

A KBE Application for Automatic Aircraft Wire Harness Routing

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Wire harness design is an increasingly complex task. Knowledge Based Engineering (KBE) and optimization techniques can be used to support designers in handling this complexity. The wire harness design process can be divided in three main parts, namely electrical design, configuration design and geometrical routing. This paper describes the latest progress in the development of a KBE application aiming at the automation of the routing phase. Discrete optimization techniques are used to design shortest path harnesses, while complying with different type of constraints. Some preliminary results have been presented in a previous paper, where only geometrical constraints were addressed. However, wire harness design is affected also by other types of rules and constraints, which need to be accounted to obtain more realistic design results from the optimization process. This paper describes some new developments in the routing application to account for the presence of critical zones inside the aircraft. As study case, the presence of heat sources inside the airframe is considered, which either force the harness to be routed elsewhere, or require the use of wire protections, with obvious consequences on weight and manufacturing. First, some mathematic transformation techniques are used to model the presence of heat sources inside the routing environment. Then the A* algorithm is used for compute the 3D routing, aiming at minimum wire harness weight. The main architecture of the routing application is presented and its functionality is demonstrated with samples of wire harness routing inside a wing. The results show that the proposed KBE application can automate the routing of wire harness while taking into account different rules and constraints. The modeling approach for a heat source can be generalized and extended to address other criticality such as abrasion, electromagnetic interference, corrosion, etc. The achieved level of automation relieves designers from the repetitive work associated with the frequent changes affecting the design environment.

Nomenclature

f_{AB}	=	Cost between point A and B
d_{AB}	=	Distance between point A and B
κ	=	Cost coefficient of cube
μ	=	Linear density
$f(n)$	=	Cost of current state n
$g(n)$	=	Movement cost between start state and current state n
$h(n)$	=	Estimated movement cost between current state n and end state
T	=	Temperature
t	=	Time
Q	=	Heat conduction power
L	=	Thickness of rib

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- λ = Thermal conductivity
 r = Radius
 δ = Protection type coefficient

I. Introduction

A. Background

The design of wire harnesses for aircraft is becoming more and more complex. The complexity is associated with the increase in number of on-board electrical and electronic systems and with the increasing number of constraints associated with electromagnetic interference, corrosion, abrasion, degradation, installability, maintainability and so on. However, despite its technical challenges and many improvement opportunities, wire harness design has received only minor academic attention. Even in industry, the design of wire harness is often considered an activity of secondary importance and is associated with the end of product development cycle^[1].

Reality is quite different. Wire harnesses form one of the most complicated aircraft systems comprising hundreds of cables and thousands of wires. The complexity of wire harnesses increases with the complexity of the systems they connect. An aircraft such as the A380 accommodates 530km of cables, 100,000 wires and 40,300 connectors^[2]. This huge number of harnesses has to be routed inside a relatively narrow space, while accounting for the room reserved for cargo, passenger and equipment. Figure 1^[3] illustrates a small part of wire harness system in the Airbus A380.

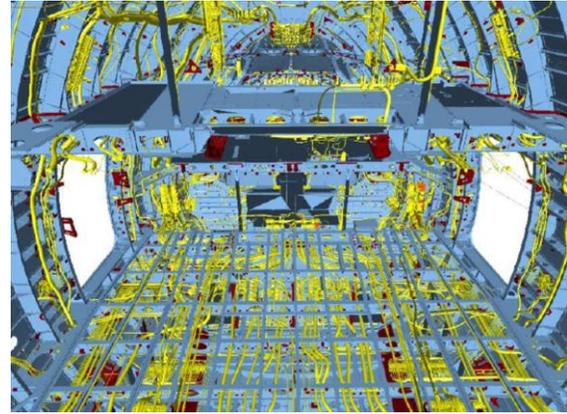


Figure 1. Wire harness systems in A380

Wire harness design process is subject to a large number of requirements, rules and regulations addressing mechanical, electrical, and structural issues. Managing the related amount of information presents a significant challenge for electrical wire harness engineers. Also the production of wire harnesses is a rather complex and very labor intensive process. This is in clear contrast with present demand for short time to market and low cost manufacture. Eventually, such complexity makes wire harnesses design error prone, with consequences as dramatic as months of delay in the schedule of an aircraft almost ready for delivery program^[4]. On the other hand, the process is very much rule based and therefore a good case for automation using knowledge engineering techniques. Automation of the process can help to improve the design quality. Knowledge Based Engineering (KBE) and Multi-disciplinary Design Optimization (MDO) are two technologies that can be used for such automation.

