CHALLENGES IN EUROPEAN AEROSPACE
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A Methodology to Enable Automatic 3D Routing of Aircraft Electrical Wiring Interconnection Systems

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ABSTRACT

Harness 3D routing in aircraft Electrical Wiring Interconnection System (EWIS) design is very complex because of both the intrinsic complexity of EWIS and the increasing number of design constraints. The complexity hinders the improvement of the design efficiency and makes the design error prone. Considering that many harness components are selected from catalogues and the design work is largely repetitive and mostly rule based, there are many opportunities to automate a significant part of the design process. Nevertheless, none or very limited solutions to automate the 3D routing have been found. Aiming for the automation of harness 3D routing, in this research, an innovative approach has been proposed that models and solves the 3D routing problem as an optimization problem. The challenge to solve above optimization problem is that the number of design variables, namely the number of clamping points, is not known a priori. The number is actually an output of the 3D routing. In order to handle this challenge, a two-step, hybrid optimization strategy has been devised. The first step, called *Initialization*, generates a preliminary harness definition using a road map based path finding method without knowing the number of design variables. The second step, called *Optimization* uses conventional optimization method to refine the preliminary harness definition while satisfying all design constraints. This approach has been implemented into a software application and several cases have been executed to validate the system functionality. The results have demonstrated that the tool is capable of handling cases of representative complexity and design constraints and deliver 3D harness models in full automation.

1 DESIGN CHALLENGES IN THE DEVELOPMENT OF THE AIRCRAFT ELECTRICAL WIRING INTERCONNECTION SYSTEMS

The Electrical Wiring Interconnection System (EWIS) is a very complex system due to the inconnection requirements of aircraft avionics. The EWIS of the A380 (Figure 1), for example, contains 530km of cables, 100,000 wires and 40,300 connectors[2]. The complexity of the EWIS is deemed to further increase in new generation More-Electrical-Aircraft (MEA) and Full-Electrical-Aircraft (FEA) [3]. Significant advances in the design method of such a system are necessary, not only to efficiently address the growing amount of electronic systems to be interconnected, but also to comply with the growing amount of safety constraints stipulated by Certification Authorities[4].

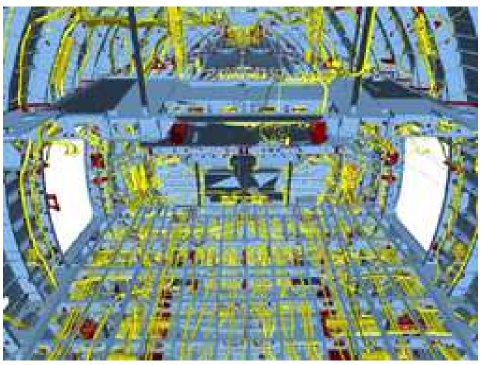


Figure 1: Part of the Airbus A380[1]

The EWIS design process (see flow chart in Figure 2), consists of two main phases, generally addressed as electrical design and the physical design. In the electric design phase, the power and data signal interconnection between the various electronic components is defined; in the second phase the actual routing of the many wire harnesses is developed. The physical design can be divided further into three activities, namely Space Reservation, Main Routing Architecture design and 3D Routing. During the Space Reservation step, space is reserved in the aircraft to allow routing and integration of the EWIS. In this phase, EWIS designers and other designers responsible for the integration of other systems (e.g., air conditioning and anti-icing) compete for the scarce space available on the aircraft for EWIS routes. The outcome of the Main Routing Architecture (MRA) design is the definition of the so-called motor way network (i.e. MRA) which designates the preliminarily routes to connect the main aircraft systems. In the 3D Routing phase the actual harnesses models are generated inside the aircraft Digital Mock-Up (DMU), making use of the reserved space and MRA, in order to connect the various systems according to the electrical definition established in the electrical design phase.

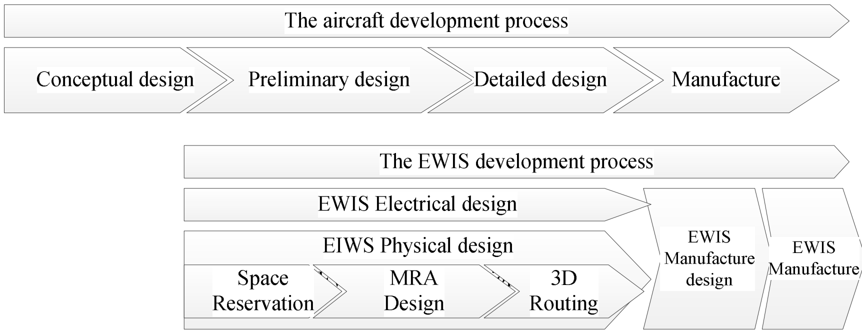


Figure 2: Overview of the EIWS design (bottom) in the overall aircraft development process (top)

The 3D routing of wire harnesses is particularly complex, not only because of the intrinsic complexity of the EWIS system, but also because of the sheer amount of design requirements to be respected (e.g. no go areas, areas requiring special cables protections, allowable bend radius of cables, allowed structure to clamp the harness, etc.), and the frequent changes in the aircraft structure that might force the designers, for example, to reconsider the position of some attachment points, or even define new routes because of reduced space availability. Due to the limited time allocated to perform their work and the frequent last minutes changes, wire harness designers work under high pressure and their work, which is still mostly manual (supported by Computer Aid Design (CAD) systems), is prone to errors. The methodology proposed in this paper addresses specifically this critical phase in the physical design process.

Considering the fact that a large amount of harness components are selected from catalogues and that the nature of the wire harness design work is largely repetitive and mostly rule based, there are a lot of opportunities to automate the design process, thus releasing design engineers from lengthy and repetitive work and potentially increasing their creativity. A number of researchers [5-9] have focused on the automation of EWIS design. However, none or very limited solutions to automate the 3D routing part of the EWIS design process have been found. Also the current leading Mechanical CAD (MCAD) tools used in industry are not able to generate wire harness 3D models automatically and still demand a lot of manual work by expert designers.

