(3), p. 04015057.

[2] Liu, Q., and Wang, C., 2011, "A Discrete Particle Swarm Optimization Algorithm for Rectilinear Branch Pipe Routing," Assem. Autom., **31**(4), pp. 363–368.

[3] Sui, H., and Niu, W., 2016, "Branch-Pipe-Routing Approach for Ships Using Improved Genetic Algorithm," Front. Mech. Eng., **11**(3), pp. 316–323.

[4] Zhang, Y., and Bai, X. L., 2013, "Research on the Automatic and Optimized Pipe Routing Layout for Aero-Engines Based on Improved Artificial Fish Swarm Algorithm," Appl. Mech. Mater., **437**, pp. 275–280.

[5] Yan, J., Zuo, D. W., Jiao, G. M., and Li, J. P., 2007, "Survey on the Design and Planning of Cable Harness Assemblies in Electromechanical Products," Appl. Mech. Mater., **10–12**, pp. 889–893.

[6] Ng, F. M., Ritchie, J. M., and Simmons, J. E. L., 2000, "The Design and Planning of Cable Harness Assemblies," Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., **214**(10), pp. 881–890.

[7] Trommnau, J., Kühnle, J., Siegert, J., Inderka, R., and Bauernhansl, T., 2019, "Overview of the State of the Art in the Production Process of Automotive Wire Harnesses, Current Research and Future Trends," Procedia CIRP, **81**, pp. 387–392.

[8] Billsdon, R., and Wallington, K., 1998, "Wiring Harness Design: Can a Computer Help?," Comput. Control Eng. J., **9**(4), pp. 163–168.

[9] Lindfors, N., Pesonen, A., Franck, C., and Kuosmanen, P., 2003, "Cabling Design Utilizing 3D CAD in Product Development of an Electric Device," DS 31: Proceedings of the 14th International Conference on Engineering Design, A. Folkeson, K. Gralen, M. Norell, and U. Sellgren, eds., Stockholm, pp. 29–30.

[10] Mingji, H., and Dong, X., 2010, "Research on Flexible Cable Geometric Modeling Technology in Virtual Maintenance Based on VRML," International Conference on Mechanic Automation and Control Engineering, IEEE, Wuhan, China, pp. 772–775.

[11] Han, N., and Guo, L., 2017, "The Research on Routing Optimization Method Using Undirected-Graph in Cable Harness Design," Proceedings of the ASME 2017 International Mechanical Engineering Congress and Exposition. Volume 11: Systems, Design, and Complexity, Tampa, FL, pp. 1–6.

[12] Valentini, P. P., 2011, "Interactive Cable Harnessing in Augmented Reality," Int. J. Interact. Des. Manuf., **5**(1), pp. 45–53.

[13] Ritchie, J., Simmons, J., Holt, P., and Russell, G., 2002, "Immersive Virtual Reality as an Interactive Tool for Cable Harness Design," Proceedings of PRASIC, Brasov, România, pp. 249–255.

[14] Simmons, J., Ritchie, J., and Holt, P. O. B., 2002, "Immersing the Human in the Design: Design-for-Manufacture of Cable Harnesses," Proceedings of SCI 2002 (Sixth Multi-Conference on Systemic, Cybernetics and Informatics), Orlando, FL, July 14–18.

[15] Ritchie, J. M., Robinson, G., Day, P. N., Dewar, R. G., Sung, R. C. W., and Simmons, J. E. L., 2007, "Cable Harness Design, Assembly and Installation Planning Using Immersive Virtual Reality," Virtual Reality, **11**(4), pp. 261–273.

[16] O'B Holt, P., Ritchie, J. M., Day, P. N., Simmons, J. E. L., Robinson, G., Russell, G. T., and Ng, F. M., 2004, "Immersive Virtual Reality In Cable and Pipe Routing: Design Metaphors and Cognitive Ergonomics," ASME J. Comput. Inf. Sci. Eng., **4**(3), pp. 161–170.

[17] Lin, C., Rao, L., D'Ambrosio, J., and Sangiovanni-vincentelli, A., 2014, "Electrical Architecture Optimization and Selection—Cost Minimization via Wire Routing and Wire Sizing," SAE Int. J. Passeng. Cars-Electron. Electr. Syst., **7**(2), pp. 502–509.

[18] Cerezuela, C., Cauvin, A., Boucher, X., and Kieffer, J.-P., 1998, "A Decision Support System for a Concurrent Design of Cable Harnesses: Conceptual Approach and Implementation," Concurrent Eng., **6**(1), pp. 43–52.

[19] Shang, W., Liu, J., Ning, R., and Liu, J., 2012, "A Computational Framework for Cable Layout Design in Complex Products," Phys. Procedia, **33**, pp. 1879–1885.

[20] Van Der Velden, C., Bil, C., Yu, X., and Smith, A., 2007, "An Intelligent System for Automatic Layout Routing in Aerospace Design," Innov. Syst. Software Eng., **3**(2), pp. 117–128.