KBE can be defined as engineering with the use of a special class of software tools called KBE systems. These KBE systems come with associated engineering methods and methodologies, and allow engineers to capture and reuse product and process engineering knowledge. The wire harness design problem is characterized by a high number of constraints originating from different disciplinary areas that have been established over the past decades. The underlying knowledge of experienced engineers and their handbooks can be captured and re-used in a KBE tool. In many cases an iterative search is necessary to find a route. To this purpose, the inclusion of a proper optimizer can automate the exploration of the design domain.

The design process of wire harnesses can be divided in three phases: electrical design, configuration design and geometrical routing^[5]. The research work presented in this paper specifically addresses the 3D routing of wire harnesses, which belongs to third and last phase. The outcomes of the first two phases, such as connectivity requirements, electrical diagram and rules for recomputing the wire^[5], are considered to be available as input for the routing.

The geometry routing phase is used to transfer the electrical diagram into physical 3D paths in the aircraft. The output of this phase includes both a geometry representation of these paths, as well as sets of properties for the various wire harnesses. This step is very labor intensive and subject to many design changes as well. Indeed, the harness route is generally dominated by the position of the airframe components, the installation of the various aircraft systems and the applying domain rules, such as , protection of corrosion, electro-magnetic interference, bend radius and clamping. As a consequence, any designed route has to be checked and possibly modified for any design change in these areas. Such complexity makes wire harness routing not only repetitive but also error prone.

B. Previous work

The work described in this paper is the extension and further development of the optimization approach presented by the authors in reference [6]. The proposed approach was based on the use of a discrete optimization method to generate minimum length wire harness paths and is summarized in this section. As a first step, the continuous representation of the aircraft structure (i.e., of the geometrical environment where the wire harnesses must be routed) is discretized and represented by a set of small cubes (see Figure 2). Based on the size of the given airframe geometrical model, a boundary box is generated and filled with a set of uniform cubes. The left, front, bottom corner of the boundary box is set as origin of the routing coordinate system, i.e. (0,0,0). The number of cubes in the boundary box is a user defined parameter and affects both the accuracy and computation cost of the model. The length of each cube edge is normalized, such that each cube has size $1 \times 1 \times 1$ and can be represented with one set of coordinates, for instance (1,2,3). This operation simplifies the optimization process, while the actual size of the wire harness path is re-computed in the actual reference system during post processing.

In parallel with the boundary box discretization, the geometry model of the given aircraft airframe (or a part of it) is meshed using a commercial grid generation tool. For the current research, ICEM CFD by ANSYS is used to mesh the surfaces of the various airframe components. Then, the coordinates of the grid nodes are extracted from the mesh file and used to rebuild the geometry of the airframe inside the discretized boundary box. In Figure 3, the colored cubes inside the boundary box indicate the structure of aircraft and are treated as geometrical obstacles (hence impossible to go through) during the automated wire harness routing process. The non-colored cubes in Figure 3 represent the free space in the routing environment.

The implemented optimization approach is based on the evaluation of a cost function in each cube. The cost of wire harness going through free space is evaluated as the product of the distance between start and end point and the cost coefficient of this space. Equation (1) shows the method used to calculate the cost of routing a wire harness between point A and B, as represented in Figure 2.

$$f_{AB} = d_{AB} \cdot \kappa_0 = d_{AB} \cdot 1 = d_{AB} \quad (1)$$

The routing cost between point A and B is represented by f_{AB} while, d_{AB} is the distance between point A and B and κ_0 is a cost coefficient to account for the geometry constraints. This cost coefficient is a property of each cube and represents the cost of a wire harness going through the given cube using the Manhattan method^[7] divided by a unit cost. The cost coefficient of a cube in free space is equal to one, such that the cost of routing a wire harness from A to B depends only on the travelled distance. The cost coefficient of those cubes representing physical obstacle areas, is set to infinite, such that it becomes impossible for the given wire harness go through the airframe.

The A* algorithm^[8] is used to get optimal 3D routing solutions. The projection headings of wire harnesses are artificially constrained to 0, 45 and 90 degree, which is the result of a tradeoff between computation cost and realistic path routing. A KBE tool, Genworks GDL^[9] which is an extension of Common Lisp, is adopted for development of the routing application.

According to the given airframe geometry and the definition of the harness start and end point, the previously developed application was able to generate an optimal 3D routing path, using the path length as objective function. In case of any modification of the routing environment, the application was taking care of updating the models and computes a new optimal solution. Figure 4 shows an example of minimum path length routing inside a wing.