2 KNOWLEDGE BASED ENGINEERING AND MULTIDISCIPLINARY DESIGN OPTIMIZATION TO AUTOMATE 3D ROUTING OF WIRE HARNESSES

This paper proposes a novel methodology to address the 3D routing challenges discussed in Section 1. In particular the proposed methodology aims at the following two main objectives:

1. Automate the generation of the 3D wire harness models, by capturing and systematically reusing the experts' knowledge;

2. Automatically update wire harness models when changes occur, either in the routing environment, or in the electrical design phase of the EWIS.

The proposed approach is based on the hypothesis that solving the routing problem is equivalent to solving an optimization problem. In this case, the objective function to minimize represents a cost function that accounts for both the total cost of the wire harness and the cost of the protection layers and support components required to route the harness in area with harsh environment (heat, vibration, etc.). The design variables represent the position of the various clamping points where the cables are fixed to the aircraft structure. The reader can imagine the position of these clamping points as the waypoints in a GPS route planner. The various design rules, such as minimum allowed

bend radius, maximum distance between contiguous clamping points, and minimum distance between cable and support structure, can be formulated as constraints for the optimization problem.
The technical implementation of the proposed approach is built on a combination of Knowledge Based Engineering (KBE)[10] and Multidisciplinary Design Optimization (MDO)[11] technologies. KBE technology is exploited to capture the typical rule-based approach of the wire harness design and to enable the automation of all the geometry manipulations and checks required to perform the routing task. MDO is used to systematically explore the large design space provided by the 3D routing problem, to discover minimum cost solutions that comply with the multitude of design constraints.
Section 3 of this paper provides an overview of the EWIS architecture and the main design rules involved in wire harness routing. Sections 4 to 6 describe the actual definition of the optimization problem and its technical implementation. In Section 7 examples are provided that demonstrate the capability of the proposed approach to meet the two set objectives.

3 DESCRIPTION OF AIRCRAFT EWIS AND 3D ROUTING RULES

Subsection 3.1 provides a description of the aircraft EWIS and clarifies the focus area of the proposed methodology. Subsection 3.2 provides details on the design rules and checks to be applied during 3D routing. Both subsections introduce the terminology that is then used in the formulation of the optimization problem.

3.1 Description of the aircraft EIWS

The aircraft EWIS is a large and complex system that propagates through almost every part of the airframe and the engines. To facilitate manufacturing and installation, it is designed as a set of separate harnesses, which, during assembly, are connected at the so called production breaks points. The way the EWIS is split into different sets of harnesses strongly depends on the zones of the aircraft where the EWIS is routed. These zones are called *wiring zones* and differ from each other because of their environmental conditions, such as heat, vibration, and moisture. As consequence, each wiring zone demands different design rules. In practice, each wiring zone is independent from the others for what concerns the design and installation process. The earlier mentioned

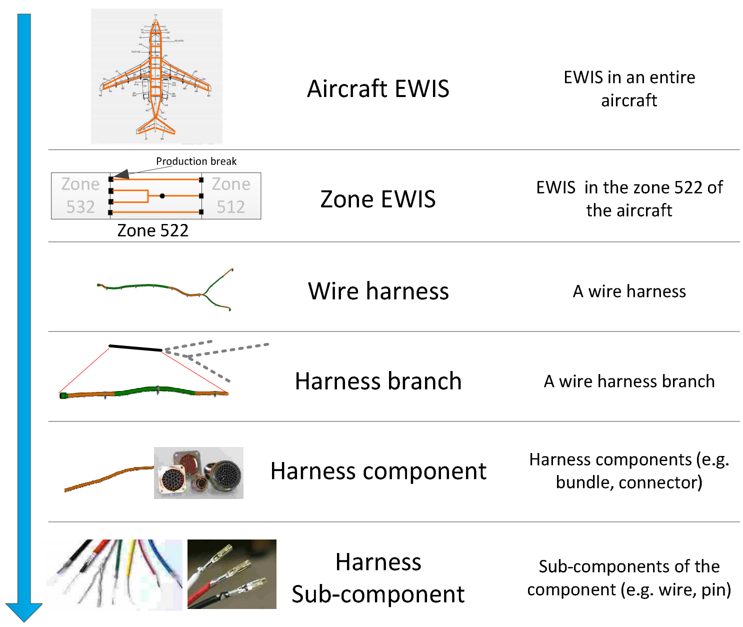


Figure 3: Hierarchical structure of the EWIS

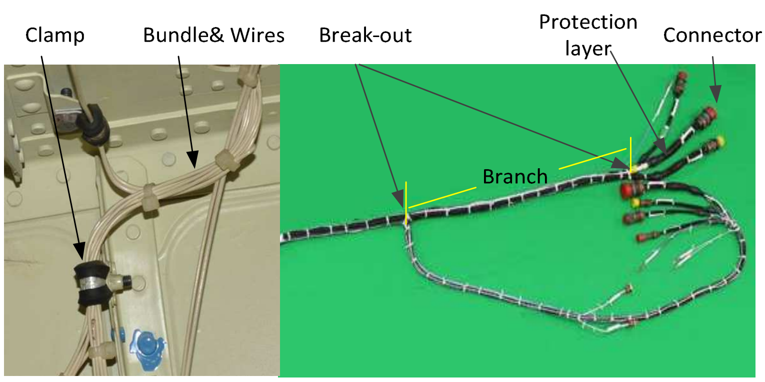


Figure 4: Examples of wire harnesses and their main components

production breaks represent the only interface between the adjacent zones. The production breaks are predefined and generally not modified during the 3D routing process.

Each wiring zone includes one or more harnesses, which connect the production breaks and the pieces of equipment installed in the given zone. Each wire harness is generally divided further into branches, components, and sub-components, as illustrated in the EWIS hierarchy structure shown in Figure 3 and the two annotated examples in Figure 4. A wire harness can contain one or more branches; each branch contains one bundle, and may include one or two connectors, protection layers, and some clamps; each bundle contains one or more wires, where electrical or data signals are transmitted. The points where more branches converge or split into multiple branches on a wire harness are called *break-out* points. When break-outs are present, it means the given harness has multiple origins and/or multiple destinations. As a consequence, a branch is defined as a part of a harness that locates between two break-outs or a break-out and a connector (including the connector).