[21] Pemarathne, W. P. J., and Fernando, T. G. I., 2016, "Wire and Cable Routings and Harness Designing Systems with AI, a Review," IEEE International Conference on Information and Automation for Sustainability (ICIAfS), IEEE, Galle, Sri Lanka, pp. 1–6.

[22] O'Rourke, J., and Mallinckrodt, A. J., 1995, *Computational Geometry in C*, Computers in Physics.

[23] Gilbert, E. N., and Pollak, H. O., 1968, "Steiner Minimal Trees," SIAM J. Appl. Math., **16**(1), pp. 1–29.

[24] Jeng, D. J. F., and Watada, J., 2007, "Non-Deterministic Algorithm for Routing Optimization: A Case Study," Second International Conference on Innovative Computing, Information and Control, ICICIC 2007, Kumamoto, Japan.

[25] Marianov, V., Gutiérrez-Jarpa, G., Obreque, C., and Cornejo, O., 2012, "Lagrangean Relaxation Heuristics for the P-Cable-Trench Problem," Comput. Oper. Res., **39**(3), pp. 620–628.

[26] Schwarze, S., 2015, "The Multi-Commodity Cable Trench Problem," 23rd European Conference on Information Systems, ECIS 2015, Münster, Germany, pp. 1–14.

[27] Vasko, F. J., Landquist, E., Kresge, G., Tal, A., Jiang, Y., and Papademetris, X., 2015, "A Simple and Efficient Strategy for Solving Very Large-Scale Generalized Cable-Trench Problems," Networks, **67**(3), pp. 199–208.

[28] Calik, H., Leitner, M., and Luipersbeck, M., 2017, "A Benders Decomposition Based Framework for Solving Cable Trench Problems," Comput. Oper. Res., **81**(C), pp. 128–140.

[29] Zyma, K., Girard, J. N., Landquist, E., Schaper, G., and Vasko, F. J., 2017, "Formulating and Solving a Radio Astronomy Antenna Connection Problem as a Generalized Cable-Trench Problem: An Empirical Study," Int. Trans. Oper. Res., **24**(5), pp. 943–957.

[30] Winter, P., 1993, "Euclidean Steiner Minimal Trees with Obstacles and Steiner Visibility Graphs," Discret. Appl. Math., **47**(2), pp. 187–206.

[31] Müller-Hannemann, M., and Tazari, S., 2010, "A Near Linear Time Approximation Scheme for Steiner Tree among Obstacles in the Plane," Comput. Geom. Theory Appl., **43**(4), pp. 395–409.

[32] Parque, V., and Miyashita, T., 2018, "Obstacle-Avoiding Euclidean Steiner Trees by n-Star Bundles," Proceedings—International Conference on Tools with Artificial Intelligence, ICTAI, IEEE, Volos, Greece, pp. 315–319.

[33] Ajwani, G., Chu, C., and Mak, W. K., 2011, "FOARS: FLUTE Based Obstacle-Avoiding Rectilinear Steiner Tree Construction," IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst., **30**(2), pp. 194–204.

[34] Hu, Y., Feng, Z., Jing, T., Hong, X., Yang, Y., Yu, G., Hu, X., and Yan, G., 2004, "FORst: A 3-Step Heuristic for Obstacle-Avoiding Rectilinear Steiner Minimal Tree Construction," J. Inf. Comput. Sci., **1**(3), pp. 107–116.

[35] Lin, C.-W., Chen, S.-Y., Li, C.-F., Chang, Y.-W., and Yang, C.-L., 2008, "Obstacle-Avoiding Rectilinear Steiner Tree Construction Based on Spanning Graphs," IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst., **27**(4), pp. 643–653.

[36] Weber, A., and Friedrich, C. J., 1929, *Alfred Weber's Theory of the Location of Industries*, The University of Chicago Press.

[37] Hamacher, H. W., and Klamroth, K., 2000, "Planar Location Problems with Barriers Under Polyhedral Gauges," Ann. Oper. Res., **96**(1/4), pp. 191–208.

[38] Katz, I. N., and Cooper, L., 1981, "Facility Location in the Presence of Forbidden Regions, I: Formulation and the Case of Euclidean Distance with One Forbidden Circle," Eur. J. Oper. Res., **6**(2), pp. 166–173.