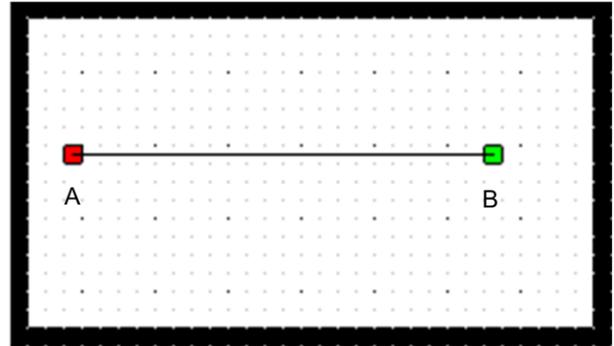


Figure 2. Harness routing in free space

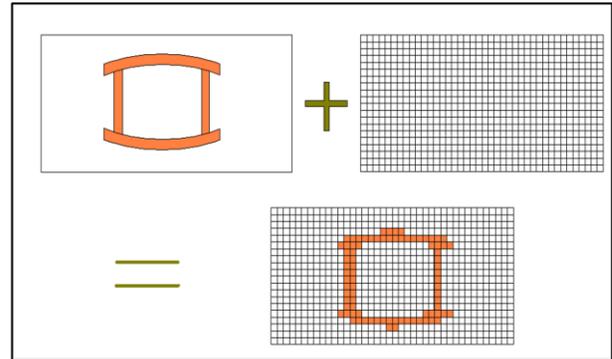
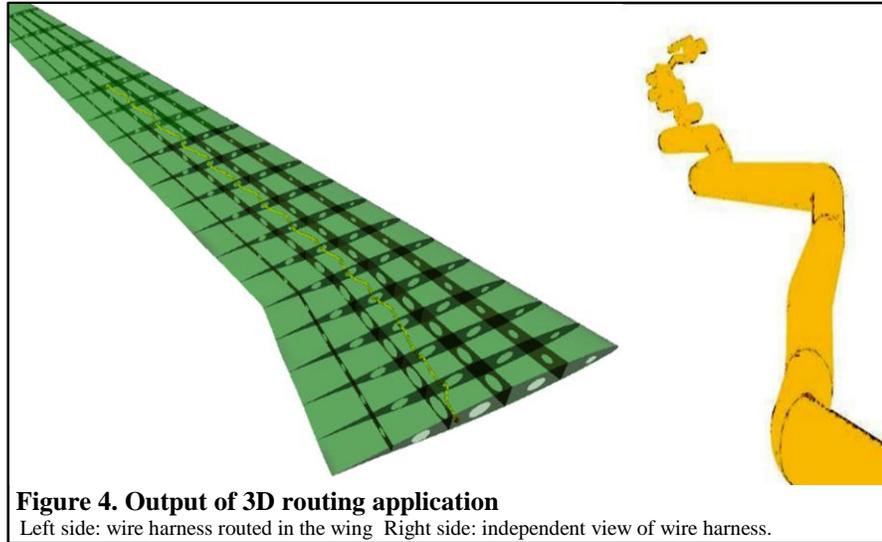


Figure 3. Discretization of routing environment



C. Motivation of current work

The complexity of the wire harness routing environment inside an aircraft is not only depending on the presence of physical obstacles. During design process, engineers have to handle lots of areas which are prohibited or restricted for wire harness to go through. These are dominated by domain rules such as protection of corrosion, protection of abrasion, protection of degradation, and electro-magnetic interference. Furthermore, the routing process must respect constraints on harness bend radii and clamping.

Abrasion, corrosion and degradation of wire harness are mainly caused by vibration, chemical attack and high temperature. According to design specification, the wire harness needs protection while going through these areas, which typically results in the increase of the wire harness total weight. Figure 5^[10] shows the application of abrasion protection to a wire harness.

In this research, a similar approach has been identified to tackle the problem of routing harnesses in different critical areas that require the use of some form of protection, such as sleeves against corrosion and abrasion. Accounting for the presence of critical zones, next to the physical constraints, would allow the optimization algorithm to obtain more realistic solutions. To this purpose, the routing method proposed in reference [6] has been modified and minimum wire harness weight has been selected as new objective function for the optimization.

The adapted KBE application is described in the next sections, where the mathematical transformations implemented to model a critical area in the routing environment and the required modifications to the cost function definition are thoroughly discussed. The functionality of this application is demonstrated with a case study of wire harness routing in presence of heat sources.