3.2 The 3D routing rules

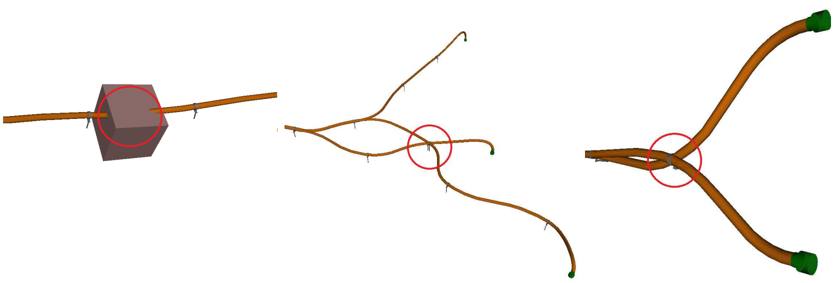
The 3D routing process is constrained by many design rules. Some of these design rules are described in the design specifications issued by the authorities to guarantee the safety of the aircraft; others have been developed by wire harness manufactures themselves, on the basis of experience and best practice. A subset of these rules has been selected in this research to prove the feasibility of the proposed approach for automatic 3D routing. The selected subset is representative of the various categories of rules and does not compromise the scalability of the proposed approach. These include the rules to check allowed bending radii, to check the geometry collision and maintain geometry attraction, for the definition of the clamping system, and for routing in critical wiring zones (in presence of heat sources or high flammability risk). All these rules are discussed in some detail in the following sub-sections.

..3.2.1 Bend radius violation check

A wire bundle or a cable must be bent within its allowed limits to avoid damage. The minimum allowed bend radius of a wire bundle is determined by the product of its diameter and allowed bend radius ratio, namely $\varsigma \times D^{bundle}$. D^{bundle} is the bundle diameter and ς is the allowed bend radius ratio, which mainly depends on the bundle material. The principle to select the bend radius ratio can be found in design specifications MIL-W-5088L[12] and Aircraft EWIS Best Practices[13]. The bend radius violation free of a bundle could be represented by an inequation $r_{min}^{bending} \geq \varsigma \times D^{bundle}$. $r_{min}^{bending}$ is the minimum bend radius of the bundle centre curve.

..3.2.2 Collision checks and geometry attraction rules

When routing wire harnesses inside a wiring zone, it is necessary to check for three types of collisions: 1) collision between the harness and aircraft components, 2) collision between different branches of the same harness, and 3) collision between the given harness and previously generated harnesses. Examples are illustrated in Figure 5. None of these three types of collisions is allowed.



(1) (2) (3)

Figure 5: Examples of three types of collision: (1) between harness and geometry structure, (2) between branches of the same harness, (3) between harnesses in the same wiring zone

During 3D routing, harnesses have to be fixed to the airframe by means of some clamping device (from here on addressed as clamp). Indeed not all airframe components are suitable or allowed to be clamped. For example, wire harnesses cannot be fixed on aircraft systems. Rules are necessary to guarantee only allowable parts are used for clamping. To minimize space occupation, as well as the weight of the clamps, it is convenient to route the harnesses in proximity of the fixable structure (i.e. the structure that allows harnesses to be fixed on). In order to enable such design behaviour, so called *geometry attraction* rules have been implemented in this research.

..3.2.3 Clamping rules

Wire harnesses need to be fixed on the fixable structure at proper values of *fixing* and *clamping distance* (Figure 6). The fixing distance is the distance between the harness centre curve and its fixing structure, measured in correspondence of the clamp. Harnesses must be installed with a sufficient slack to avoid any tension in bundles and wires. However, the fixing distance must be sufficiently large to avoid any contact (hence abrasion) between the slacked harness and the structure. On the other hand, the fixing distance should not be too large in order to limit the size (i.e. the cost and weight) of the clamps, stand-off, and brackets, as well the space occupied by the EWIS. Inside the fuselage, for example, the normal slack value is ½ inch (measured from the bundle centre curve, in between two contiguous clamps). Therefore, the minimum fixing distance which does not lead to chaffing and abrasion can be calculated by the Equation (1). In practice, the actual fixing distance is always larger than this value to guarantee some margin.

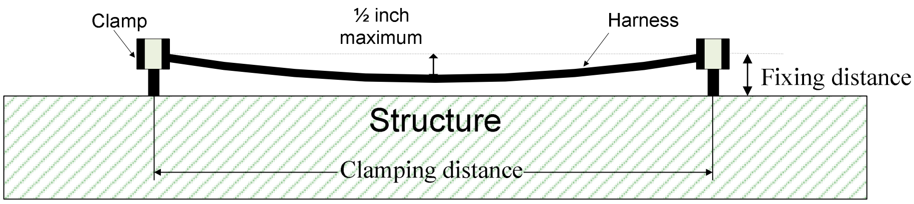


Figure 6: Definition of clamping and fixing distance

$$min\ fixing\ distance = 1/2 inch + harness\ radius \qquad (1)$$

The *clamping distance* is the distance between two adjacent clamping points. In this research, not only clamps but also connectors and break-outs are considered as clamping points. The maximum allowed clamping distance depends on the harness material and the routing environment. For a normal harness routed in a no-vibration zone (e.g. fuselage) this distance is 24 inches. For rigid harnesses this distance is extended to 42 inches [12]. Inside engine mounted wings the clamping distance is smaller due to the engine vibration.

..3.2.4 Grey areas rules

In aircraft, there are lot of hazardous zones, such as humid, hot and vibratory areas. These zones are neither forbidden (i.e. black) nor free (i.e. white) for harnesses to go through. By employing special precautions such as protection covers and extra clamps, harness can be routed in those areas, which are addressed here as *grey areas*. In this research, routing rules have been implemented for hot and flammable zones, which influence the use of bundle protection and clamps respectively.