[39] Aneja, Y. P., and Parlar, M., 1994, "Algorithms for Weber Facility Location in the Presence of Forbidden Regions and/or Barriers to Travel," Transp. Sci., **28**(1), pp. 70–76.
[40] Klamroth, K., 2004, "Algebraic Properties of Location Problems with One Circular Barrier," Eur. J. Oper. Res., **154**(1), pp. 20–35.
[41] Conru, A. B., 1994, "A Genetic Approach to the Cable Harness Routing Problem," Proceedings of the First IEEE Conference on Evolutionary Computation. IEEE World Congress on Computational Intelligence, IEEE, Orlando, FL, pp. 200–205.
[42] Conru, A. B., and Cutkosky, M. R., 1993, "Computational Support for Interactive Cable Harness Routing and Design," 19th Design Automation Conference: Volume 1—Mechanical System Dynamics; Concurrent and Robust Design; Design for Assembly and Manufacture; Genetic Algorithms in Design and Structural Optimization, Albuquerque, NM, Sept. 19–22, pp. 551–558.
[43] Kimura, H., 2011, "Automatic Designing System for Piping and Instruments Arrangement Including Branches of Pipes," International Conference on Computer Applications in Shipbuilding 2011(ICCAS2011), pp. 93–99.
[44] Zhu, Z., La Rocca, G., and van Tooren, M. J. L., 2017, "A Methodology to Enable Automatic 3D Routing of Aircraft Electrical Wiring Interconnection System," CEAS Aeronaut. J., **8**(2), pp. 287–302.
[45] Kabul, I., Gayle, R., and Lin, M. C., 2007, "Cable Route Planning in Complex Environments Using Constrained Sampling," Proceedings of the 2007 ACM Symposium on Solid and Physical Modeling—SPM '07, pp. 395–402.
[46] Hermansson, T., Bohlin, R., Carlson, J. S., and Söderberg, R., 2016, "Automatic Routing of Flexible 1D Components with Functional and Manufacturing Constraints," Comput. Des., **79**(C), pp. 27–35.
[47] Masoudi, N., Fadel, G., and Wiecek, M. M., 2019, "Planning the Shortest Path in Cluttered Environments: A Review and a Planar Convex Hull-Based Approach," ASME J. Comput. Inf. Sci. Eng., **19**(4), p. 041011.
[48] Dijkstra, E. W., 1959, "A Note on Two Problems in Connexion with Graphs," Numer. Math., **1**(1), pp. 269–271.
[49] Klamroth, K., 2006, *Single-Facility Location Problems with Barriers*, Springer Science & Business Media.
[50] Kuhn, H. W., 1973, "A Note on Fermat's Problem," Math. Program., **4**(1), pp. 98–107.
[51] Masoudi, N., 2020, "Geometric-Based Optimization Algorithms for Cable Routing and Branching in Cluttered Environments," Clemson University.
[52] Hormann, K., and Agathos, A., 2001, "The Point in Polygon Problem for Arbitrary Polygons," Comput. Geom., **20**(3), pp. 131–144.
[53] Redish, A. D., and Jacquenot, G., 2008, "Fast InPolygon Detection MEX. Retrieved May 31, 2020.".
[54] Whitley, D., 1994, "A Genetic Algorithm Tutorial," Stat. Comput., **4**(2), pp. 65–85.
[55] Goldenberg, D. E., 1989, *Genetic Algorithms in Search, Optimization and Machine Learning*, Addison Wesley, Reading, MA.
[56] Fonseca, C. M., and Fleming, P. J., 1993, "Genetic Algorithms for Multiobjective Optimization: Formulation Discussion and Generalization," Proceedings of the Fifth International Conference on Genetic Algorithms, ES. Forrest, ed., Citeseer, pp. 416–423.
[57] Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., 2002, "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II," IEEE Trans. Evol. Comput., **6**(2), pp. 182–197.
[58] Szykman, S., and Cagan, J., 1997, "Constrained Three-Dimensional Component Layout Using Simulated Annealing," ASME J. Mech. Des., **119**(1), pp. 28–35.
[59] Miao, Y., Blouin, V. Y., and Fadel, G. M., 2003, "Multi-Objective Configuration Optimization With Vehicle Dynamics Applied to Midsize Truck Design," Proceedings of the ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 2: 29th Design Automation Conference, Parts A and B, ASME, Chicago, IL, pp. 319–327.
[60] Grignon, P. M., and Fadel, G. M., 2004, "A GA Based Configuration Design Optimization Method," ASME J. Mech. Des., **126**(1), pp. 6–15.
[61] Yin, S., Cagan, J., and Hodges, P., 2004, "Layout Optimization of Shapeable Components With Extended Pattern Search Applied to Transmission Design," ASME J. Mech. Des., **126**(1), pp. 188–191.
[62] Dandurand, B., Guarneri, P., Fadel, G. M., and Wiecek, M. M., 2014, "Bilevel Multiobjective Packaging Optimization for Automotive Design," Struct. Multidiscip. Optim., **50**(4), pp. 663–682.
[63] Sridhar, R., Chandrasekaran, M., Sriramya, C., and Page, T., 2016, "Optimization of Heterogeneous Bin Packing Using Adaptive Genetic Algorithm," IOP Conference Series: Materials Science and Engineering, IOP Publishing, p. 012026.
[64] Jessee, A., Peddada, S. R. T., Lohan, D. J., Allison, J. T., and James, K. A., 2020, "Simultaneous Packing and Routing Optimization Using Geometric Projection," ASME J. Mech. Des., **142**(11), p. 111702.
[65] Panesar, A., Brackett, D., Ashcroft, I., Wildman, R., and Hague, R., 2015, "Design Framework for Multifunctional Additive Manufacturing : Placement and Routing of Three-Dimensional Printed Circuit Volumes," ASME J. Mech. Des., **137**(11), p. 111414.