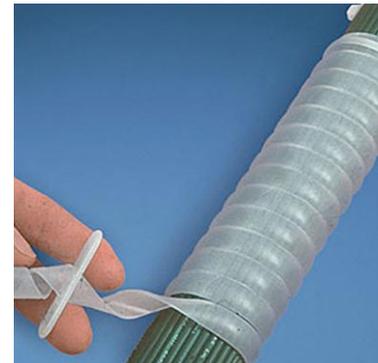


Figure 5. Protection of abrasion

II. Implementation of automatic wire harness routing

In order to generate realistic wire harness routings, next to the presence of physical constraints such as structural components, it is necessary to account for the presence of certain critical areas, which would demand re-routing the given harness through a longer path and/or the use of costly (in terms of weight and manufacturing) protections. As concept demonstrator, a hot zone has been chosen to demonstrate the implemented strategy of harness routing across critical areas.

A. Routing issue

Hot zone generally exists inside the aircraft routing environment due to presence of high temperature equipment. A typical design guideline extracted from military specifications^[11] is the following: “Wiring shall be kept separate from high-temperature equipment, such as resistors, exhaust stacks, heating ducts and de-icers, to prevent insulation deterioration”. In general, bypassing these areas leads to longer, more complicated and heavier harnesses. Besides weight and balance problem, the total cost of the harness can increase, both because of the extra used material (longer cables, more connectors, etc.) and the increased installation workload.

On the other hand, one should evaluate the convenience of increasing the level of protection for a given wire harness such to avoid long detours around critical areas. “Wiring shall be supported to meet the following requirements: prevent arcing or overheated wiring from causing damage...”^[11]. Indeed, tapes, jackets, sleeves, conduits, etc. are generally employed to provide extra cable protection. Obviously, these solutions might raise the total weight and manufacturing cost of wiring system. Performing an adequate tradeoff between, for example, the installation of a short cable with extra protection and a longer cable without protection is a real challenge for wire harness design engineers.

A proper combination of KBE and MDO could offer designers the required decision support.

B. Mathematic transformation

In order to evaluate the cost of routing a given harness through a hot zone, it is necessary to “transform” the hot zone into a discrete mathematical expression, compatible with the routing environment modeling introduced in I.B. As a first step, equation (2) is used to model the temperature field around a high temperature device, where T is the temperature, t is time and x, y, z are the coordinates of a given point. In our research, the temperature field is

assumed to be stable, so $\frac{\partial T}{\partial t} = 0$.

$$T = T(x, y, z, t) \quad (2)$$

Then, the continuous temperature field is discretized, using a similar method to the geometrical transformation described above for the airframe. A new boundary box is positioned around the given heat source and filled with a set of uniform cubes. After that, each cube is assigned a temperature value, according to its position with respect to the heat source. Then, an empirical equation is adopted to calculate $\kappa_T(T)$, which is the temperature-specific cost coefficient for each cube in a given heat source boundary box. As a matter of fact, different temperature-specific coefficients can be defined for cables that feature different heat protections. This equation is various for there are tens of thousands of cable protections with different density and weight can be chosen for similar protection.

In this research, equation (3) is used to calculate the cost coefficient component of a high temperature source in the form of a linear penalty function. In different cases, such as different heat source or different critical zone different equations can be used to get the cost coefficient value. The form and parameter of equations come from the knowledge of experienced domain engineers. In equation(3), $\kappa_T(T)$ is the temperature-specific cost coefficient, T is the temperature and δ is a coefficient which depends on the type of protection locally applied to the harness.

$$\kappa_T(T) = \delta \cdot (T - 20) \quad (3)$$

Finally, the discrete fields defined around each heat source are mapped on the cubes of the original routing environment boundary box, where the physical constraints were initially defined. The total cost coefficient κ_{tot} of each cube is then computed as the summation of the geometry component κ_0 (defined in part I.B) and temperature component $\kappa_T(T)$, as shown in equation(4).

$$\kappa_{tot} = \kappa_0 + \kappa_T(T) \quad (4)$$

C. Routing environment

By means of the discretization approach described above, both hot zones and structural components are modeled using one set of cubes with various cost coefficients. Figure 6 shows an outcome of the above transformation. The white cube imply the absence of any sort of obstacle or criticality, the black cubes are used to represent the presence of a geometry constrain. The gray cubes represent hot zones with different level of temperature (or critical zone in general, according to type of modeled critical area). Darker tones of grays are used to indicate higher cost coefficients.