..3.2.4.1 Hot zones rules

Hot zones are common areas in an aircraft. They are located around high-temperature equipment such as resistors, exhaust stacks, and heating ducts. Harness exposed to high temperature suffers deterioration and deformation. Therefore, it is necessary to 'insulate wires that must run through hot areas with a high-temperature insulation material...'[12]. The extra cost incurred by the use of dedicated protection can be avoided by routing the harness outside these hot zones if applicable, at the cost of a longer harness. It is difficult to predict the most cost efficient solution without a proper simulation.

..3.2.4.2 Flammable zones rules

Areas in the surrounding of flammable fluids or gas pipes are examples of typical flammable zones. An arcing fault caused by broken wires in this area may result in a fire. For wire bundles routed above fluid lines, the design specifications demand that "the clamps should be of compression type and should be spaced so that, assuming a wire break, the broken wire will not contact hydraulic lines, oxygen lines, pneumatic lines, or other equipment whose subsequent failure caused by arcing could cause further damage. [13]" The larger amount of clamps that is necessary to route in these zones affects the total cost and weight of the harnesses. This extra clamping cost can be avoided by routing the harness outside flammable zones, at the cost of a longer harness. Similarly to the earlier mentioned case of hot zone, it is difficult to predict the most cost efficient solution.

4 DESIGN METHODOLOGY FOR AUTOMATIC 3D ROUTING

As anticipated in Section 2, the method proposed in this paper to automate wire harness 3D routing is based on the hypothesis that a routing problem can be solved as an optimization problem. In this case, the objective function is defined as a harness cost function, which depends on the followings parameters:

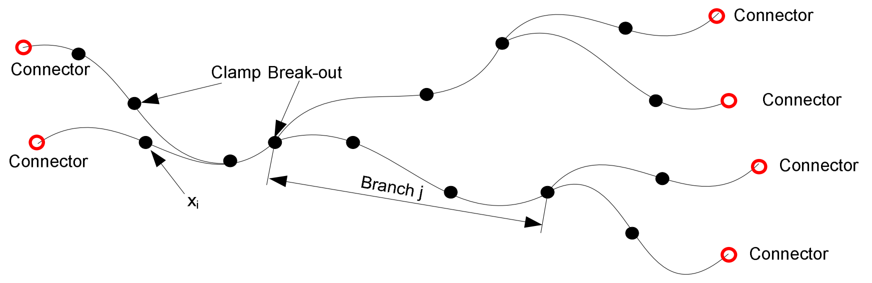


Figure 7: wire harness representation as used for the routing optimization

- The length of the harness, computed as the summation of all the bundles length in the harness branches
- The amount of clamps used to fix the harness on the airframe
- The amount and type of protecting layers used when routing the harness through harsh areas.

The design variables are represented by the coordinates of the clamping points and break-out points of the wire harness (see the black dots in Figure 7). These points work as way-points to route the wire harness inside the aircraft Digital Mock-up (DMU).
The optimization parameters (i.e. the parameters that do not vary during the optimization) are:

- the position of the points where the given harness connect with the harnesses of a contiguous wiring zone (i.e. production breaks) or the receptacles of the various electrical systems
- the bundle diameters, determined by the number and gauge of the wires of this bundle.

The optimization constraints are formulated on the basis of the earlier discussed design rules (i.e. minimum bend radius, maximum clamping distance, and minimum fixing distance). Equation (2) shows the mathematical formulation of this non-linear optimization problem.

$$
\begin{aligned}
&\min_{x} f(x) \\
&f(x) = \sum_{j=1}^{m} f_j(x) = \sum_{j=1}^{m} L_j(x) Co_j(x) \\
&\text{with respect to } x \\
&\text{subject to } C_i(x) \le 0
\end{aligned} \tag{2}
$$

The objective function $f(x)$ is the cost of the entire harness. It is represented by the summation of each branch cost $f_j(x)$, where j is the index of each branch (Figure 7). x is the design variables vector and it represents the clamps and break-out points. These design variables are also the way points to generate the centre curve of bundles. The branch cost $f_j(x)$ is computed as the product of L_j and $Co_j(x)$. L_j is the length of branch j and depends on the design variables x. $Co_j(x)$ is the cost coefficient of branch j and depends on its bundle diameter, the amount of clamping elements, and required protective layers for the grey areas. The coefficient may be different in different routing zone and/or when applying different design specifications. $C_i(x)$ is the constraint function to account for each design rule mentioned before.

4.1 Two-step optimization strategy

The challenge to solve the optimization problem described above is that the number of design variables is not known a priori. Indeed, the number of clamping points is an output of the harness routing process. In order to handle this chicken-and-egg type of problem, a two-step, hybrid optimization strategy has been devised. In the first step, called *Initialization*, a grid of potential clamping points (i.e. the road map) is generated in front of the structural elements where the harness is allowed to attach. Then an optimization approach is applied to route a simplified harness model on such grids. As results of this initialization step, a preliminary routing of the harness is obtained together with the number and position of its way-points (i.e. the number of clamping and break-out points and their coordinates). At this point, being the number of design variables and their initial values known, a second optimization process can be applied. In this second step, called *Optimization*, the actual geometrical model of the wire harness is used, and the design variables are varied by the optimizer in order to minimize the cost objective function, while satisfying all the constraints. These two steps will be elaborated in the next two sections.

4.2 The KBE framework for hybrid optimization

KBE technology has been used to support the two-step optimization process by reading in the geometry of the aircraft (i.e. the routing environment), modelling the cables as b-splines curves, measuring length and bend radii, checking for geometry collisions, and so forth. In practice, a KBE application has been developed (using the commercial KBE system GDL[14]), to take care of all the geometry modelling and querying operations necessary 1) to compute the variable states and the objective function and 2) to evaluate the constraints function during the various optimization iterations.

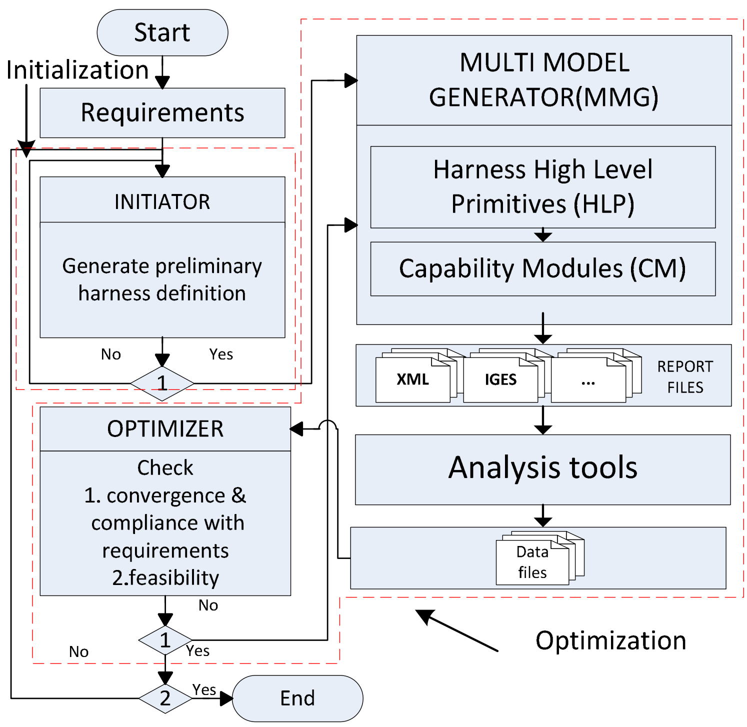


Figure 8: the Harness Design and Engineering Engine (DEE)

The computational framework developed to support the hybrid optimization approach is called Harness Design and Engineering Engine (HDEE) and is based on the DEE concept described in [15-17]. Figure 8 illustrates the four main components of the DEE: the Initiator, the Optimizer, the Multi Model Generator (MMG), and the Analysis tools and their connections. The Initiator is responsible for generating the preliminary harness definition. The Optimizer is in the charge of the systematic exploration of the routing space and convergence checks. The MMG is the component responsible for the generation of the harness geometry model and the extraction from such model of the specific data required for the analysis tools. These analysis tools include modules to calculate the cost of the harness and check whether the harness configuration satisfies the design rules, such as bend radius violation and geometry collision. The first of the two optimization steps, the *Initialization*, is performed by the Initiator block and is discussed in Section 5. The other three blocks are used in the *Optimization* phase, which is described in section 6.

5 3D ROUTING INITIALIZATION

The *initialization* step is responsible for generating a preliminary harness definition, which is then used as starting point for the second *optimization* step. In the initialization phase, a road map-based optimization method is adopted. Similar to a conventional GPS navigation system or a path finding process for computer games[18, 19], this optimization method first builds a road map (e.g. a grid of nodes and connections) and then uses it to find a convenient path for the harnesses. However, typical path finding methods/algorithms, such as those implemented in GPS route planners, are able to find only paths that have one start and one destination point. These methods cannot solve the path finding problem for wire harnesses that have multiple start and destinations (addressed as multi-destination), as the one schematized in Figure 7. In this research, the bi-level optimization strategy is proposed to handle the multi-destination feature.

5.1 The bi-level optimization strategy

The bi-level optimization decomposes the path finding an entire harness into harness (global) level and branch (local) level, as shown in Figure 9. These levels are coordinated by the break-out points. The global level optimization moves the break-out points to different nodes of the road map to explore the routing space. Meanwhile the local, road map based optimization finds the path between adjacent break-outs or between break-out and receptacle and returns the cost of the harness paths to the global optimizer to support its decision for the next iteration. This process iterates until the harness configuration is converged. The generation of the road map and the global and local optimization processes are detailed below.

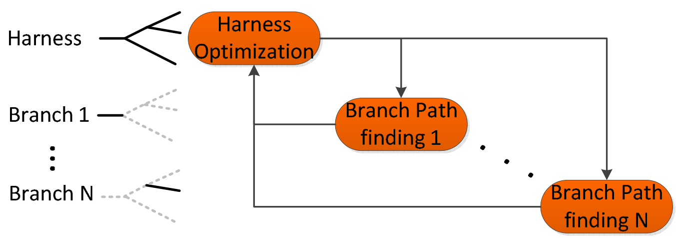


Figure 9: Architecture of the bi-level path finding method

5.2 Road map generation: routing environment discretization

The routing road map is a discretization of the 3D routing space. It is built in 3 steps (Figure 10):

1. *Offset surfaces generation*. In this step, the fixable surfaces of the aircraft DMU are used to generate a set of offset surfaces. The non-fixable surfaces in DMU, such as those of pipes or other system where it is not possible to fix wire harnesses, are excluded. The offset distance is determined by the fixing distance value, which was discussed in Section 3.2.4.
2. *Offset surfaces tessellation*. In this second step the offset surfaces are tessellated into triangles. The tessellation size, i.e. the distance between adjacent nodes in the tessellation, is fixed on the basis of the clamping distance value discussed in Section 3.2.4.
3. *Tessellated surfaces merge.* In this third step, the nodes on the adjacent tessellated surfaces are connected in order to generate one continuous 3D road map in front of the fixable structure. In this step, the geometry collision and clamping distance are considered for all edges of the map. If an edge collide with a geometry component or is longer than the allowed clamping distance, this edge will be excluded from the final 3D road map.