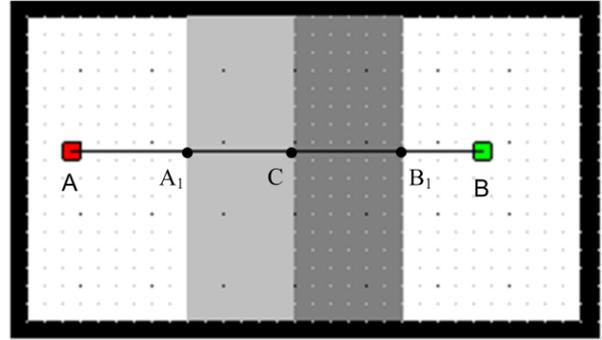


Figure 6. Harness routing in free and gray spaces

Routing in this environment is different from the simple case of Figure 2. Harness routing in free space. The cost function of routing a given wire harness from A to B is now computed as the summation of various sub costs. Equation (5) is used to calculate the cost function for the example case illustrated in Figure 6.

$$\begin{aligned} f_{AB} &= \sum d_i \cdot \kappa_i \cdot \mu_i = d_{AA_1} \cdot \kappa_{AA_1} \cdot \mu_{AA_1} + d_{A_1C} \cdot \kappa_{A_1C} \cdot \mu_{A_1C} + d_{CB_1} \cdot \kappa_{CB_1} \cdot \mu_{CB_1} + d_{B_1B} \cdot \kappa_{B_1B} \cdot \mu_{B_1B} \\ &= \left((d_{AA_1} \cdot \mu_{AA_1} + d_{B_1B} \cdot \mu_{B_1B}) \cdot 1 + d_{A_1C} \cdot \mu_{A_1C} \cdot \kappa_{A_1C} + d_{CB_1} \cdot \mu_{CB_1} \cdot \kappa_{CB_1} \right) \end{aligned} \quad (5)$$

d_i is the length of the wire harness segment passing through the zone i where the total cost coefficient is equal to κ_i . In one type of gray area, the total cost coefficient of each cube is the same. It equals to 1 in the free area. The coefficients μ_i represent the linear weight density of the wire harness segments. It follows that the cost function f_{AB} represents the total weight of a harness routed between point A and B.

D. Routing algorithm

A* is still used as searching algorithm. The evaluation function $f(n)$ of A* is represented below.

$$f(n) = g(n) + h(n) \quad (6)$$

Here, n is the current state, and $g(n)$ is the cost to go from the initial state to the current state n . $h(n)$ is an estimated cost of moving from current state to the destination state. In 3D routing applications, the initial state means that node n is located on start position and the destination state indicates that node n has already moved to the goal position.

From the initial state, a lot of function $f(n)$ evaluations are computed to reach the destination state. With a suitable heuristic value of $h(n)$, A* can surely find an optimal solution if it exists. This property is named after admissibility^[12]. If A* has admissibility, the cost of the evaluation function $f(n)$ never decreases in any descendant states. This property of A* is called monotonicity^[12]. In A* algorithm, $h(n)$ is introduced to describe the heuristic information. In order to evaluate the heuristic ability, the concept of informedness is adopted. Informedness is a property which is obtained comparing two heuristics and determining the optimal path^[12]. When considering two A* algorithms, with different heuristic information for the same searching problem, if $h_1(n) \leq h_2(n)$, then $h_2(n)$ is acknowledged to have more information than $h_1(n)$ (i.e., its level of informedness is higher) .

The method to calculate the total cost $f(n)$ for the routing environment described in Section C, is actually the same as the one used for the simpler case of I.B, apart from the fact that the linear density of the harness μ is now included (It should be noted that, for this research, the linear density of a given wire harness is considered uniform, i.e. the μ value of different wire harness segments are the same). In the end, the increases wire harness mass due to the use of certain (heat) protections is accounted by introducing the new $\kappa_T(T)$ cost coefficient, without changing the searching algorithm properties described above.

The movement cost $g(n)$ is equal to the summation of the cost of each cube between the start point and the current node. The heuristic value $h(n)$ is equal to the estimated distance multiplied by the linear density coefficient. Because of the new cost coefficient to account for the hot zone cubes, the heuristic value used in above method does not take advantage of full heuristic information and may lead to a longer searching time. However, with admissibility, also this method guarantees an optimal solution, and takes less time for heuristic value calculation.