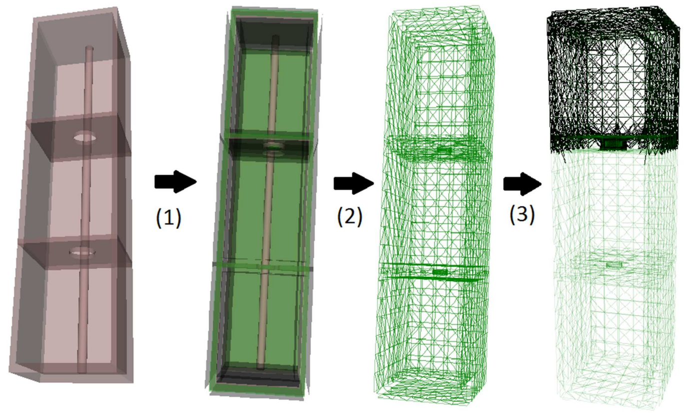


Figure 10: The 3 steps to generate the harness road map (1) Offset; (2) Tessellation; (3) Map generation

Once the road map is generated, it will be possible to proceed with the preliminary 3D routing. Each node on the map will be used as potential clamping point, and any wire harness branch will be defined as a poly-line built by chaining contiguous edge elements in the road map.
Attributes are assigned to the various edge elements of the road map to store information about the length of the given edge, and specific coefficient values to account for their presence in a certain harsh environment area (the grey zones discussed in Section 3.2.5). The cost coefficients to account for the number of required clamps and the need of protection cover on each edge of the road map might differ according to the grey zone(s) crossed by the given edge.

5.3 Local level optimization

A* algorithm [20] is adopted to handle the local level optimization. This optimization algorithm is able to find the optimum path between two given points, addressed as source node and destination node, without knowing a priori the number of design variables. The special A* algorithm used in this research differs from other A* algorithms in the two following aspects.

..5.3.1 Cost calculation method:

A* algorithm uses cost function $f(n) = g(n) + h(n)$ to evaluate the cost of the traversed nodes aiming to find the optimum path. Each of the nodes is addressed as n when it is evaluated. $g(n)$ is the movement cost from the source node to the current node n. $h(n)$ is an estimated movement cost from current node n to the destination node. The movement cost is generally represented by a distance. The cost of a harness branch is the product of the harness length and the unit length cost. The calculation method is shown in Equation (3). The unit length cost consists of three parts: the unit length cost of the bundle Cob; the unit length cost of the clamp Coc; and the unit length cost of the protection covering Cop.

$$\begin{aligned}
& f(r_{bundle}, p_u, D, C_m, C_i L, D_{clamp}, coe_{covering}, th_{cover}) \\
& = LCo = L(Cob + Coc + Cop) \\
& = L(\pi r_{bundle}{}^2 p_u D + \frac{(C_m + C_i)}{D_{clamp}} + coe_{covering} \pi p_u D(2 r_{bundle} th_{cover} + th_{cover}{}^2))
\end{aligned} \tag{3}$$

L : length of bundle; the summation of the length of road map edges

r_{bundle} : the radius of bundle cross section

p_u : unit price

D : density of bundle

D_{clamp} : clamping distance

C_m, C_i : material cost and installation cost of a clamp

$Coe_{covering}$: cost coefficient of bundle covering, representing different covering materials

th_{cover} : thickness of bundle covering

When calculating $g(n)$, the actual value of the parameters will be used. When calculating the heuristic value $h(n)$, the maximum clamping distance and cost coefficient of covering in the non-grey area will be used to keep the Admissibility[20] (i.e. making sure it could find out the optimum path) of the algorithm.

..5.3.2 Bend radius check

During the implementation of the A* algorithm, the Curve Segment Bend Radius Pre-Calculation (CSBPC) approach is used to check harness bend radius violations. This approach uses the current node n, the previous adjacent node $n-1$ and the next adjacent node $n+1$ to generate a fitted curve (see Figure 11). At the start and end points the approach uses the vectors of the two points to build two auxiliary nodes $n-1$ and $n+1$ respectively since these two nodes do not exist. Then it uses the minimum radius of this fitted curve to represent the minimum bend radius of the harness centre curve to check, by means of a bend radius violation check function, whether the next node $n+1$ is suitable for the harness. The check starts from the start point and continues until the target point is found that it has minimum cost on $f(n)$ and does not violate the minimum bend radius condition.

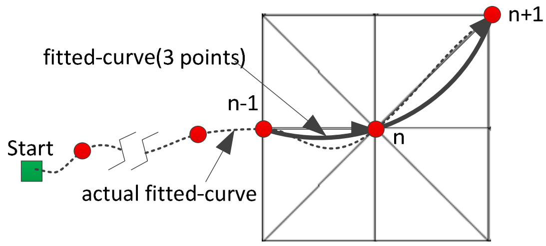


Figure 11: The minimum bend radius check in the Initialization

5.4 Global level optimization

The objective function for the global level optimization is defined as the summation of all branches cost. See Equation (4).

$$f(x)=\sum_{j=1}^{N_b} f_j(x) \qquad (4)$$

Here, f_j is the cost of the harness' branch j. N_b is the total number of branches and is determined by the number of connectors. The vector x contains the design variables of the global level optimization, which are the harness break-outs position.

The global level optimization uses the Hill Climbing algorithm [21, 22]. The algorithm moves each break-out to new locations on its adjacent nodes of the road map. At the same time it evaluates the cost function and finds out the best combination from the set. If the best one is better than the benchmark in terms of objective function, this value will be set as the new benchmark and this design variables combination (i.e. this new collocation of the break-outs) will be accepted. The accepted design variables will be used as start position in the next loop. This process iterates until no further improvements can be found. An intermediate state in the harness Initialization process is shown in Figure 12.

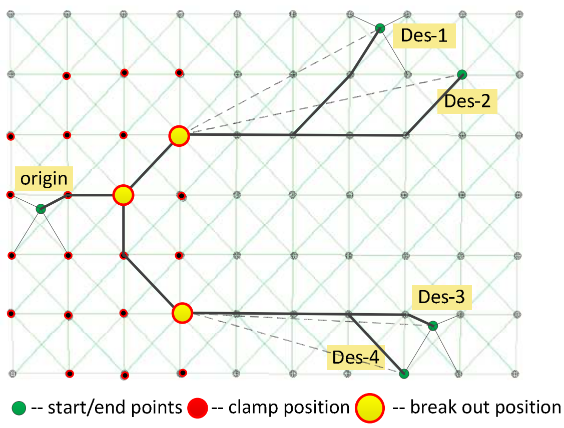


Figure 12: An intermediate iteration step of harness Initialization

6 HARNESS 3D ROUTING OPTIMIZATION

After the generation of the preliminary harness definition, the Optimization phase can start, with the clamping points and break-out positions as design variables. The Optimization is in charge of refining the position of clamps and break-outs (but not their number!) to solve the limitations of the

Initialization, namely, to eliminate the violations of some design rules and to optimize the preliminary harness routing even further.

6.1 Limitations of the Initialization step

The preliminary harness routing performed in the Initialization step by means of the road map has a number of limitations, which generally prevent achieving not only an optimal wire harness routing, but even a feasible solution.

..6.1.1 Inter-harness and inner-harness geometry collision

A wiring zone contains some harnesses. The path finding in Initialization is implemented on each harness individually, without considering the presence of other harnesses. Hence, in some cases, different harnesses may share the same edge and/or vertex of the road map, which means geometry collision between different harnesses. Different branches of the same harness may also have the similar problem.

..6.1.2 Geometry collision between harness and geometry components

In the Initialization, a wire harness is defined as a polyline chaining a number of edges of the road map. In reality, the wire harness is not a line but a kind of pipe with a certain diameter. Its centre line is not a polyline but a spline curve fitting the nodes of the polyline generated by the Initialization. As a consequence, when generating the actual geometry of the wire harness starting from the polyline produced by the Initialization, geometry collision between harness and aircraft DMU components may occur.

..6.1.3 Bend radius violation

In the Initialization, CSBPC method is applied to exclude some extreme bend radius violation solutions. This method uses the minimum bend radius of the curve generated with three adjacent nodes to represent the minimum bend radius of the actual harness to carry out the violation check. This method cannot guarantee these two minimum bend radix are the same. It also cannot guarantee a bend-radius-violation-free solution for an entire harness.

..6.1.4 Non-optimum result

In the Initialization, the bi-level optimization method finds out the optimum harness in terms of the road map based problem definition. The road map limits the harness to the edges of the map. Therefore the so-called optimum harness in the Initialization might not be the optimum result in terms of the original problem definition and it could be optimized further to get a better result.

6.2 Optimization approach in the Optimization phase

The previous mentioned limitations make the result of the Initialization only a preliminary harness definition. In the Optimization phase to finalize the path finding a more conventional optimization process is used to move the position of break-outs and clamping points (i.e. the design variables) freely in the routing space. The architecture of this optimization framework is illustrated in Figure 13.
The initial values of the design variables x_0 are the Initialization outputs. These values are sent by the Initiator to the harness MMG. The harness MMG makes use of a predefined set of parametric harness components, called High Level Primitives (HLP), to build actual geometry models of the wire harness according to the input design variables. Other specific modules in the MMG, called Capability Modules (CMs), extract from the harness geometry model the specific set of data z_i required by the HDEE analysis tools. These analysis tools include modules to calculate the cost of the harness and to check the violation of the design rules. The analysis tools results f and C_i are sent back to the optimizer to support the decision making for next iterations.

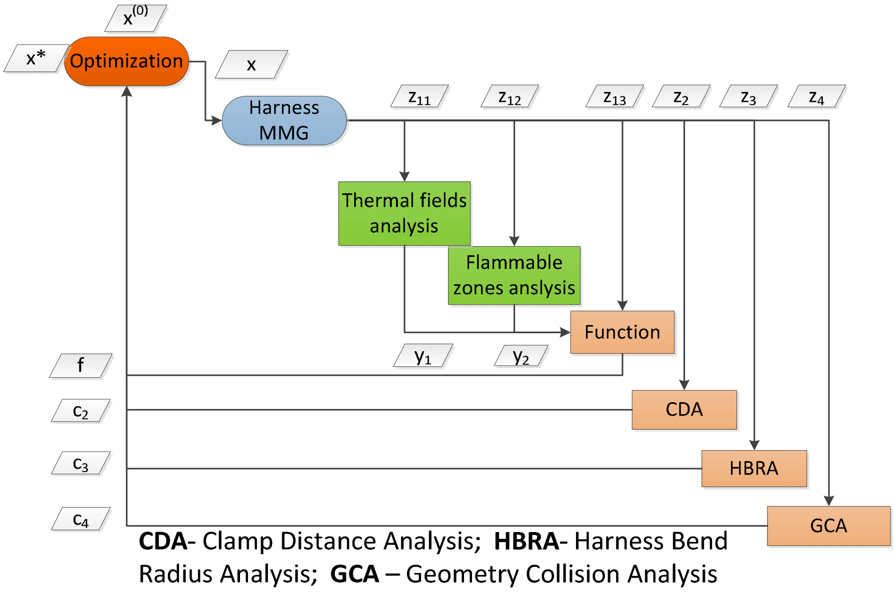


Figure 13: The framework of harness design optimization

The Generalized Pattern Search (GPS)[23] is selected as the optimization algorithm. This algorithm, also known as black-box search, is gradient-free. It is able to handle the Boolean output of some analysis tools, such as the geometry collision check tool. This algorithm carefully moves the design variables to new position to get new harness configurations. This feature is very useful since the Initialization already generates a promising harness definition. The algorithm moves the design variable x_i one by one to $x_i \pm \Delta x$ to get new harness configurations. The time complexity of the algorithm on the number of design variables is $O(n)$. This feature keeps the calculation efficiency linear to the complexity of the harness, i.e. the number of clamps and break-outs.