E. Automatic wire harness routing application

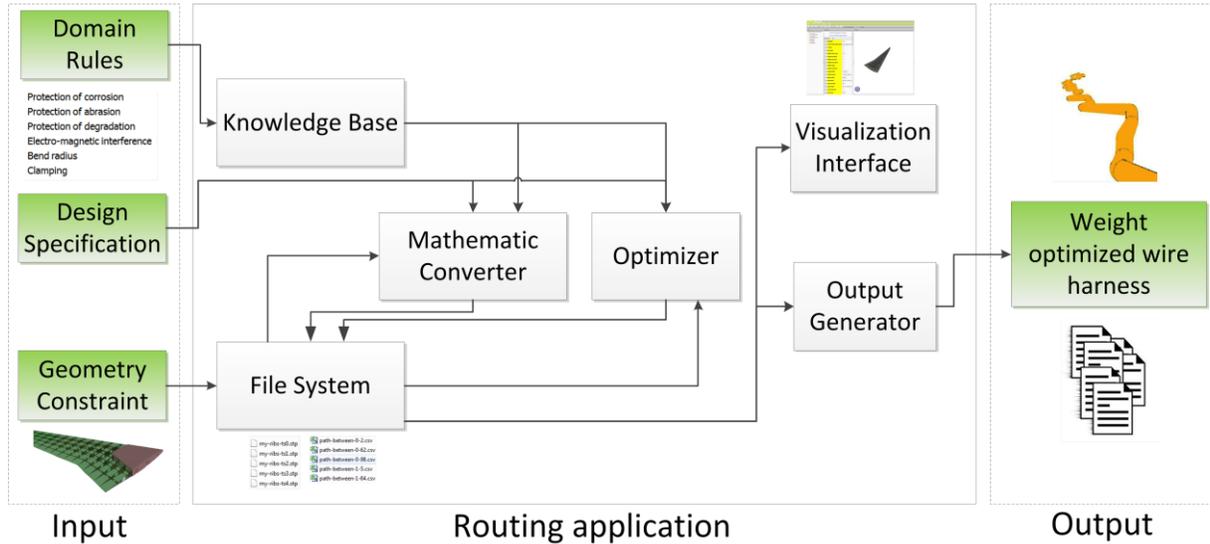


Figure 7. Automatic wire harness routing application

On the basis of the method described above, an improved routing application is currently under development, whose main structure is illustrated in Figure 7. The inputs of the application consist of the design specification, the geometry constraint and a set of domain rules. The design specification provides explicit information about the requirements for wire harness and how the wire harness is routed. The geometry constraint is actually the geometry model of the airframe where the given harnesses must be routed. It includes the definition of both structural components and installed systems. The domain rules are a series of recommended wire harness design guidelines from different disciplines. They are not specific guidelines for wire harness design in a certain vehicle but general requirements, such as (GSFC: GSFC-733-HARN-01, *DESIGN AND MANUFACTURING STANDARD for ELECTRICAL HARNESSSES*) of NASA, (*MIL-W-5088L MILITARY SPECIFICATION: WIRING AEROSPACE VEHICLE*), for design of wire harness in different vehicles.

The various domain rules should be stored in a dedicated Knowledge Base to guarantee flexibility. If some of the information stored in the Knowledge Base changes, for example the weight of shielding decreases, then a new optimal harness routing can be easily recomputed. Now, a comma-separated values (CSV) file is used to store simple rules to simulate the Knowledge Base. The File System contains the STEP files used to store the geometry constraint plus various data files that are generated during routing process.

The Mathematic Converter is the module responsible for the transformation of the continuous routing environment into the required discrete representation. Using the discrete representation of geometry constraint, domain constraint and design specification the Optimizer module can generate an optimal wire harness routing and save it in the File System. While the routing environment is changed, the Optimizer can update automatically to get a new optimal solution.

The Visualization Interface can transform the abstract data generated in above optimization to geometry model by using the function of GDL and show the model immediately. The Output Generator module uses the output functions of GDL to generate the geometry models of the routed harnesses and export them in the form of neutral files such as STEP^[13] and/or IGES^[14]. The data set including wire harness properties such as total length and weight is also generated and exported by the Output Generator.

III. Initial case study

To verify the functionality of the tool and methods described above a case study has been set up and described in this section. By using a given start and end point, the application is requested to find a minimum weight path in the

modified routing environment. While the routing condition is changed, the application has to update automatically to get new optimal solution.

The routing environment for this case study is an aircraft wing generated by DARwing^{[15][16]} with modifications. A high temperature device is added to the above environment, which is located on a rib of thickness equal to 1cm. This device is treated as a heating source. To simplify the problem, the heating source has been modeled as a cylinder of radius equal to 10cm. The temperature of this cylinder is uniform and equal to 200°C. The center of the cylinder is located on the rib, with coordinate center equal to (4.5 0.01 0.1). There is no air-flow in the routing environment and the surrounding temperature is assumed to be equal to 20°C. The power of heat dissipation of this device is 1000W. The thermal conductivity of aluminum alloy rib is 121W/m·°C. There is a stable temperature field around this device. Equation (2) is used to calculate this temperature field.