Since the pattern search is not able to handle the design constraints, the objective function is modified and shown in Equation (5).

$$\begin{aligned} &\min_x \theta(x) \\ &\theta(x) = f(x) + c_{clamp}(x) + c_{bend}(x) + c_{geometry}(x) \\ &\textit{with respect to } x \end{aligned} \tag{5}$$

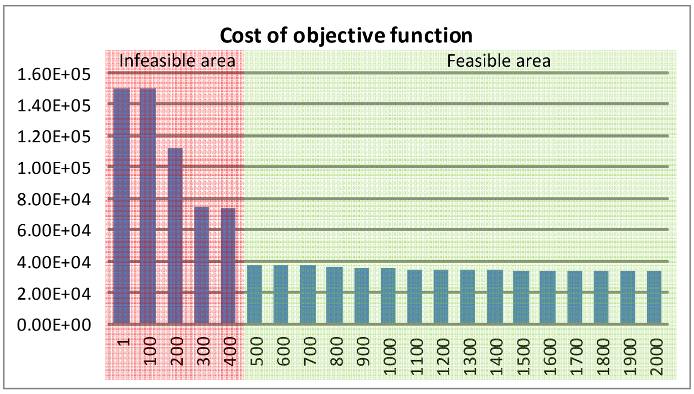


Figure 14: The decrease trend of the cost function

The constraint functions are accounted as penalty in the objective function. The penalty value associated with each constraint violation is very high. Therefore the optimizer will endeavour to eliminate them first. An example change of cost function $\theta(x)$ is shown in Figure 14. The preliminary harness configuration of this example has three constraint violations: 1) bend radius violation, 2) geometry collision between two branches and 3) geometry collision between harness and the routing environment. With the progress of the optimization, the optimizer moves the design variables to eliminate the constraints gradually. The elimination of constraint violation makes $\theta(x)$ drops steeply. While the optimization reaches the feasible area, the constraints part of $\theta(x)$ equals to 0. $\theta(x)$ becomes the original objective function $f(x)$.

The optimization continues until one of the following stop scenarios is met.

1) If n<N & converged, then STOP   Feasible solution
2) If n=N & not converged, then STOP   Feasible solution
3) If n=N & not converged, then STOP   Infeasible solution
4) If n<N & converged, then STOP   Infeasible solution

Here, n is the total number of iteration and N is the maximum allowed number of iterations.
This optimization is implemented per harness. However, the geometry collision between more harnesses is solved by adding the previously routed harness to the geometry component list of the routing environment.

7 RESULTS

The proposed method has been successfully implemented into a demonstrator software application, the HDEE, and several test cases have been executed to validate the system functionality. These tests have demonstrated that the tool is capable of handling cases of representative complexity and design constraints and deliver 3D models of routed harnesses in full automation. When changes are enforced either in the routing environment or in the definition of the electrical system, the optimization process can be run again to efficiently account for any modification. Figure 15 shows the result of the automatic 3D routing of a few wire harnesses in two fuselage sections. Figure 16 presents the capability of the tool to handle different design constraints. Figure 17 demostrates that the tool is able to update the routing result when the routing environment is changed.

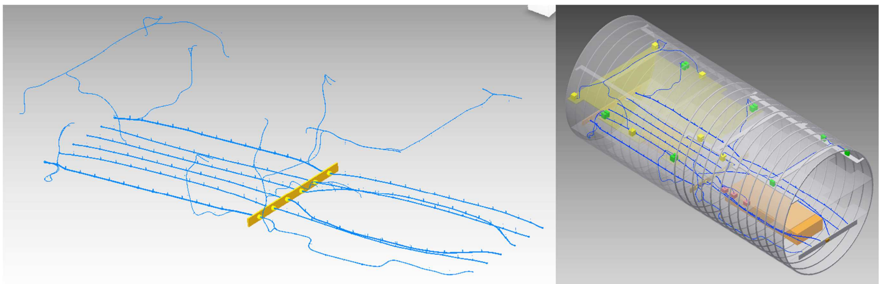


Figure 15: The view of wire harnesses, independently (left) and in fuselage routing environment (right)

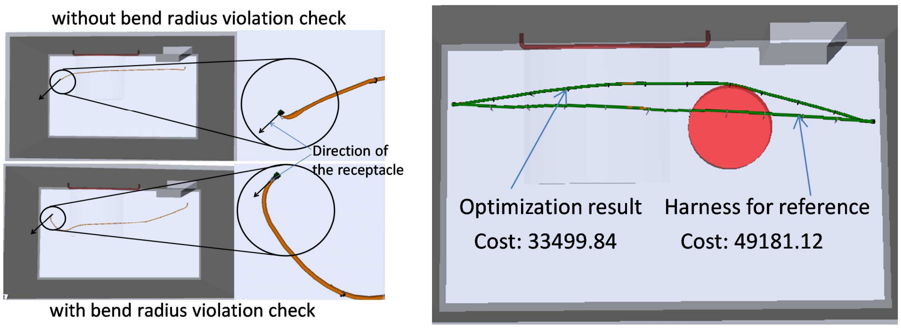


Figure 16: Capability to handle the bend radius violation (left) and hot zone (right)

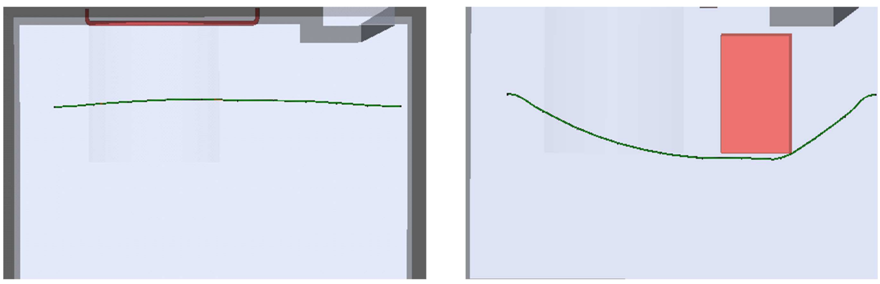


Figure 17: update the routing result when a geometry obstacle occurs

The geometry of the test environment was generated on purpose using a commercial CAD product and used as input to the HDEE for automatic 3D routing system. The harness models generated by the HDEE are fit to be re-imported in the CAD system.

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