According to heat transfer principles, the influence of radiation and convection can be ignored for relatively low temperature as well as no air-flow. The heat transfer via air can also be neglected because of relatively low thermal conductivity of the air. The main heat transfer occurs via the rib. In this case, the heating transfer via the rib is resorted to cylinder heat conduction.

$$Q = 2\pi L\lambda(T_1 - T_2) / \ln \frac{r_2}{r_1} \quad (7)$$

Equation (7) is used to calculate the temperature distribution. Q is the heat diffusion power, and L is the thickness of the rib. λ is the thermal conductivity. r_1 and r_2 are the radii from center of the heating source to the position on the rib. T_1 and T_2 are their centigrade temperatures respectively. The computed temperature field on the rib surface is presented in Figure 8.

Using the method described in II.B, the continuous temperature field is transformed into a discrete expression. In this transformation, the coefficient δ used in equation (3) is set equals to 0.01. With a combination of discrete expression of the temperature field and the geometry model, the routing environment is generated.

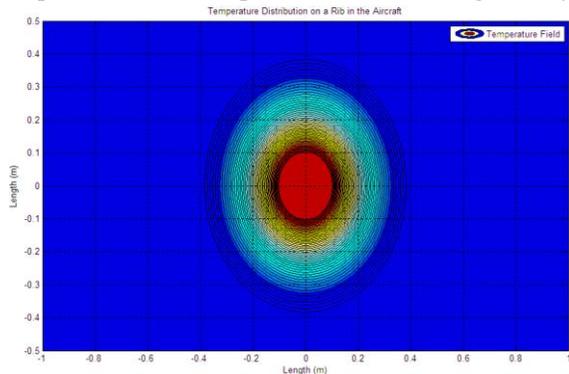


Figure 8. Temperature distribution on a rib

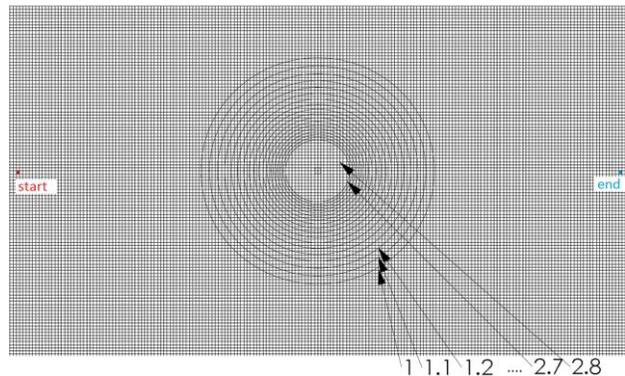


Figure 9. Discrete expression of hot zone

Figure 9 shows the outcome of this process. The numbers on the bottom are the cost coefficients of cubes located in different temperature zones. The start and end point of the wire harness, shown in Figure 9, are located at (3.5 0.02 0.1) and (5.5 0.02 0.1), respectively. The size of each cube here is 1cm×1cm×1cm. The linear density of the wire harness is 1 kg/m.

The above stated parameters have been used to test the optimal path finding ability and automatic update ability of the routing tool. The results are described in the next section.

IV. Results

A. Optimization ability

In wire harness design process, the intuitive outcome in the form of straight line connecting start and end point is shown in Figure 10. Protector is used in hot area to provide a protection of degradation but leading to the increase of total wire harness weight which is 2.74kg.

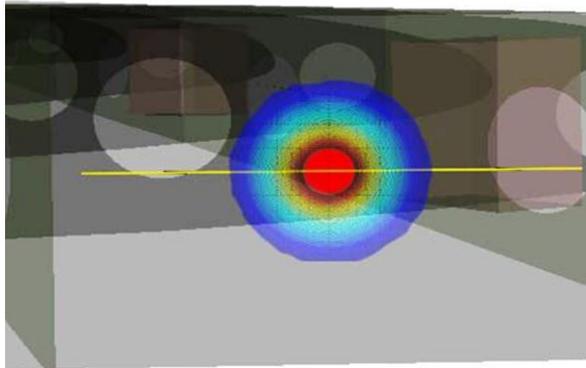


Figure 10. Intuitive outcome of wire harness
Weight : 2.74kg

By using parameter given in III, in case I, the automatic wire harness routing application finds the minimal weight path automatically of which the cost (weight) is 2.37kg . Figure 11 shows this path, which avoids hot area entirely.

Comparing with the intuitive outcome, the total weight of wire harness generated by automatic wire harness routing application is 13.5% less. The optimized function of this application is validated.

B. Automatic update

Wire harness design is a long term task. During the design process, lots of design conditions will be changed. For example, the protector which is lighter but has the same protective function as the previous one will be introduced for the innovative technology. This provides an opportunity for wire harness to be modified to get a new optimal solution. In this section, the weight decrease of protector is simulated by decreasing of coefficient δ . The followed two cases, of which the physical routing environment is the same as above one, are used to validate the automatic update ability of the application.

Two different values δ 0.004 and 0.002 are used for case II and case III. Then, discrete expression of routing environment is regenerated. Using given parameters, the routing application explores the routing environment and generates two outcomes respectively.

Because less cost for wire harness going through the hot zone, in case II , the application adopted partly bypass the hot area as an optimal solution. And its total weight is 2.21kg . The outcome of it is shown in Figure 12.

For even lest cost, the best solution in case III is wire harness going through hot area in the form of a stright line, of which the weight is 2.11kg .

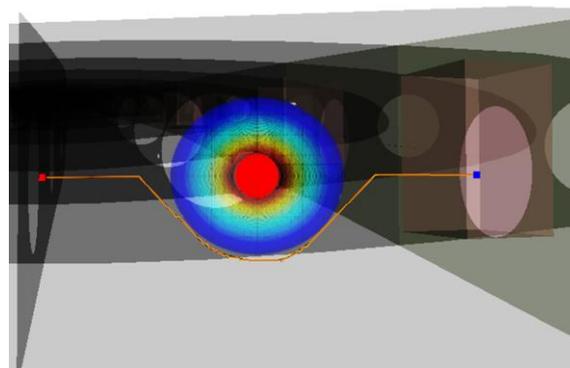


Figure 11. Optimal outcome of wire harness I
($\delta = 0.01$) Weight : 2.37kg

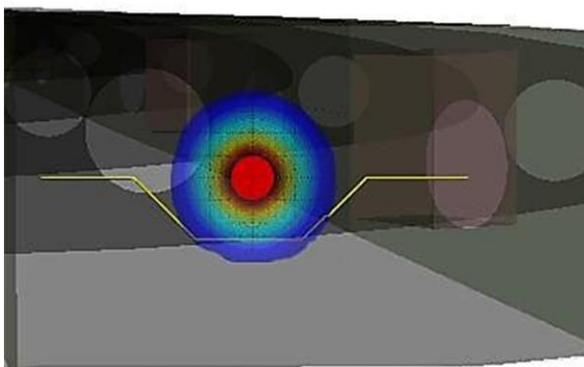


Figure 12. Optimal outcome of wire harness II
($\delta = 0.004$, Weight : 2.21kg)

Comparing with totally bypassing solution in case I, these two updated solutions save 6.7% and 11.0% weight respectively.

The geometry models, which are shown from Figure 10 to Figure 13, come from the screen shots of GDL visualization interface. These models are stored in readable computer-aided design files such as STEP or IGES file

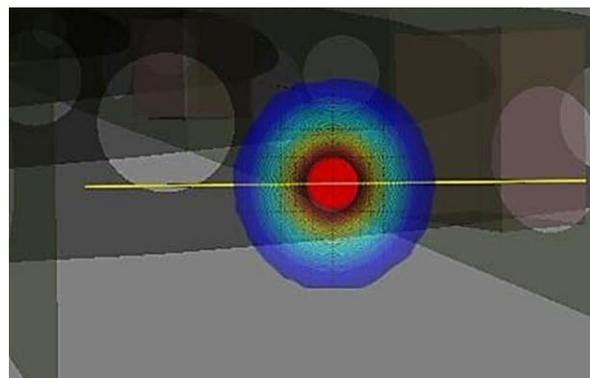


Figure 13. Optimal outcome of wire harness III
($\delta = 0.002$, Weight : 2.11kg)

for future inspection and modification via other commercial software. Other data files containing the harness properties, such as length, weight, are also generated.

V. Conclusion

This paper has described a method for automatic wire harness routing based on optimization. At the beginning, the complexity of the wire harness design process is discussed. The need and opportunities of developing a wire harness design support tool are evident. Building on the initial results described in a previously presented publication, a new software application for automatic routing of wire harness is described in this paper. The presented application extends the results presented by the authors in a previous publication. The proposed routing tool is able to account both for geometrical and domain specific constraints, such as the presence of critically hot areas. The A* searching algorithm is used to compute, in full automation, optimal harness paths. When changes occur in the definition of the routing environments, the tools allow a fast re-computation of the wire harness route, while guaranteeing compliance to all the constraints.

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